Is Thrust Well-Defined?

(Considerations in Aerodynamic Force Decomposition)

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Based on paper AIAA 2021–2552 (also provides references for this presentation)

Motivation — NASA N+3 Project (2008–2014)

- MIT/Aurora/Pratt effort to develop D8 aircraft concept, with focus on BLI
- Culminated in powered wind tunnel model tests in 14- by 22-foot Langley tunnel
- Measured: Total aero force vector, Propulsor power, BLI's reduction of cruise power



Some Questions Commonly Raised

- "How does BLI reduce **drag**?"
- "How do you account for BLI's effect on **thrust**?"



A better question: What exactly do **drag** and **thrust** even mean here?

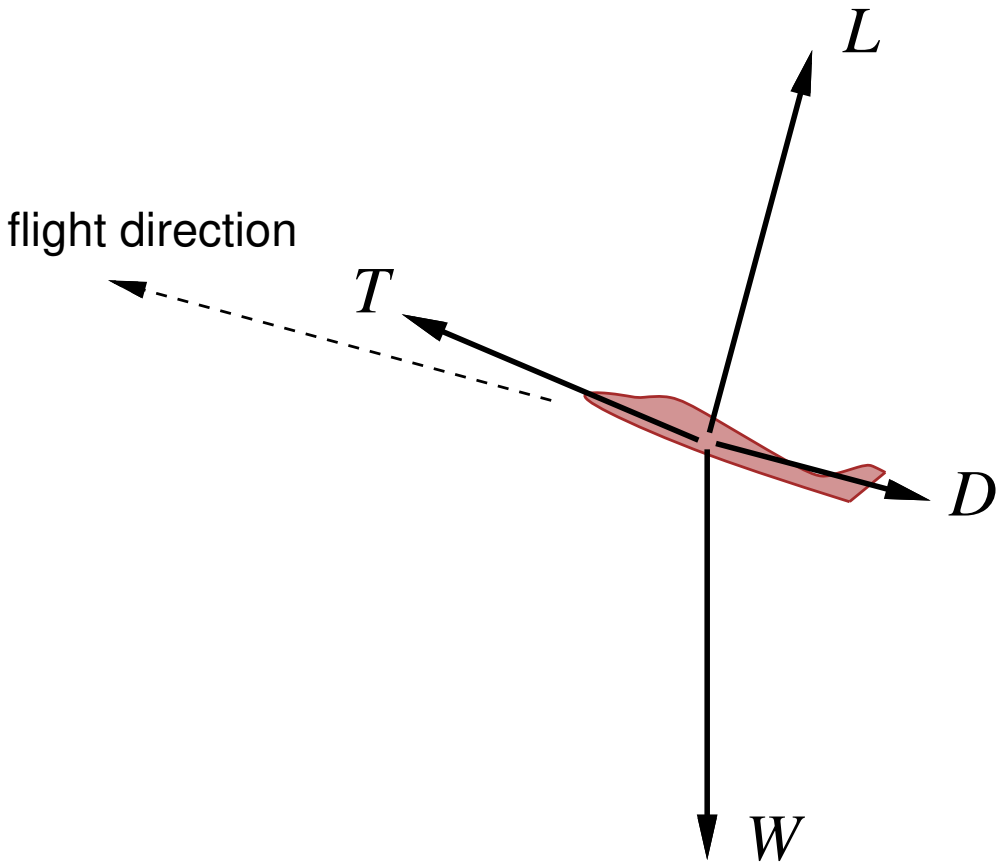
And what exactly do we mean by **drag** and **thrust** for a non-BLI aircraft?

Presentation Summary

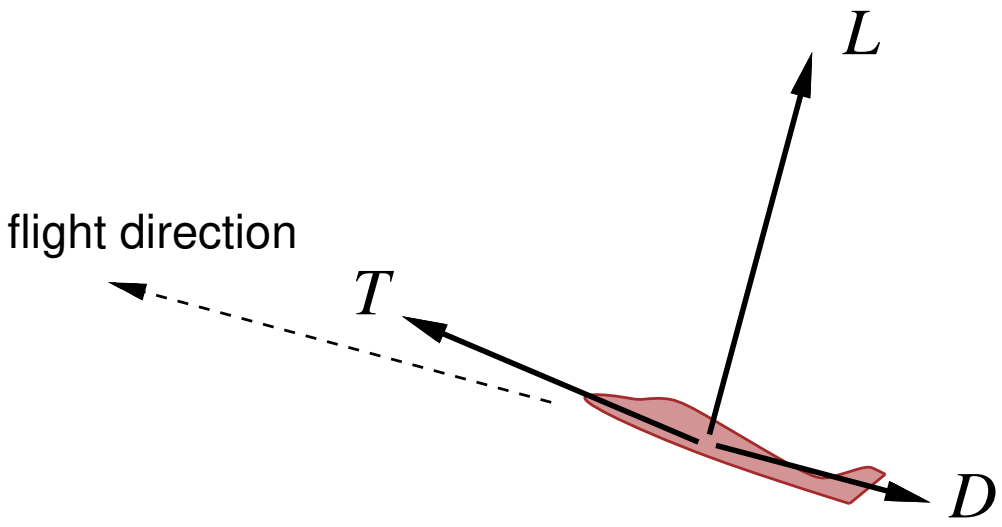
- Aerodynamic forces and decomposition
  - Rigorous definitions (near-field, far-field, aerodynamic force)
  - Sketchy definitions (drag, thrust, "thrust vector", etc.)
  - Approximations to definitions
  - Correlation-based estimates
- Decomposition evaluation via known test cases (uh-oh...)
- Application to especially challenging cases
  - BLI
  - Blown lift
  - Moments in general
- Decomposition attributes
  - Exactness
  - Consistency
  - Uniqueness
  - Extractability

Forces On An Airplane — I

The Popular View



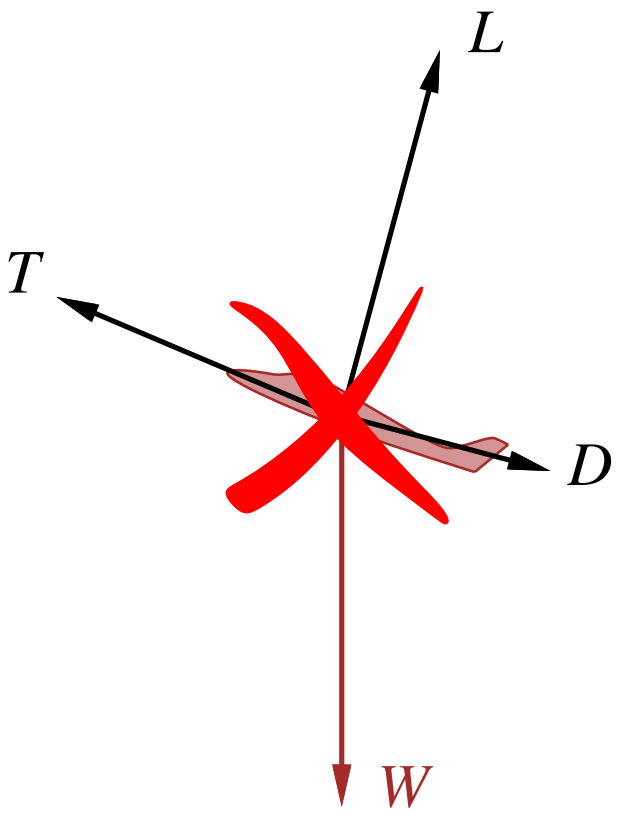
Forces On An Airplane — II

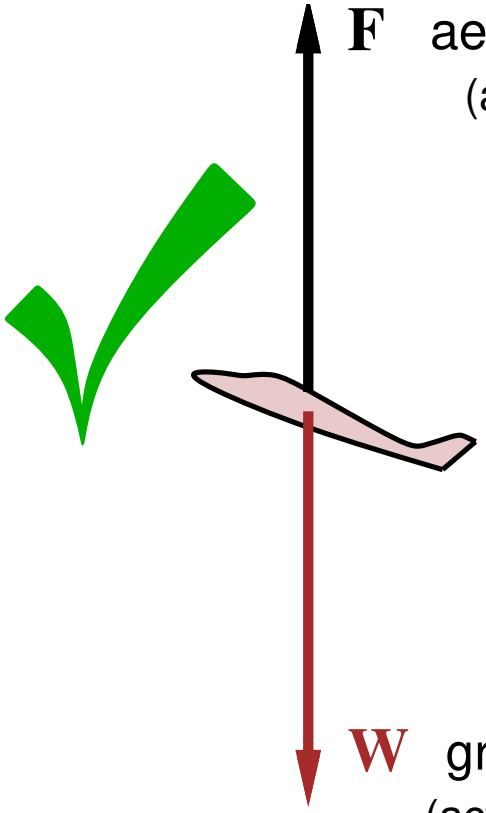


- Lift, Thrust, Drag can, and have been, estimated by measurement or analysis — since before the Wright brothers
- But can these force components be defined from the geometry and flowfield?
  It matters . . .
  . . . for objective truth to validate estimates
  . . . for physical insight into e.g. drag-production mechanisms
  . . . for clear application to new and "difficult" cases like BLI or blown lift
- Main problem: define thrust and drag forces, and also lift force while you're at it
- Related problem: decompose drag into profile, induced, wave. . . drag components

Forces On An Airplane — III

The First Step





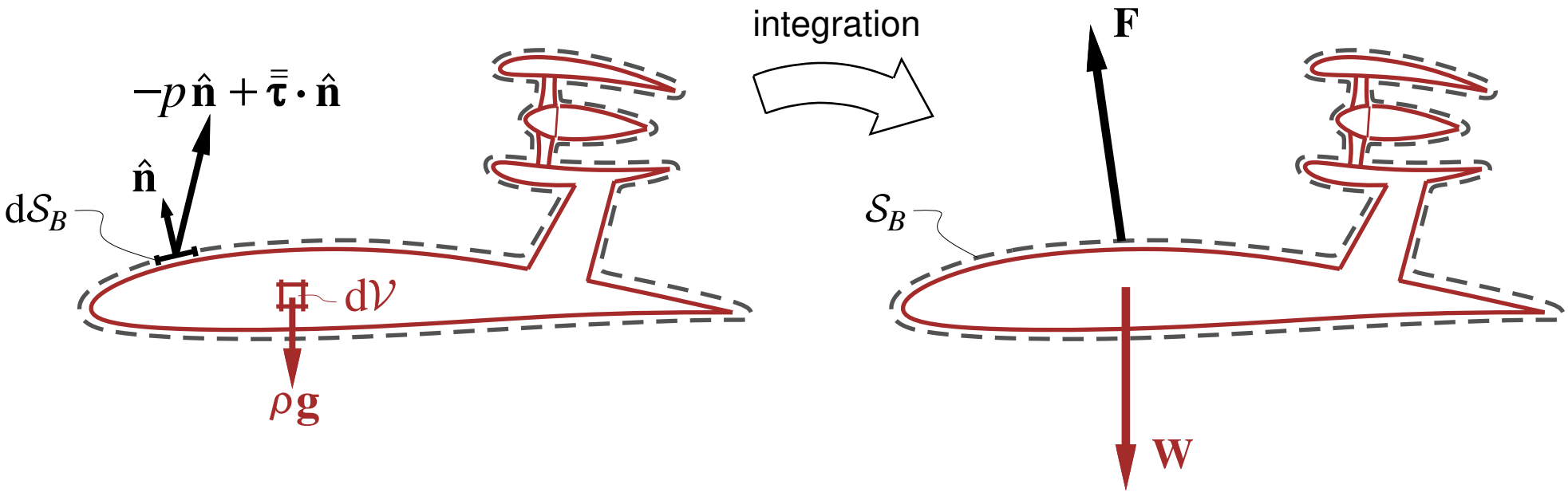
F aerodynamic force vector
(acts on airplane surface)

W gravity force vector
(acts on airplane volume)

Near-Field (aircraft surface) Force Definition

$$\mathbf{F} \equiv \oiint \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_B \quad ; \quad p_{\text{ref}} \text{ is arbitrary}$$

$$= \quad \mathbf{F}_{\text{pressure}} \quad + \quad \mathbf{F}_{\text{friction}}$$

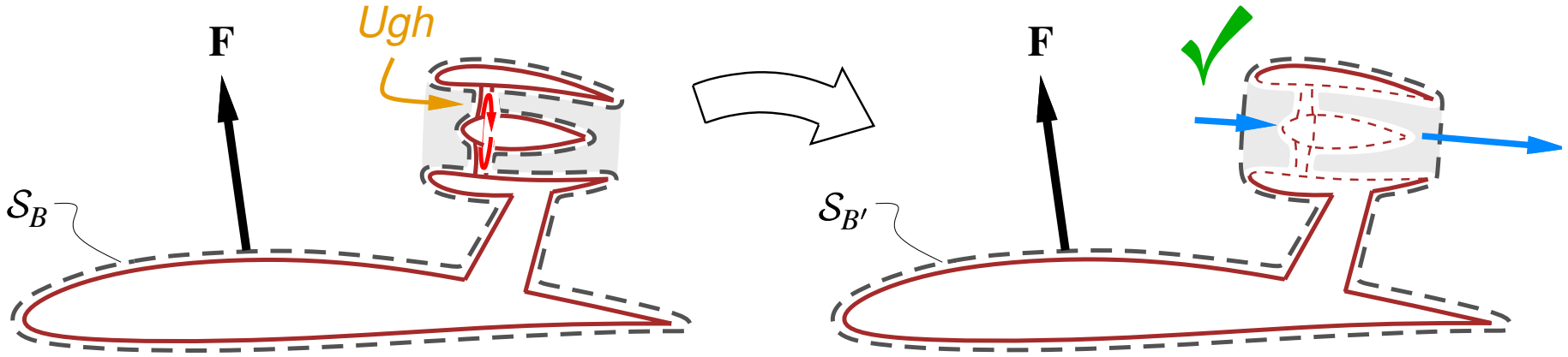


$$\mathbf{W} \equiv \iiint \rho\mathbf{g}\,\mathrm{d}\mathcal{V} = m\mathbf{g}$$

Alternative Near-Field Force Definition

$$\mathbf{F} = \oiint \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V}\cdot\hat{\mathbf{n}})\mathbf{V} \right] \mathrm{d}\mathcal{S}_{B'}$$

$$= \mathbf{F}_{\text{pressure}'} + \mathbf{F}_{\text{friction}'} + \mathbf{F}_{\text{flux}'}$$



Equivalent, since momentum integral over shaded volume is zero:

$$\iiint \left\{ \nabla \cdot \left[(p - p_{\text{ref}})\,\bar{\bar{\mathbf{I}}} - \bar{\bar{\boldsymbol{\tau}}} + \rho\mathbf{V}\mathbf{V}^{\mathsf{T}} \right] + \frac{\partial(\rho\mathbf{V})}{\partial t} \right\} \mathrm{d}\mathcal{V}_{\text{shaded}} = \mathbf{0}$$

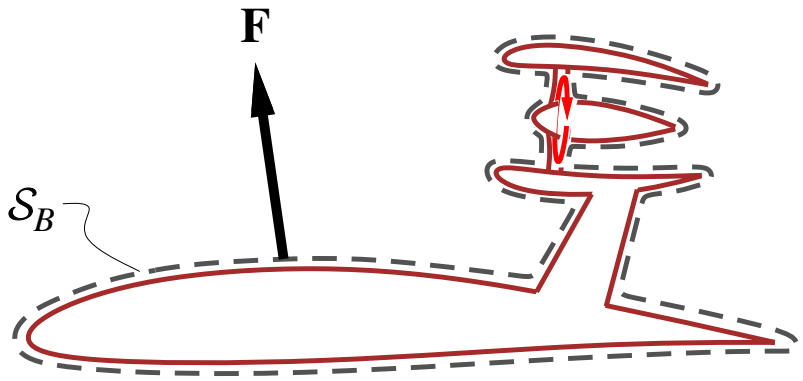
Using $\mathcal{S}_{B'}$ is much preferable:

- Avoids integration over engine interior surfaces, some of which move
- Avoids integration over interior surface of e.g. ventilated cabin
- Avoids unsteady integrand on $\mathcal{S}_B$, since integrand on $\mathcal{S}_{B'}$ is typically steady

Comparison of Near-Field Force Definitions

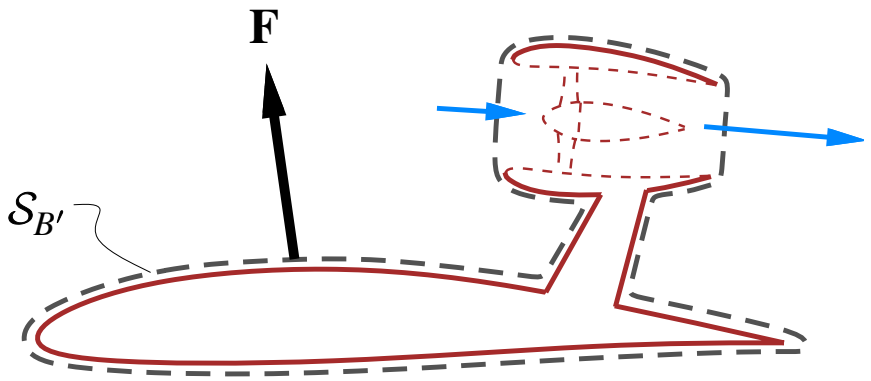
Defined on $\mathcal{S}_B$ (covers any moving parts):

$$\mathbf{F} = \mathbf{F}_{\text{pressure}} + \mathbf{F}_{\text{friction}}$$



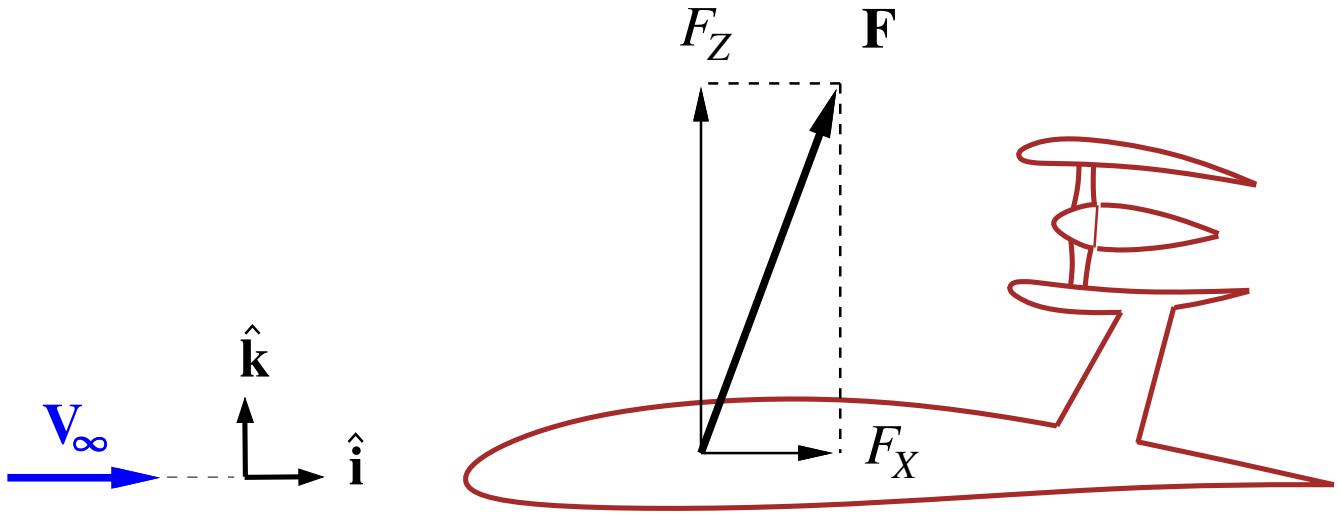
Defined on $\mathcal{S}_{B'}$ (generally fixed):

$$\mathbf{F} = \mathbf{F}_{\text{pressure}'} + \mathbf{F}_{\text{friction}'} + \mathbf{F}_{\text{flux}'}$$



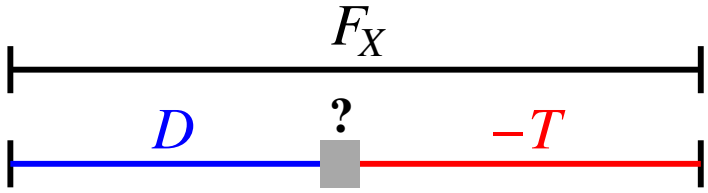
- The two overall $\mathbf{F}$ values are identical, but ...
  $\mathbf{F}_{\text{pressure}} \neq \mathbf{F}_{\text{pressure}'}$ and $\mathbf{F}_{\text{friction}} \neq \mathbf{F}_{\text{friction}'}$, since $\mathcal{S}_B$ and $\mathcal{S}_{B'}$ are different
- Familiar $\mathbf{F}_{\text{pressure}'} + \mathbf{F}_{\text{friction}'}$ breakdown is actually incomplete
- Remaining $\mathbf{F}_{\text{flux}'}$ part is not a meaningful thrust ...
  It misses pressure contributions on propulsor inflow and outflow portions of $\mathcal{S}_{B'}$

Force Components in Freestream Axes



$$F_X \equiv \mathbf{F} \cdot \hat{\mathbf{i}} = D - T$$
$$F_Y \equiv \mathbf{F} \cdot \hat{\mathbf{j}} = Y$$
$$F_Z \equiv \mathbf{F} \cdot \hat{\mathbf{k}} = L$$

Breakdown of F_X into individual D and $-T$ parts still needs to be defined

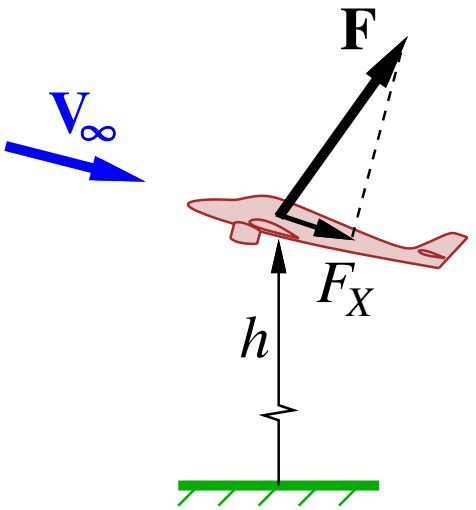


But is this breakdown even necessary? It depends . . .

Q: Do We Need Separate Drag and Thrust Values?

A1: NO. Aircraft energy rate depends only on total F_X

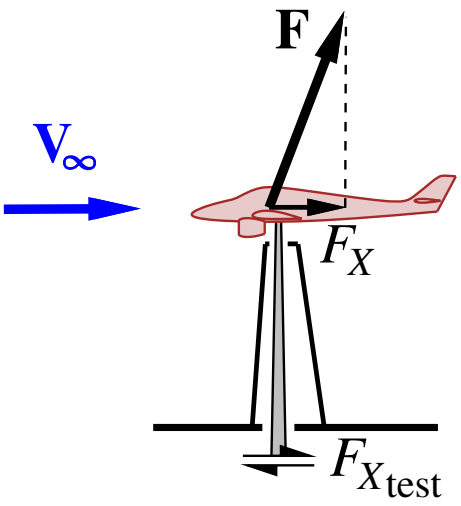
$$m\,\frac{\mathrm{d}}{\mathrm{d}t}\left(gh+\tfrac{1}{2}V_\infty^2\right) \;=\; -\mathbf{F}\cdot\mathbf{V}_\infty \;=\; -F_X V_\infty$$
$$= \;0 \;\text{ in steady level flight}$$



A2: NO. F_X is what's measured directly in a powered wind tunnel model test, or computed with CFD

$$F_X \;\simeq\; F_{X_{\text{test}}}$$

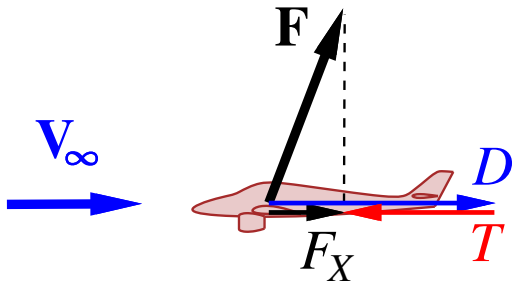
$$F_X \;\simeq\; F_{X_{\text{CFD}}}$$



Q: Do We Need Separate Drag and Thrust Values?

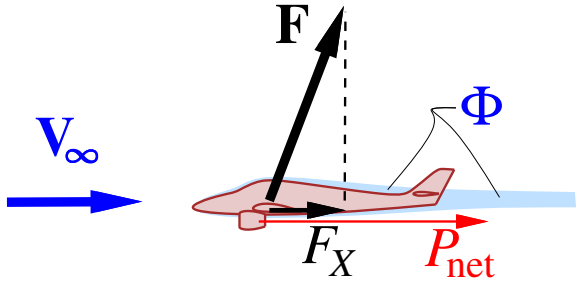
A3a: YES, if used to estimate total streamwise force:

$$F_X = D - T$$

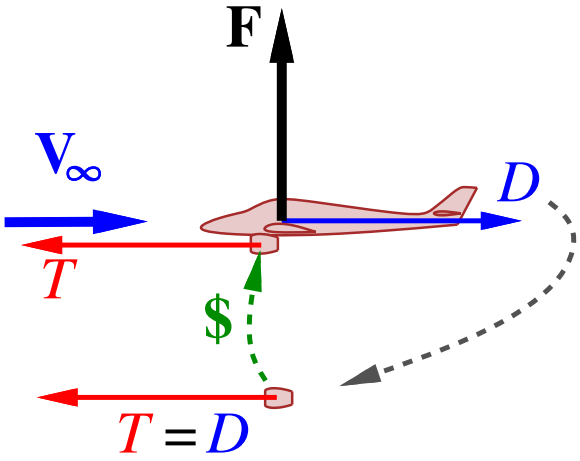


A3b: NO, if power balance is used instead:

$$F_X V_\infty = \Phi - P_{\text{net}}$$



A4: YES. Drag is needed to determine (and pay for) required thrust $T = D$ for cruise



Total F_X is rigorously defined, but how do we <u>define</u> drag and thrust separately?

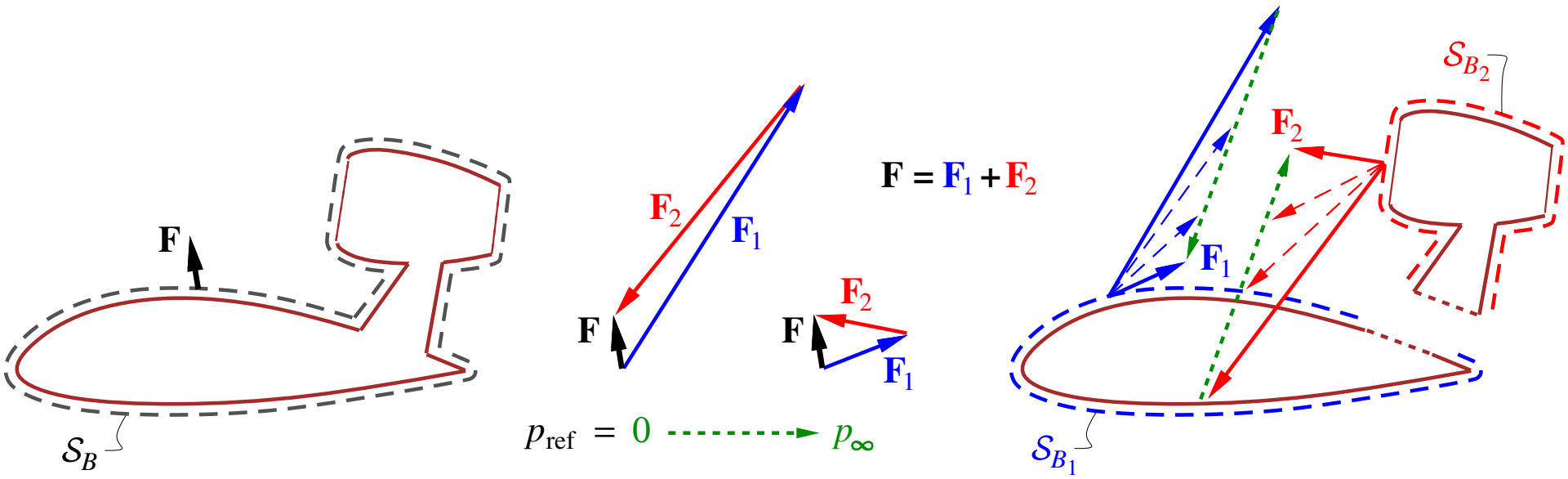
Problems with Geometric Force Decomposition — I

Q: Can we define drag and thrust via force integrals over airframe and engine pod?

$$\mathbf{F}_{\text{airframe}} \stackrel{?}{=} \mathbf{F}_1 \equiv \iint \Big[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V}\cdot\hat{\mathbf{n}})\mathbf{V} \Big]\, \mathrm{d}\mathcal{S}_{B_1}$$

$$\mathbf{F}_{\text{engine}} \stackrel{?}{=} \mathbf{F}_2 \equiv \iint \Big[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V}\cdot\hat{\mathbf{n}})\mathbf{V} \Big]\, \mathrm{d}\mathcal{S}_{B_2}$$

A: Not uniquely. Arbitrary pressure offset p_{ref} does not affect total $\mathbf{F} = \mathbf{F}_1 + \mathbf{F}_2$, but does (greatly) affect $\mathbf{F}_1$, $\mathbf{F}_2$ on geometry pieces



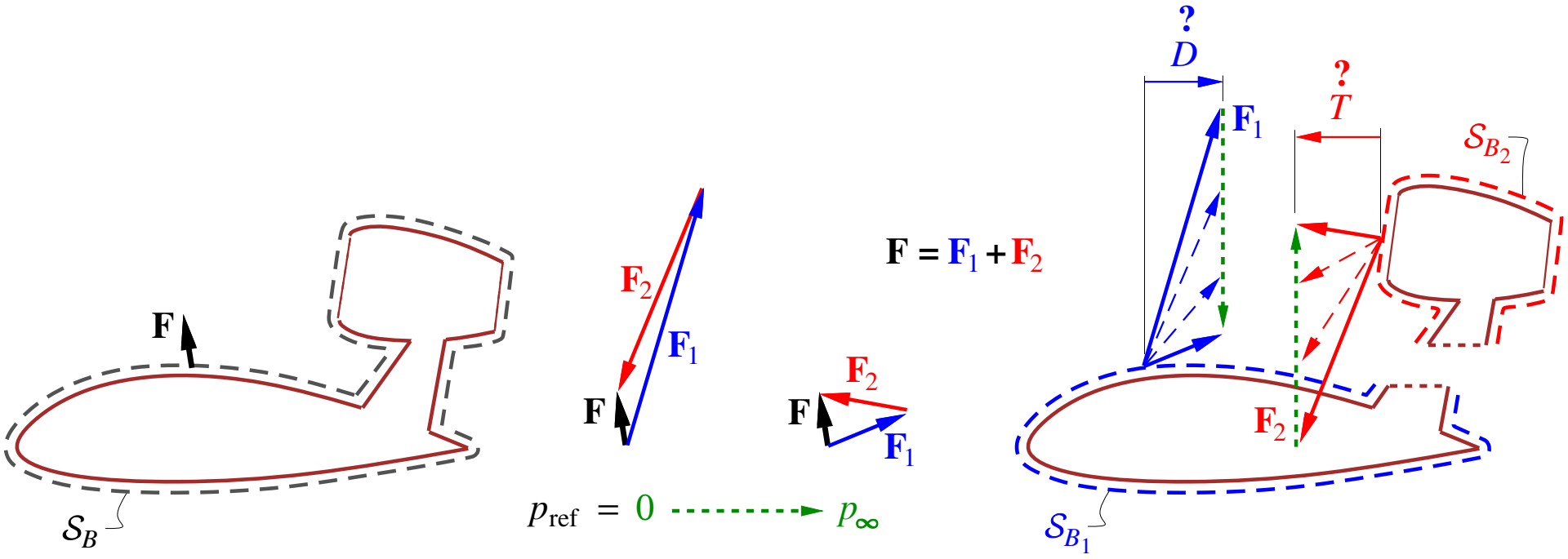
Problems with Geometric Force Decomposition — II

Q: Can we make "cut" parallel to $\mathbf{V}_\infty$, so p_{ref} has no influence on D,T parts?

$$D \stackrel{?}{=} \hat{\mathbf{i}} \cdot \iint \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V} \cdot \hat{\mathbf{n}})\mathbf{V} \right] \mathrm{d}\mathcal{S}_{B_1}$$

$$-T \stackrel{?}{=} \hat{\mathbf{i}} \cdot \iint \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V} \cdot \hat{\mathbf{n}})\mathbf{V} \right] \mathrm{d}\mathcal{S}_{B_2}$$

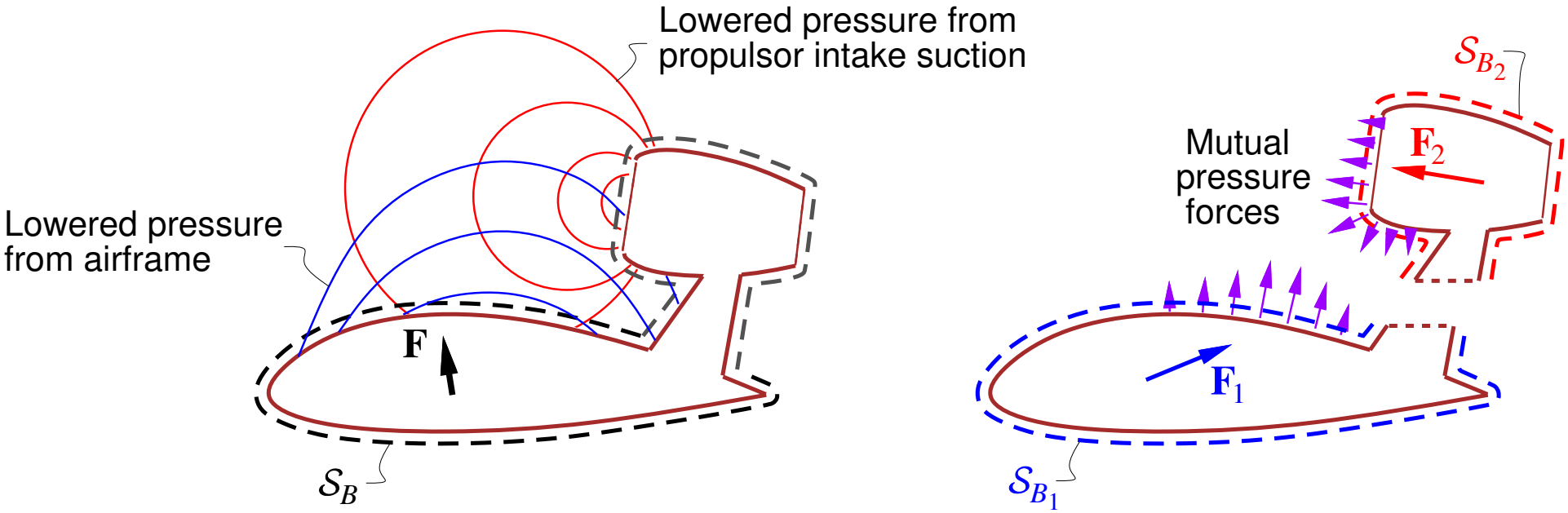
A: Yes, but result is questionable. Forces on nacelle exterior count as part of thrust.



Also . . .

Problems with Geometric Force Decomposition — III

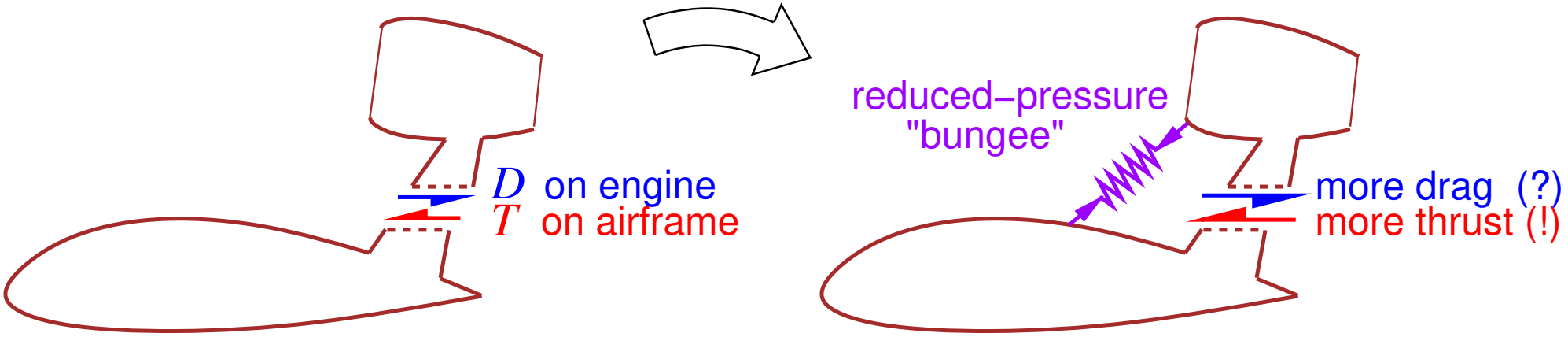
A(cont'd): $\mathbf{F}_1$ and $\mathbf{F}_2$ used for drag and thrust include opposing pressure-couple contributions between nearby airframe and engine



- Low pressure from propulsor inlet, imparted on airframe, counts as "lift" (plausible)
- Low pressure from airframe, imparted on propulsor inlet, counts as "thrust" (??)

Problems with Geometric Force Decomposition — IV

Effect of added pressure-force couple between propulsor and airframe:

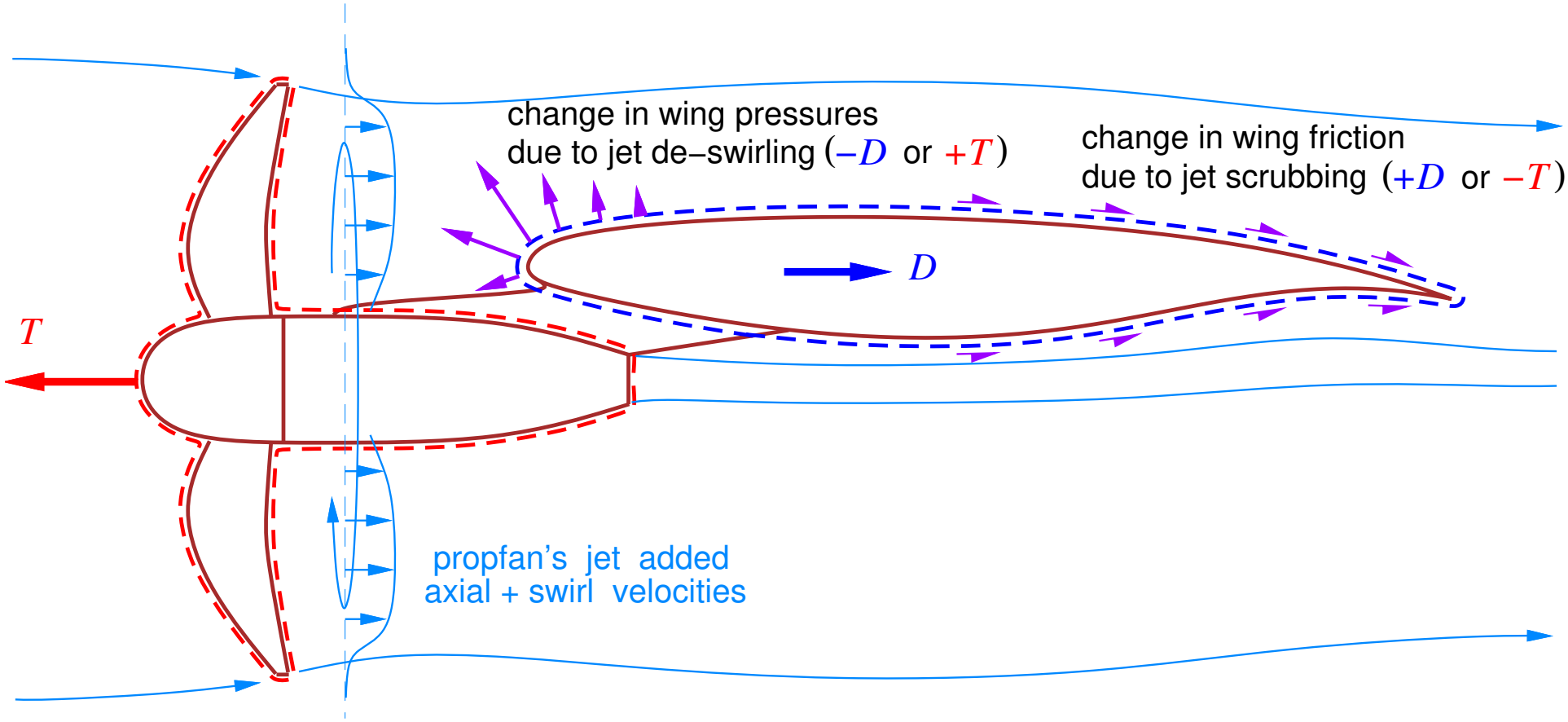


Are the changes in "thrust" and "drag" meaningful? Not really

But who gets the credit for the added "thrust"?
But who gets the blame for the added "drag"?

Problems with Geometric Force Decomposition — V

Vortical-flow interactions have similar issues:

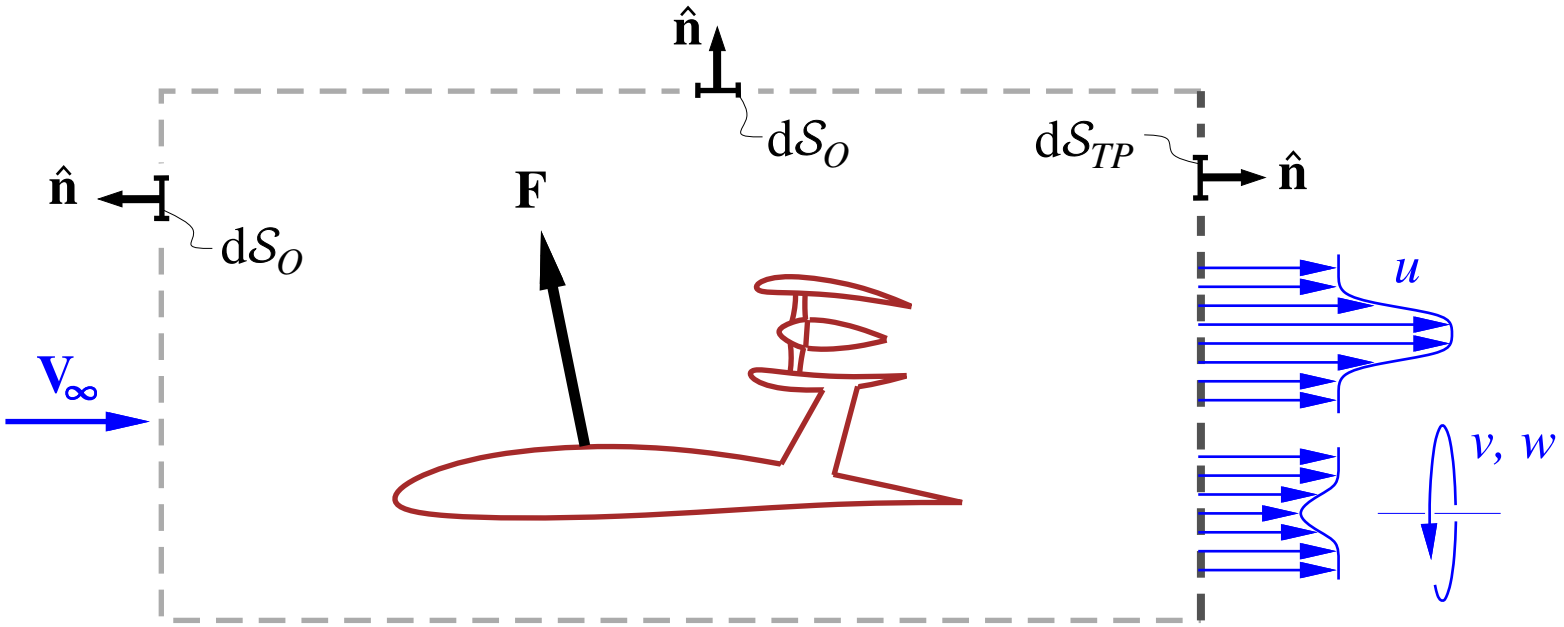


Who gets the credit for de-swirl of the prop jet?
Who gets the blame for added jet scrubbing losses?

We need another approach . . .

Far-Field (off airplane surface) Force Definition

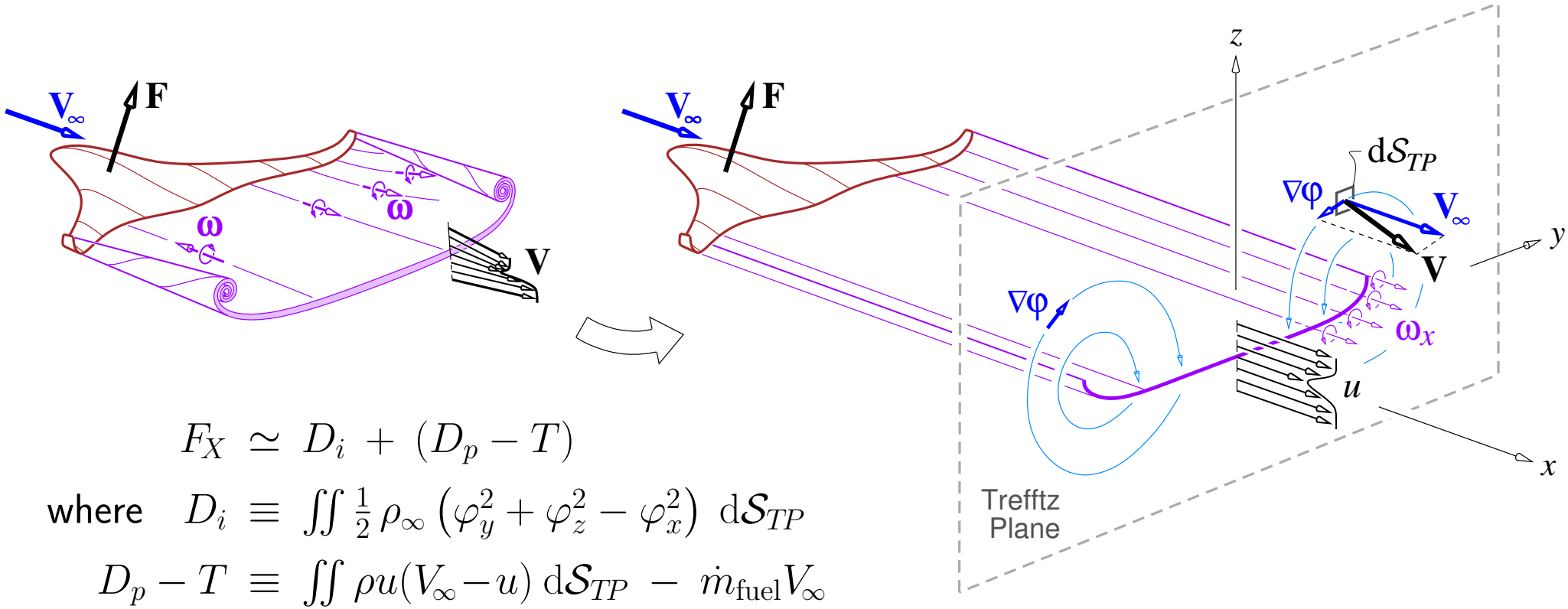
$$\mathbf{F} = \oiint \left[(p_\infty - p)\,\hat{\mathbf{n}} + \rho\,(\mathbf{V}\cdot\hat{\mathbf{n}})(\mathbf{V}_\infty - \mathbf{V}) + \bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{i}} \right] \mathrm{d}\mathcal{S}_O - \dot{m}_O \mathbf{V}_\infty$$



- For any $\mathcal{S}_O$, gives exactly the same $\mathbf{F}$ value as near-field definitions
- Viscous term $\bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{i}}$ is typically negligible on a distant $\mathcal{S}_O$
- Can be manipulated into an integral over only the exit Trefftz Plane surface $\mathcal{S}_{TP}$

Classical Far-Field Force Decomposition

Idealization of wake flow at Trefftz-Plane enables classical far-field force expressions



$$F_X \simeq D_i + (D_p - T)$$

where $D_i \equiv \iint \frac{1}{2}\rho_\infty \left(\varphi_y^2 + \varphi_z^2 - \varphi_x^2\right) \, \mathrm{d}\mathcal{S}_{TP}$

$$D_p - T \equiv \iint \rho u(V_\infty - u) \, \mathrm{d}\mathcal{S}_{TP} - \dot{m}_{\text{fuel}} V_\infty$$

$$F_Y = \rho_\infty V_\infty \iint -z\,\omega_x \, \mathrm{d}\mathcal{S}_{TP} + \iint (\rho_\infty V_\infty - \rho u)\, v \, \mathrm{d}\mathcal{S}_{TP}$$

$$F_Z = \rho_\infty V_\infty \iint \; y\,\omega_x \, \mathrm{d}\mathcal{S}_{TP} + \iint (\rho_\infty V_\infty - \rho u)\, w \, \mathrm{d}\mathcal{S}_{TP}$$

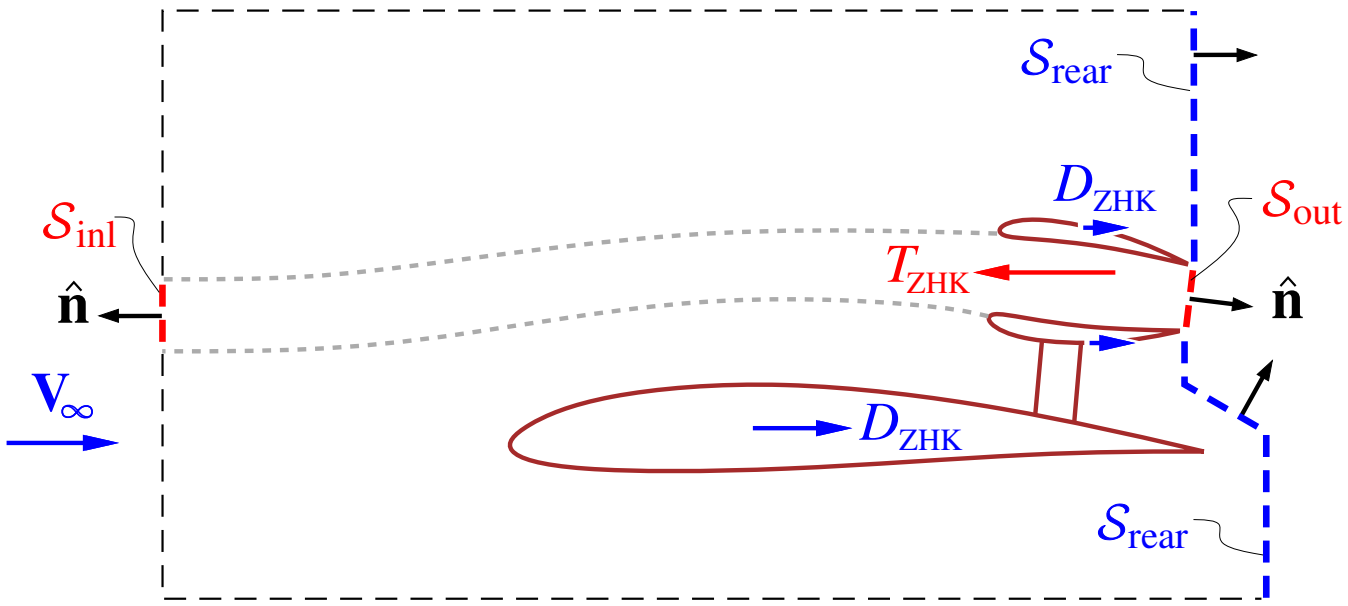
Still not obvious how to define D_p and T separately, but we're close ...

Hybrid Near-field/Far-field Forces — I

Zucrow/Hill/Kerrebrock thrust and complementary drag:

$$T_{\text{ZHK}} \equiv \iint \left[(p - p_\infty)\, n_X + \rho(\mathbf{V}\cdot\hat{\mathbf{n}})\, u - \hat{\mathbf{i}}\cdot\bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_{\text{out}} - \dot{m}_{\text{inl}} V_\infty$$

$$D_{\text{ZHK}} \equiv \iint \left[(p_\infty - p)\, n_X + \rho(\mathbf{V}\cdot\hat{\mathbf{n}})(V_\infty - u) + \hat{\mathbf{i}}\cdot\bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_{\text{rear}}$$



Pro: $D_{\text{ZHK}} - T_{\text{ZHK}} = F_X$ exactly ($D_{\text{ZHK}} - T_{\text{ZHK}}$ is equivalent to far-field F_X definition)

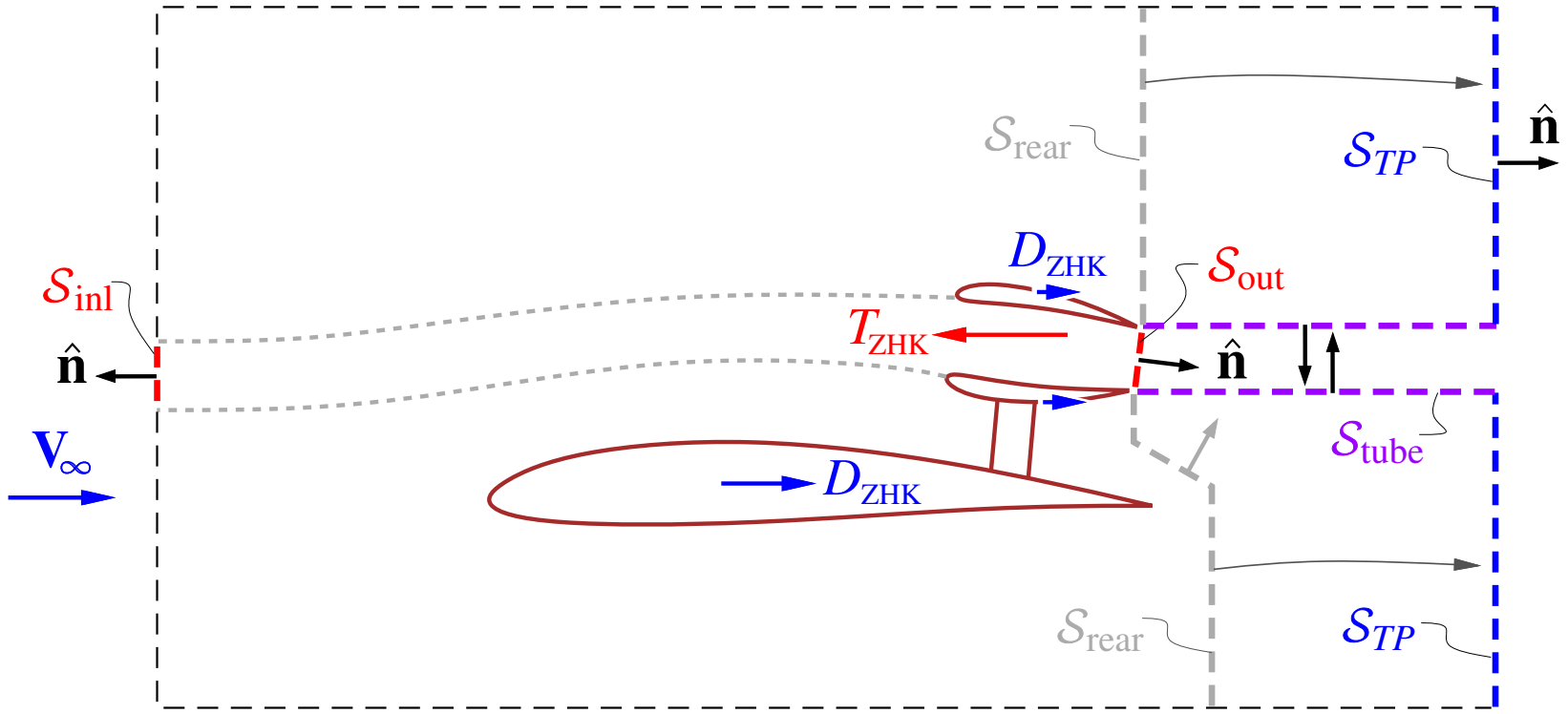
Pro: T_{ZHK} is easily approximated

Con: D_{ZHK} is intractable — only resort is direct evaluation from CFD solution

Hybrid Near-field/Far-field Forces — II

Deforming $\mathcal{S}_{\text{rear}}$ downstream, into $\mathcal{S}_{TP}$, doesn't really simplify D_{ZHK} ...

$$D_{\text{ZHK}} \stackrel{?}{=} \iint \left[(p_\infty - p)\, n_X + \rho(\mathbf{V}\cdot\hat{\mathbf{n}})(V_\infty - u) + \hat{\mathbf{i}}\cdot\bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_{TP}$$
$$+ \iint \left[(p_\infty - p)\, n_X + \rho(\mathbf{V}\cdot\hat{\mathbf{n}})(V_\infty - u) + \hat{\mathbf{i}}\cdot\bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_{\text{tube}}$$

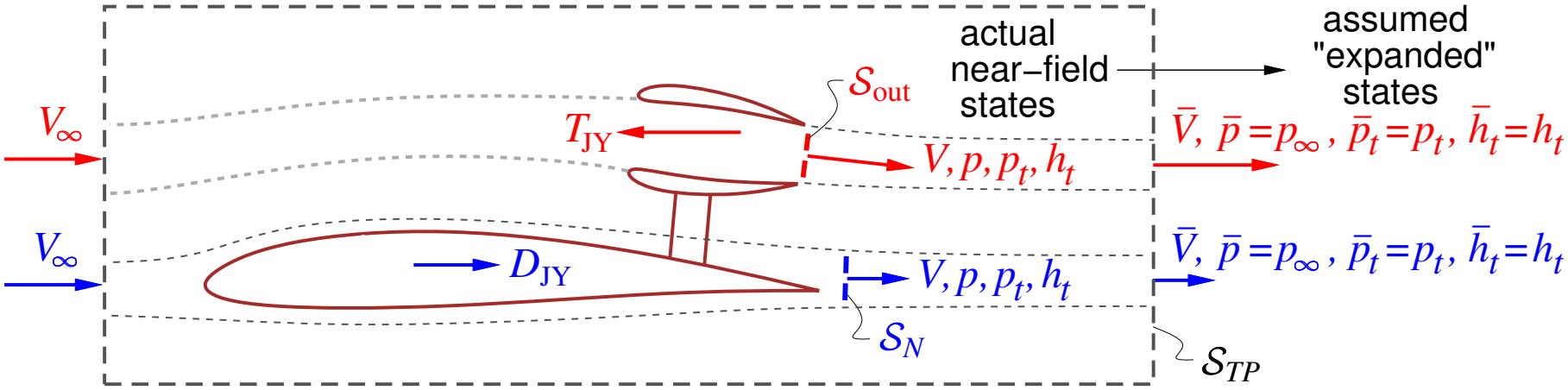


- Cannot easily estimate integral over connecting surface $\mathcal{S}_{\text{tube}}$
- Cannot easily estimate lost contribution from "hole" in $\mathcal{S}_{TP}$

Parallel-Streamtube (Jones/Young) Approximation

"Expanded" speed $\bar{V}$ defined from local p_t, h_t, and $\bar{p} = p_\infty$:

$$\bar{V}(p_t, h_t) \equiv \sqrt{2h_t \left[1 - (p_\infty/p_t)^{(\gamma-1)/\gamma} \right]} \qquad \text{(undefined if } p_t < p_\infty\text{)}$$

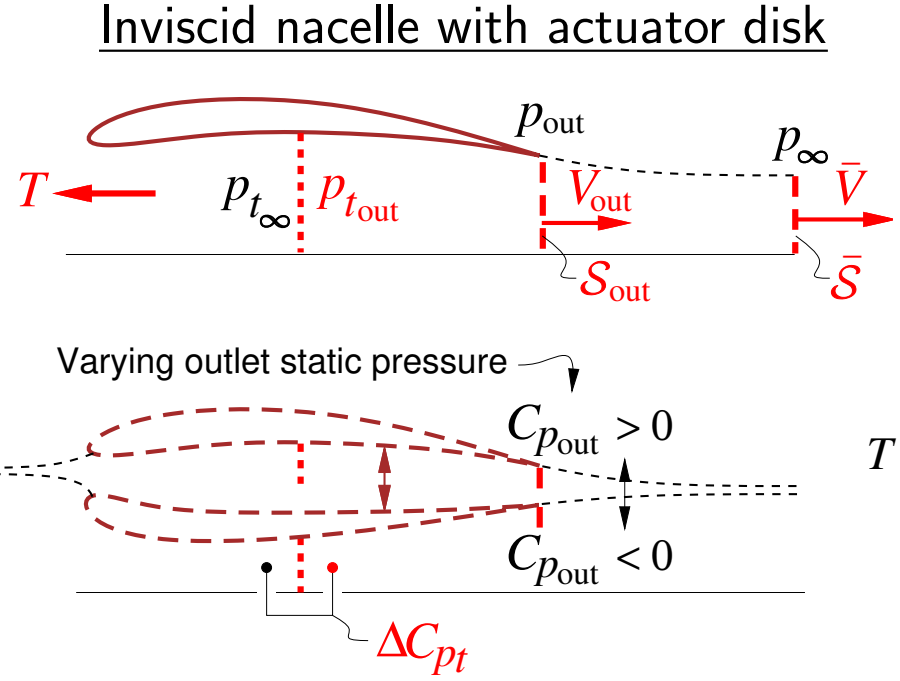


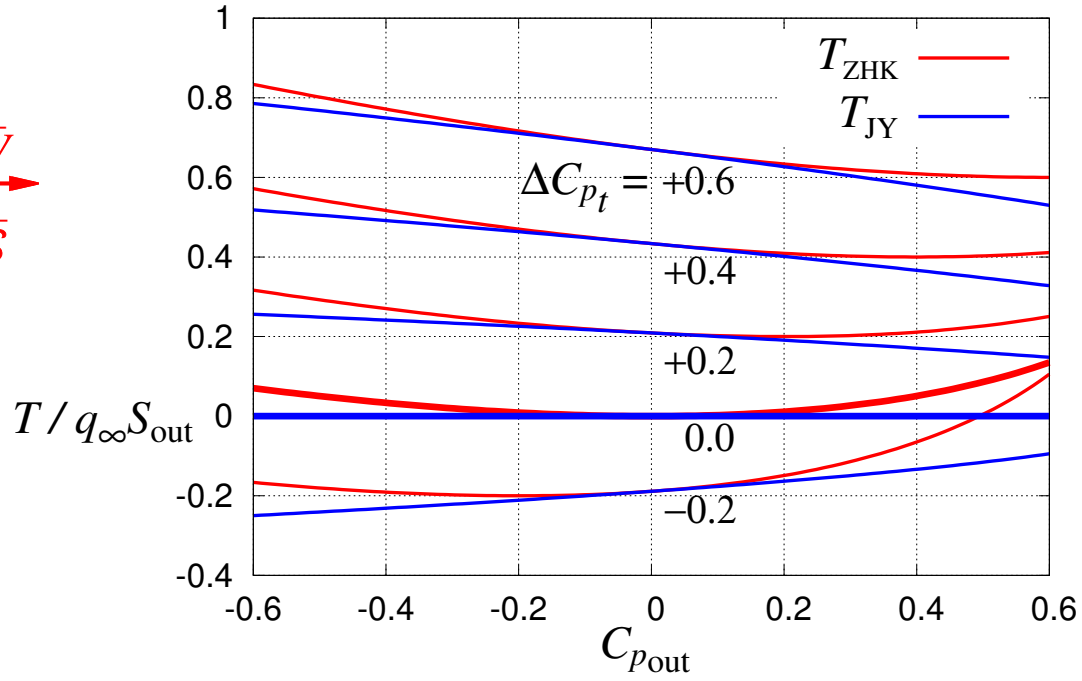
$$T_{\text{JY}} \equiv \iint \left(\bar{V} - V_\infty\right) \mathrm{d}\dot{m}_{\text{out}} + \dot{m}_{\text{fuel}} V_\infty$$

$$D_{\text{JY}} \equiv \iint \left(V_\infty - \bar{V}\right) \mathrm{d}\dot{m}_N$$

- Flow is not really isentropic from $\mathcal{S}_N$ to $\mathcal{S}_{TP}$, so will actually have $\bar{p}_t \neq p_t$
- If jet is in or near trailing vortex core, then will have $\bar{p} \neq p_\infty$
- Does not account for any trailing vorticity (induced drag)
- For all the above reasons, $D_{\text{JY}} - T_{\text{JY}} \neq F_X$ exactly

Comparison of ZHK and JY Thrust Forces



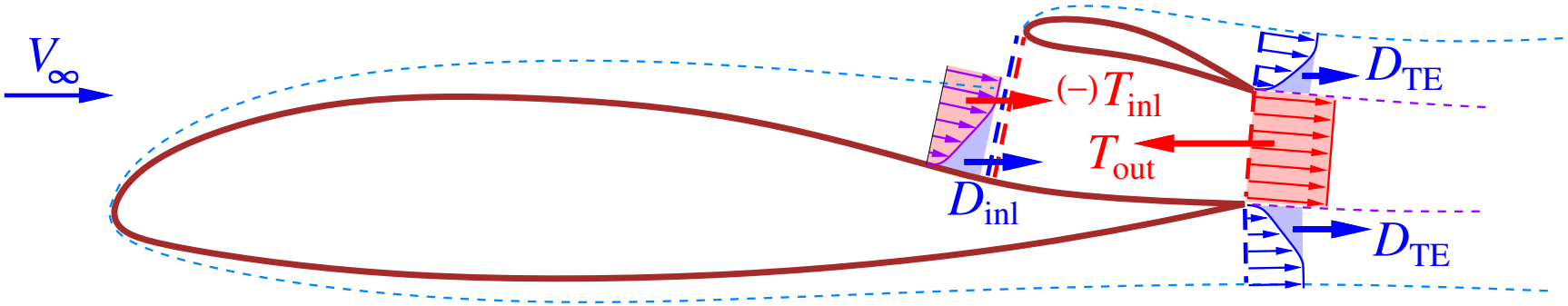


For case of zero total pressure rise $\Delta C_{p_t} = 0$, which has $F_X = 0$ exactly, ...

- JY definition predicts $T_{\text{JY}} = 0$ and hence also $D_{\text{JY}} = 0$, all as expected
- ZHK definition predicts $T_{\text{ZHK}} > 0$, and hence also $D_{\text{ZHK}} > 0$
  - "free thrust" (no fuel needed!), but also equal drag, so airplane doesn't notice
  - but airframer pays the engine vendor for this "thrust", so accountants will notice

Boundary Layer Ingestion

BLI thrust/drag analysis using Jones/Young method



TE momentum defect:	D_{TE}	$\equiv$	$\iint \left(V_\infty - \bar{V}\right) \mathrm{d}\dot{m}_{\text{TE}}$	= "Jones profile drag"
Inlet momentum defect:	D_{inl}	$\equiv$	$\iint \left(V_\infty - \bar{V}\right) \mathrm{d}\dot{m}_{\text{inl}}$	= "ingested drag" (?)
Outlet momentum:	T_{out}	$\equiv$	$\iint \bar{V} \, \mathrm{d}\dot{m}_{\text{out}}$	= "gross thrust"
Inlet momentum:	T_{inl}	$\equiv$	$\iint -\bar{V} \, \mathrm{d}\dot{m}_{\text{inl}}$	= "ram drag"

Overall profile drag: $D_{\text{JY}} = D_{\text{TE}} + D_{\text{inl}}$

Overall thrust: $T_{\text{JY}} = T_{\text{out}} + T_{\text{inl}} = T_{\text{out}} - V_\infty \dot{m}_{\text{inl}} + D_{\text{inl}}$

Total streamwise force: $F_X = D_{\text{JY}} - T_{\text{JY}} = D_{\text{TE}} - T_{\text{out}} + V_\infty \dot{m}_{\text{inl}}$

- F_X does not *explicitly* depend on "ingested drag" D_{inl}, which is reassuring
- But T_{JY} is increased by D_{inl}. Should the engine vendor get paid more for this?

Wetted-Area Force Estimation

Profile drag estimate:

$$D_p = D_{\text{plate}} + D_{\text{form}}$$

$$D_{\text{plate}} \equiv q_\infty S_{\text{wet}} C_{F(Re_\ell)}$$
$$D_{\text{form}} \equiv q_\infty S_{\text{ref}} C_{\text{form}(t/c)}$$

- D_{plate} sometimes called "friction drag", but it is not the same as D_{friction}
- Usefulness for profile drag prediction hinges on C_{form} being reliably known, but this is dubious for general body shapes

Including induced drag and thrust estimates gives total streamwise force...

$$F_X \simeq D_{\text{plate}} + D_{\text{form}} + D_i - T$$

...but it's unclear how D_i and particularly T are best obtained here

"Added Drag" Components

$$D = D_p + D_i + \Delta D_{\text{base}} + \Delta D_{\text{excr}} + \Delta D_{\text{trim}} + \ldots$$

where $\Delta D \equiv D - D_{\text{before}}$

ΔD type	Cause
Base drag	blunt trailing edge
Interference drag	two or more bodies brought into proximity
Excrescence drag	small surface defects or irregularities
Trim drag	tail load needed for moment trim
Compressibility drag	elevated Mach number
Ventilation drag	air taken into aircraft and ejected elsewhere
Cooling drag	heat transfer to/from aircraft surface
Installation drag	installation of engine on aircraft
Installation thrust loss	installation of engine on aircraft

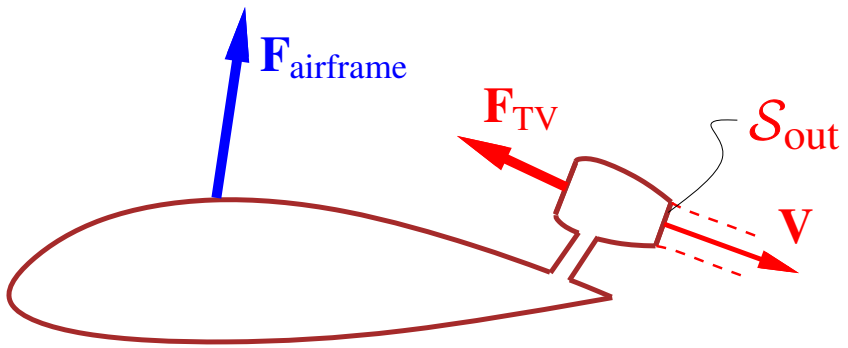
- Some of these can be negative
- None can be evaluated from a single measured or computed flowfield
- Not clear how these should affect thrust, however defined

Thrust-Vectoring Force Decomposition and Estimation

Extend ZHK thrust (scalar) into a thrust vector ...

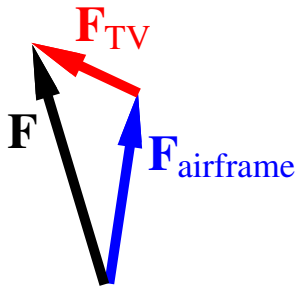
$$\mathbf{F}_{\mathrm{TV}} \equiv \dot{m}_{\mathrm{inl}}\mathbf{V}_{\infty} + \iint \Big[-\rho(\mathbf{V}\cdot\hat{\mathbf{n}})\,\mathbf{V} + (p_{\infty}-p)\,\hat{\mathbf{n}} \Big]\, \mathrm{d}\mathcal{S}_{\mathrm{out}}$$

$$= -T_{\mathrm{TV}}\,\hat{\mathbf{i}} + Y_{\mathrm{TV}}\,\hat{\mathbf{j}} + L_{\mathrm{TV}}\,\hat{\mathbf{k}}$$



Add on airframe force to estimate total force:

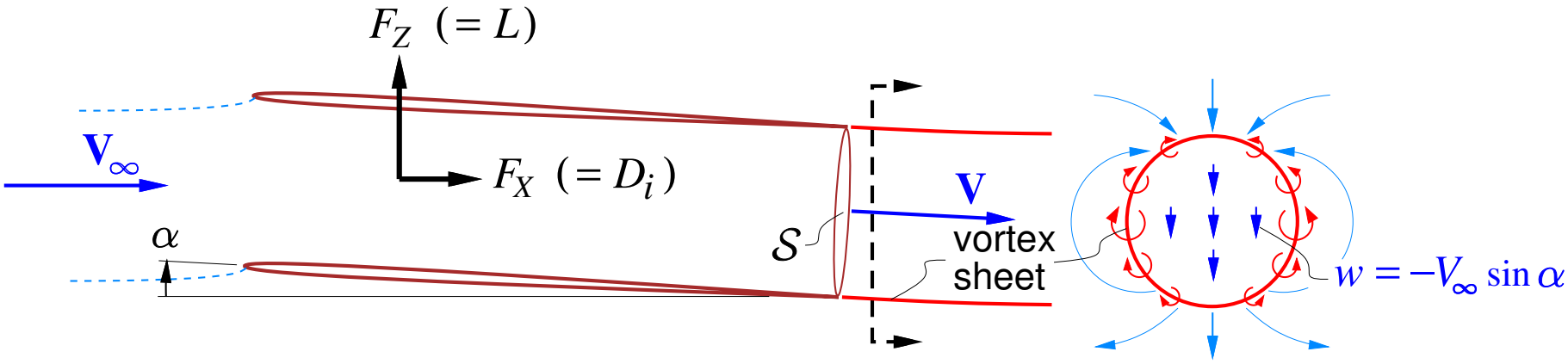
$$\mathbf{F} \simeq \mathbf{F}_{\mathrm{TV}} + \mathbf{F}_{\mathrm{airframe}}$$



Or in terms of axis components:

$$F_X \simeq -T_{\mathrm{TV}} + D_{\mathrm{airframe}}$$
$$F_Y \simeq Y_{\mathrm{TV}} + Y_{\mathrm{airframe}}$$
$$F_Z \simeq L_{\mathrm{TV}} + L_{\mathrm{airframe}}$$

"Thrust-Vectoring" Test Case: Thin Ring Wing



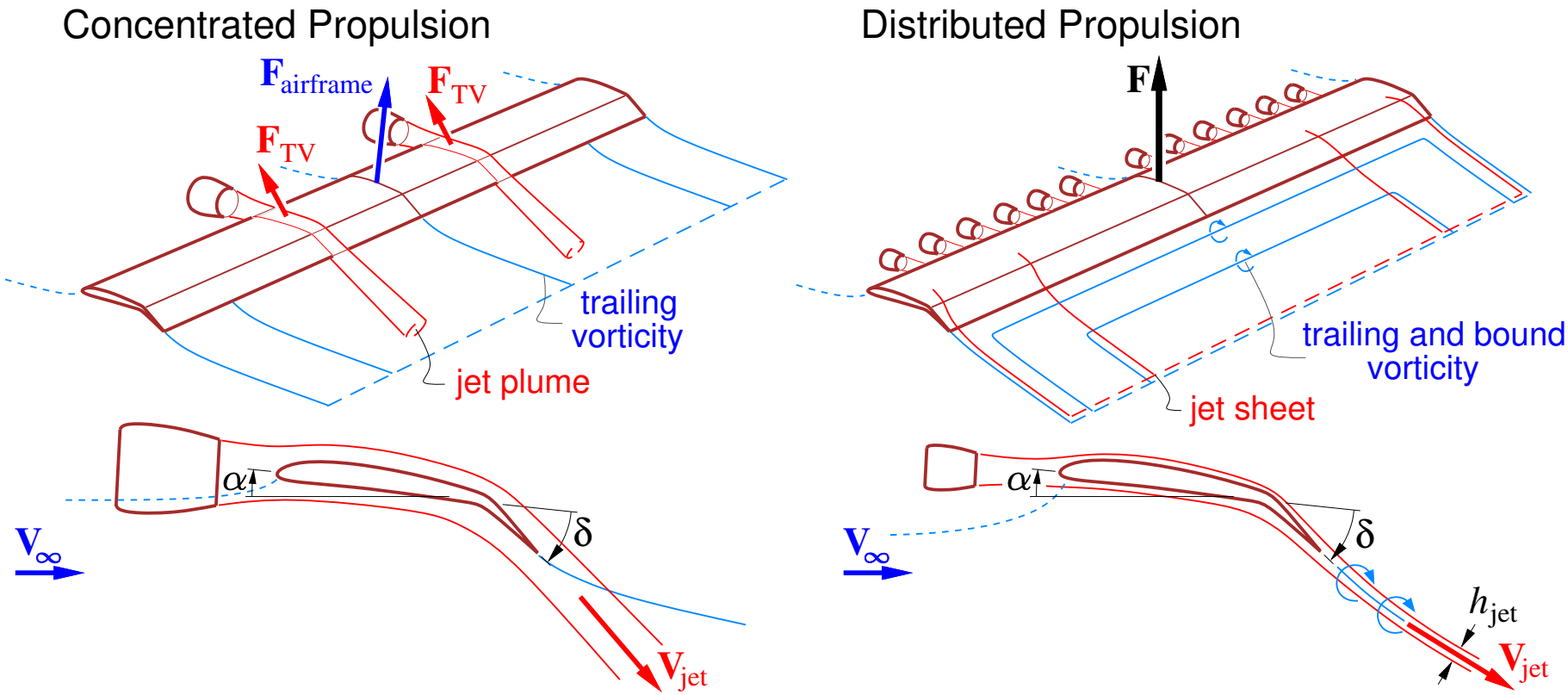
Known total forces: $\dfrac{F_X}{q_\infty \mathcal{S}} = 2\alpha^2$, $\dfrac{F_Z}{q_\infty \mathcal{S}} = 4\alpha$

TV model prediction: $-\dfrac{T_{\text{TV}}}{q_\infty \mathcal{S}} = \alpha^2$, $\dfrac{L_{\text{TV}}}{q_\infty \mathcal{S}} = 2\alpha$ (half of total)

implies ... $\dfrac{D_{\text{airframe}}}{q_\infty \mathcal{S}} = \alpha^2$, $\dfrac{L_{\text{airframe}}}{q_\infty \mathcal{S}} = 2\alpha$ (remaining half)

- TV model predicts negative "thrust". Should the engine vendor get paid less?
- Model's force split into TV and airframe parts is rather contrived here
- Suggests thrust definition for any angled propulsor will have same issues

Extreme Case for Force Decomposition: Blown Lift

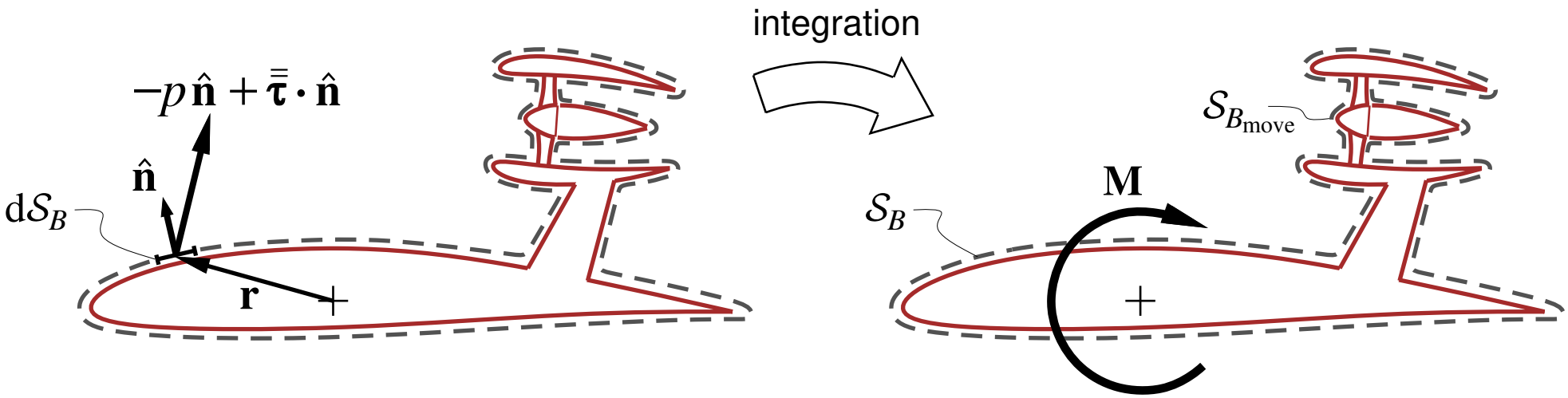


For Distributed Propulsion ...

- Airframe-wake and propulsor-jet flows are embedded and two-way coupled
- Decomposition of total $\mathbf{F}$ into thrust-vector and airframe components not feasible
- Experimental practice reflects this: only total $\mathbf{F}$ is normally measured for DP

Near-Field (surface) Moment Definition

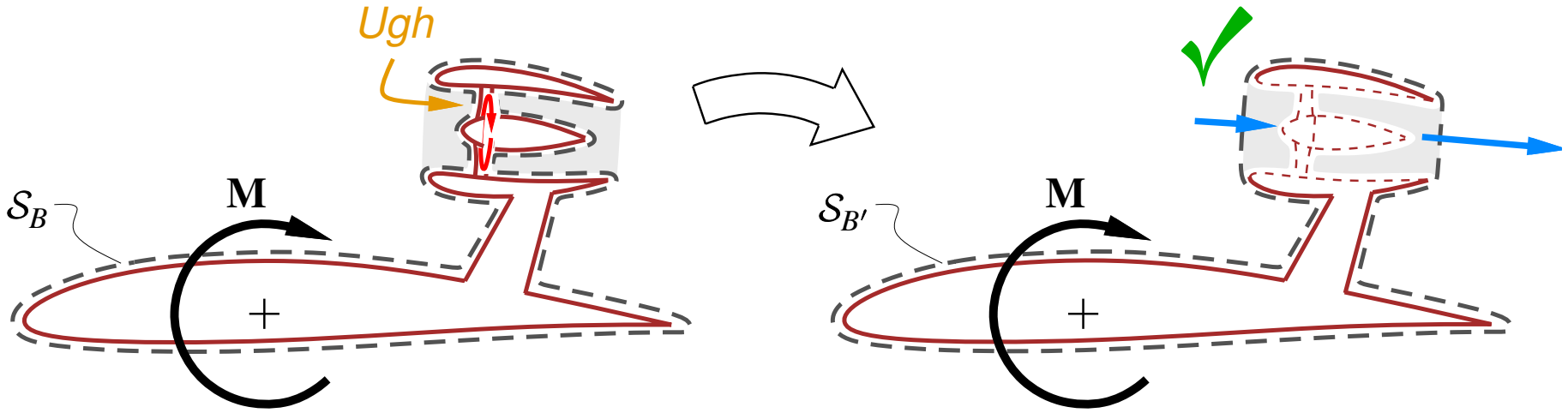
$$\mathbf{M} \equiv \oiint \mathbf{r} \times \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} \right] \mathrm{d}\mathcal{S}_B$$
$$= \quad \mathbf{M}_{\text{pressure}} \quad + \quad \mathbf{M}_{\text{friction}}$$



Alternative Near-Field Moment Definition

$$\mathbf{M} = \oiint \mathbf{r} \times \left[(p_{\text{ref}} - p)\,\hat{\mathbf{n}} + \bar{\bar{\boldsymbol{\tau}}} \cdot \hat{\mathbf{n}} - \rho(\mathbf{V} \cdot \hat{\mathbf{n}})\mathbf{V} \right] \mathrm{d}\mathcal{S}_{B'}$$

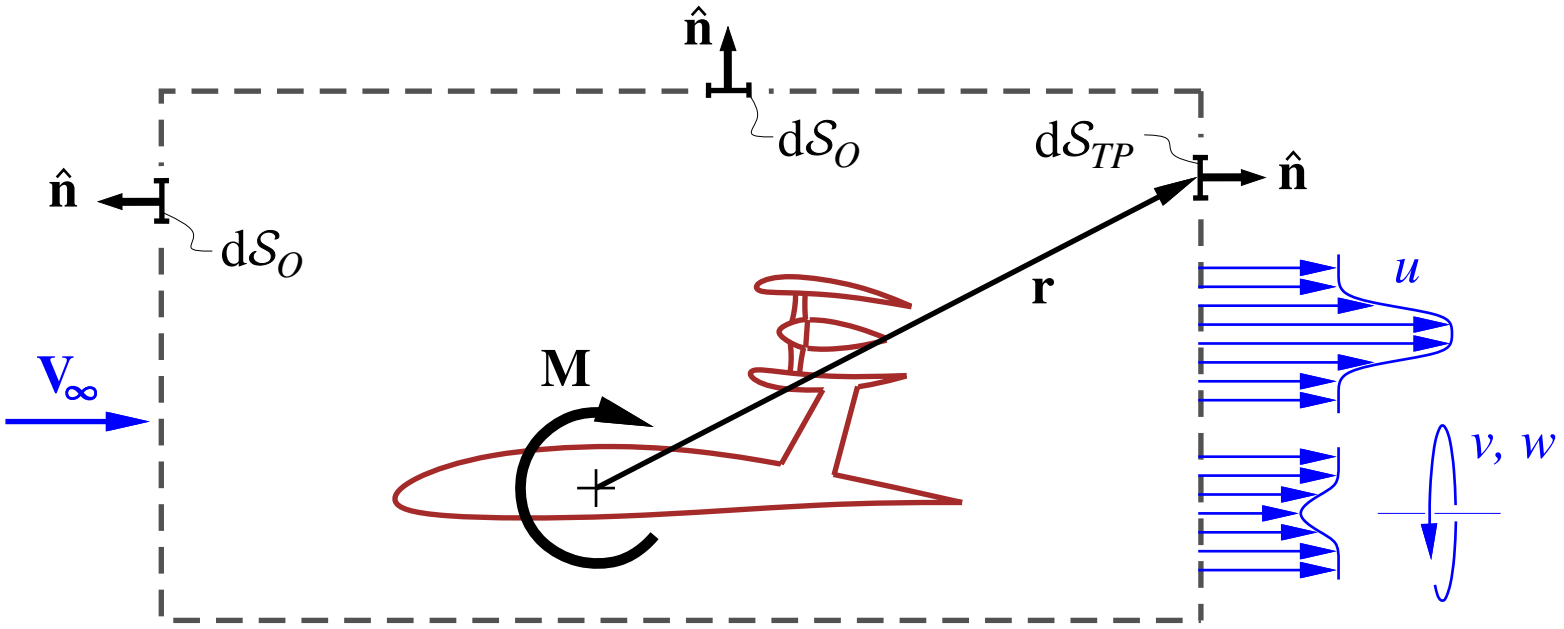
$$= \mathbf{M}_{\text{pressure}'} + \mathbf{M}_{\text{friction}'} + \mathbf{M}_{\text{flux}'}$$



- Using $\mathcal{S}_{B'}$ is much preferable, for same reasons as for $\mathbf{F}$
- Decomposition into a thrust-moment and drag-moment has same problems as for $\mathbf{F}$

Far-Field Moment Definition

$$\mathbf{M} = \oiint \mathbf{r} \times \left[(p_\infty - p)\,\hat{\mathbf{n}} - \rho\,(\mathbf{V}\cdot\hat{\mathbf{n}})\,\mathbf{V} + \bar{\bar{\boldsymbol{\tau}}}\cdot\hat{\mathbf{i}} \right] \mathrm{d}\mathcal{S}_O$$



- For any $\mathcal{S}_O$, gives exactly the same $\mathbf{M}$ value as near-field definitions, but ...
- ... $\mathcal{S}_O$ is not practical for $\mathbf{M}$ estimation because:
  - Flux term does not asymptote to zero
  - Requires accurate wake trajectory estimation from aircraft to $\mathcal{S}_{TP}$

Force Decomposition Attributes

Exactness:

$\sum \mathbf{F}_i = \mathbf{F}$ exactly

Consistency:

all $\mathbf{F}_i \to \mathbf{0}$ if $\mathbf{F} \to \mathbf{0}$ for known exact case

Uniqueness:

all $\mathbf{F}_i$ do not individually depend on arbitrary or subjective parameters

Extractability:

all $\mathbf{F}_i$ can be computed from a single CFD solution

$\to$ Ideal decomposition formulation has all these attributes

Attributes of Some Force Decompositions

Decomposition	Exact?	Consistent?	Unique?	Extractable?
$\mathbf{F} = \mathbf{F}_{\text{pressure}} + \mathbf{F}_{\text{friction}}$	$\surd$	$\surd$	$\surd$	$\surd$
$\mathbf{F} = \mathbf{F}_{\text{pressure}'} + \mathbf{F}_{\text{friction}'} + \mathbf{F}_{\text{flux}'}$	$\surd$	$\surd$	$\surd$	$\surd$
$F_X = D_{\text{ZHK}} - T_{\text{ZHK}}$	$\surd$		$\surd$	$\surd$
$F_X \simeq D_{\text{JY}} - T_{\text{JY}}$		$\surd$		$\surd$
$F_X \simeq D_{p_{\text{JY}}} + D_i - T_{\text{JY}}$				$\surd$
$F_X \simeq D_{\text{plate}} + D_{\text{form}} + D_i - T$				
$\mathbf{F} \simeq \mathbf{F}_{\text{airframe}} + \mathbf{F}_{\text{TV}}$				

Conclusions — I

Q1: Is thrust well-defined?

A1: No. There are multiple and plausible thrust definitions.

Q2: Is *a* thrust well-defined?

A2: Yes. Some thrust definitions are unambiguous, e.g. T_{ZHK}

Q3: Are any thrust definitions physically sound or physically meaningful?

A3: It depends on your engineering and scientific precision demands.
All or most thrust (and drag) definitions are useful for F_X estimation, BUT ...

- T_{ZHK} can be positive with zero power input
- T_{JY} is questionable in some situations, like when locally $p_t < p_\infty$
- Other definitions intended for CFD solutions depend on arbitrary p_{ref}
- An angled propulsor in general makes any thrust definition dubious
- Situations like BLI and blown lift make thrust/drag definitions especially dubious

Conclusions — II

- Total force definitions are rigorous, in both near-field and far-field versions
- Near-field streamwise force decomposition into thrust and drag is questionable
- Far-field streamwise force decomposition into thrust and drag is partly an art
- All useful far-field decompositions are approximate, and have pros and cons
- Only near-field moment definitions and decompositions are useful for estimation
- Decomposition attributes provide means of categorization and evaluation