APPLICATION FRONTIERS OF “DESIGNER FLUID MECHANICS”-- VISIONS VERSUS REALITY

OR

AN ATTEMPT TO ANSWER THE PERENNIAL QUESTION “WHY ISN’T IT USED?”

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ABSTRACT

Any new concept must successfully transit two sequential “filters” between research initiation and application, a technical filter (does it work?) and a technological filter (does it make sense in the “real world?”). In general, the research community is not sufficiently knowledgeable regarding the myriad metrics of the technological filter and therefore “non (application) useful” research is conducted in some cases and in others the research is not carried far enough to allow technological evaluation. It is becoming imperative that the research community be more knowledgeable concerning, and in many cases work with, the application community.

INTRODUCTION

“Designer” fluid mechanics, as defined herein, subsumes all types of technical flow control including laminar flow control, mixing enhancement, separated flow control, vortex control, turbulence control, anti-noise, favorable wave interference and “designer fluids.” What is not included is the vast preponderance of existing flow control technology which involves valves and fluidics, for which there is an immense literature/technology including much “active control.” A patent search for “flow control” devices resulted in identification of only 8 “Designer Fluid Mechanic” approaches (mainly in laminar flow control) out of 1,580 flow control patents. To the “mainline” flow control community, MEM refers to the Meter Equipment Manufacturing Company in Ohio.

The vision for Designer Fluid Mechanics includes, for example, the enablement of improved high lift, vectored thrust, drag reduction (viscous, form, drag-due-to-lift), signature reduction, enhanced combustion, reduced noise and pollution, improved flight/engine controls, reduced buffet, flutter and fatigue, heat transfer control and a host of manufacturing/process/ application specific benefits. An attempt at a taxonomy of Designer Fluid Mechanics is shown on Figure 1, which is meant to indicate a matrix multiplication.

One can readily identify three “generations” of Designer Fluid Mechanics devices/approaches. The first generation is currently in use and in many cases has been for quite some time. These first generation devices are typically relatively simple, inexpensive, passive, rigid, and, if active, are “quasi-steady state.”

The second generation is currently emerging and involves active control of relatively simple systems and is an obvious “marriage” of evolving “smart structures and materials” with flow-requirements driven variable (but quasi-steady) geometry requirements. The third generation is currently only a “gleam in the eye” and involves the vision of active/phased-locked control of highly non-linear complex/large degree of freedom dynamic systems such as “end-game” transition and turbulence (e.g., References 1-8).

The taxonomy shown on Figure 1 indicates a “rich” parameter space in terms of Designer Fluid Mechanics types and applications. What is not shown in detail on Figure 1 is the vast array of specific approaches which have been proffered and investigated over the years. The present paper will address the issue of application/“usefulness” for these various approaches; i.e., what determines which approach is ultimately employed/deployed.

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THE APPLICATION “FILTERS”

In the emerging climate of “global economic warfare,” the rate of technological change and innovation (as opposed to invention) is an important issue, along with national monetary/fiscal/regulatory policies, worker effectiveness and standard of living/wage rate, foreign competition, quantity and quality of capitol equipment and quality of management. The dominant market metric is a combination of product price/cost and features, which can be addressed technologically via a combination of product and process innovation.

The technology transfer literature suggests that a concept/idea must transit two filters between conception and application (Figure 2). The first of these is a technical filter which addresses the question “does it work?”. The second filter is an overall technological one and determines whether the concept makes sense “in the real world” in terms of market/affordability/ safety/environmental issues, etc., i.e., will the concept “transition” successfully to the market. The research community is exquisitely familiar with the details of the first, or technical, filter but far less so to not-at-all familiar with the technological issues. Figure 3 indicates a sampling of the components, particularized to aeronautics, of the technological filter in terms of its major components--engineering, safety/environment and economic/business. Each of these issues on Figure 3 obviously has to be particularized with an extensive sub-breakdown for a specific system.

As an example of the application of these filters, Reference 9 discusses the technical aspects of several wing flow control approaches. Reference 10 then goes on to describe a similar but expanded set and concludes “operational applications of these concepts are quite disappointing up to now (1995), due to lack of integration for the aerodynamic installations with airplane structure and propulsion and flight control systems at the early state of airplane design.” A similar story is available for active noise attenuation (Reference 11). The application of active attenuators has developed slowly for the following reasons. “Insufficient experience of practical installations to permit assessment in real situations, need to reduce the complexity and cost of the systems, lack of knowledge by design engineers of the potential benefits of active attenuators, insufficient evidence to convince contractors and hardware suppliers of the cost savings and reliability of active attenuators.” Such comments could be generalized to apply to any Designer Fluid Mechanics or indeed most any new technical approach.

It should be noted that large scale “research demonstrations” and even flight experiments are usually part of the technical as opposed to the crucial technological filter (see Figure 2), due to the typical utilization of “breadboard”/“iron-bird”/“add-on” approaches to “demonstration.” Very few if any of the technology filter issues (Figure 3) are typically addressed in research flight programs.

Designer Fluid Mechanics is merely one facet of a hugely complex and necessarily interactive aerospace system design process, which, to further complicate matters can differ appreciably in terms of metrics and their relative importance between military and civilian applications. One estimate suggests 10,000 separate computer programs are run during the design and manufacture of an aerospace system. Figure 4 provides, as a simplex sub-example, the issues associated with propulsion-airframe integration for a civilian supersonic cruise long haul aircraft.

In general, a “bad mark” on any one or a number of “grey marks” on several of the technological filter issues of Figure 3 is usually sufficient to obviate use of a particular Designer Fluid Mechanics approach/concept. These issues overlay an innate industry conservatism and a general human proclivity in favor of the comfortable “status quo” which mitigates against change. As competition increases, risk-aversion decreases somewhat but in terms of advanced concepts of all types, flow control/configurational, etc., etc. the reality is there are no “magic bullets,” i.e., approaches which require no R&D, present no problems and only provide huge (guaranteed) benefits. The evaluation and eventual adoption of a “new” technical approach/idea/concept is a long arduous process for which the initiators are the key element. They have the physical insight(s) and the motivation to pursue the idea. If such a pursuit included knowledge, study and problem solving concerning the multitudinous technological filter issues early on the adoption “success rate” would increase dramatically.

As research on a concept addresses these applications/“real world” issues requisite details regarding requirements and “payoffs” become increasingly competition-sensitive/proprietary and, for DOD-related issues, may even be classified. Therefore, in general, there are no open "journals" the researcher can consult for this critical information, information which should ideally influence the initial choice as well as conduct of the research project. The astute researcher has little choice but to work directly with the "end users."

DESIGNER FLUID MECHANICS APPROACHES--"USED AND "UNUSED"

In an attempt to particularize the information in the previous section to the flow control arena, the author contacted knowledgeable experts in various industries and Government, people who are involved specifically in "end product" R&D and who speak "flow control" and solicited answers to the following questions:

In your products, what flow control approaches do you use and why do you use these particular ones?

and

What flow control approaches do you not use, and why do you not use them?

The responses to this query were extraordinarily consistent. The consensus "end use metrics" are shown on Figure 5 and are consistent with the technological filter elements shown on Figure 3. Studies of Langley Research Center attempts to license research concepts generated by in-house research yielded a general theme that (in many/most cases) the research was simply not carried far enough to even allow evaluation of the technological filter issues. More specific comments on particular approaches were as expected from the discussion thus far: (1) lack of market; (2) not "protectable;" (3) systems implications unevaluated/unknown; (4) more advanced/alternative solutions already available and (5) narrow applicability.

A comment from the U.S. Navy was particularly interesting "95% of all hydro benefits in the last 20 years have derived from the use of "optional" shaping. There are dozens of (flow control) techniques that have been shown to be effective at the basic research, exploratory development and even prototyping levels. Essentially, none have reached optional use! 'Why not used'--not 'robust,' none 'traded well, were not 'sailorproof.'" Also, the NASA Aerodynamics Advisory Panel indicates "if the use of a large scale prototype is not feasible (i.e., affordable) in the vehicle development process, and the flow control device cannot be accurately represented at close to flight Reynolds numbers in the wind tunnel, then the risk factor for these devices is just too great.

Figure 6 indicates many of the "successful"/deployed flow control approaches. An examination of this list and the solicited comments discussed herein suggests the following features of a "good" (i.e., useful) flow control approach

- Simple/inexpensive
- In many cases, retrofittable
- In most cases, passive/rigid
- Reliable/"foolproof"
- Simulatable in ground facilities
- Well understood/proven

The message is consistent, what is used/"applied" thus far is robust shape changes as opposed to "active" systems.

Figure 7 provides a listing of those approaches/devices which have been "proven" technically but are not, to the best knowledge of the author, yet through the technological filter, i.e., they are in the "purgatory" between discipline research and application.

SOME ILLUSTRATIVE EXAMPLES, FLOW CONTROL VISIONS VERSUS REALITY

Viscous Drag Reduction

As is well known (e.g., References 12-17) there has been very considerable renewed research interest over the past twenty plus years in viscous drag reduction, both laminar flow control and turbulent drag reduction. The original impetus for this research was the "energy crisis" of the 70's. NASA-Langley pioneered and led these efforts from the 70's into the late 80's. Europe has taken over the leading role in the 90's. In terms of fuel efficiency or initial size/cost reduction payoffs, viscous drag reduction is avowed to have a much greater impact than technology advances in propulsion, structures and materials and even advanced aerodynamics (but not their synergistic combination). There have been, just in the last 15 years, 9 major laminar flow control flight experiments in the U.S. alone, with others in Europe. This flight activity, along with really astonishing progress in computational/predictive capability has clearly demonstrated that LFC (and riblets for turbulent drag reduction) are through the technical filter--yet, they are not utilized except, often inadvertently, by the GA/small aircraft community in terms of "natural" laminar flow, which is the portion of the technology which satisfies the KISS principle of "successful" flow control devices (e.g., simple, inexpensive, passive, rigid, well understood, proven).

Why is viscous drag reduction not more widely/generally used? The "risk" is still too large in terms of the various facets of the technology filter and, based upon the current knowledge base, "the added cost(s) of design, fabrication, installation and inservice maintenance cancel the value of reduced fuel consumption" (Reference 18). Further details regarding the application difficulties for LFC <u>and</u> riblets are available in Reference 19.

The evaluation process required to determine the applicability of LFC (in hybrid form) to transport aircraft must necessarily include consideration of aerodynamics, weights, mechanical/electrical subsystems, propulsion, structures, manufacturing, safety, reliability and maintainability, marketing and finance--i.e., components of the "second filter" (Figures 2 and 3). Figure 8 summarizes some of the remaining "application issues" for riblets and HLFC.

Vortex Control

The diversity and importance of the application set for longitudinal vortex control is extraordinary (Figure 9 and Reference 20). Well-known aeronautical examples include LEX or (wing) leading edge extensions, geometric discontinuities utilized on the more recent fighter aircraft (F-16, F-18) which provide "vortex lift" or partially attached lee-surface wing flow for enhanced maneuverability at angle of attack. Over the years, various alternative proposals of the "active" variety (moveable geometry, blowing, suction, etc.) have been put forward, researched and even, in some cases, flown (e.g., References 21-25), thus far none of these (and other) "active" approaches have been applied!

In the 1970's, NASA worked a series of "fixes" to the wake vortex hazard problem and conducted flight tests on a 747 aircraft. The general observation was that differences in detailed geometry and Reynolds number between flight and the then available ground tests were responsible for the often large laboratory-to-flight discrepancies. This provides clear support for the assertion cited previously herein that adequate ground simulation at near flight conditions is essential, in this case to even sort out the applicable physics, at least part of which was the curvature-induced "Rayleigh Stabilization" of the vortex core. Typical required "separation distances" between "heavy" and light aircraft observed in the (unmodified) low Reynolds number ground tests were the order of <u>half or less</u> those observed in the (unmodified) flight case. That is, the ground tests did not even represent the "base state" correctly. Similar shortfalls in vortex and vortex control "ground" (ashore?) simulation has also been a difficulty for the marine, especially submarine, communities/ applications.

Aircraft High Lift

The "conventional" approach to civilian aircraft high lift is that of variable geometry utilizing a mix of leading edge slats/devices and trailing edge flaps with resulting C_L values generally in the range of 2.5 to 3.5 and major cost/weight penalties in terms of a high part count and system weight/volume requirements. The military, which has a requirement for operation of heavy transport aircraft on short, unimproved runways and carrier deck operations has long studied the tremendous benefits of synergistic aero and propulsive interactions for high lift.

Probably the most defining/revolutionary (in terms of overall performance) approach to propulsive augmented lift is "circulation control," wherein a high speed jet is positioned near and just above the trailing edge to move both front and rear stagnation points under the wing. This approach can produce C_L values approaching the theoretical limit of 4π (References 26, 27). The possible benefits to commercial aircraft and airspace/airport productivity of such a flow control approach are truly revolutionary and the approach transited the technical filter long ago, including flight tests. The requisite small high pressure feedlines could even become an integral part of the wing structure. Yet the approach is still not used.

This technology, along with thrust vectoring for control and many others, offers synergistic aero/propulsion interactions and are, in the opinion of the civilian industry, too "risky" even though the fluid mechanicist can proffer some obvious risk reduction approaches for "engine out" such as cross-coupling the engine bleed systems. This is a clear case of the technical community not carrying the work far enough to provide risk mitigation, including invention/development of techniques to reduce the required efflux flow rates.

Scramjet Mixing Enhancement

In 1972 at the Langley Conference on Turbulent Free Mixing a clear trend was established of reduced mixing for free shear layers with increasing (high speed stream side) Mach number. This result lay essentially dormant for over 10 years until the NASP program of the late 80's inspired a national effort (AFOSR, ONR, NASA) in high speed mixing physics and enhancement (e.g., Reference 28). The physics responsible for the observed diminution in mixing rate with Mach number was, to a significant extent, delineated/identified and many approaches proffered/studied by the fluids community to increase mixing at high speeds to "overcome" this Mach number trend.

Unfortunately, these efforts were largely disconnected from the "real world" of scramjets, their avowed application. Almost all of the fluids research centered on a "clean" shear layer without the "complicating" but essential real engine mixing region features such as thick initial turbulent regions, 3-D mean flows with curvature(s), organized vorticity of various types, various wave systems/pressure gradients, combustion, walls, etc.--all of which generally cause enhanced mixing and would be expected to overshadow most-to-all of the effects of the various enhancement approaches studied in the "clean" experiments.

In point of fact the 1972 "Langley curve" of shear layer spreading parameter with Mach number included an (admittedly sparse) set of data indicating no observable effect of Mach number upon spreading rate for the case of a thick initial turbulent region where the shear layer is effectively "forced" by a high intensity "stream turbulent field" with large length scales/broad spectrum. This provides an example wherein the research community did not relate to/include/study the application details, thereby significantly reducing the impact of their work in the "real world." (See Reference 29 for a brief discussion of engine metrics.)

CONCLUSIONS

1. Any new flow control concept must successfully transit two filters--technical (does it work) and technological (does it make sense in the "real world").

2. In general, the fluids research community is not sufficiently knowledgeable concerning the technological requirements and metrics and therefore in some cases obviously "non-useful" research is conducted and in many cases the work is not carried far enough to allow adequate evaluation with respect to the various technology filter metrics. Recently, multidisciplinary/organizational/functional teams centered at UCLA and MacDac have/are attempting to remedy this situation (c.f., Reference 30).

3. What is needed to address the current economic realities (research support-wise and National) is "engineering research and development" with a defined set and understanding of end use metrics "up front."

4. There are significant ground facility capability shortfalls which severely limit the evaluation/adaptation/application of "Designer Fluid Mechanics" concepts, e.g.:

- High lift-- chord Reynolds number shortfall, affects attachment line transition behavior and therefore everything downstream.

- Wake vortex-- chord Reynolds number shortfall, affects vortex dissipation rate/behaviour.

- HLFC-- transonic low stream disturbance shortfall, affects ability to "certify" aircraft operation with HLC.

- Hypervelocity airbreathing propulsion-- long run time/large scale T&E free jet engine test facility required for $8 < M < 16$, obviates airbreathing space launch/TAV applications for $M > 8$.

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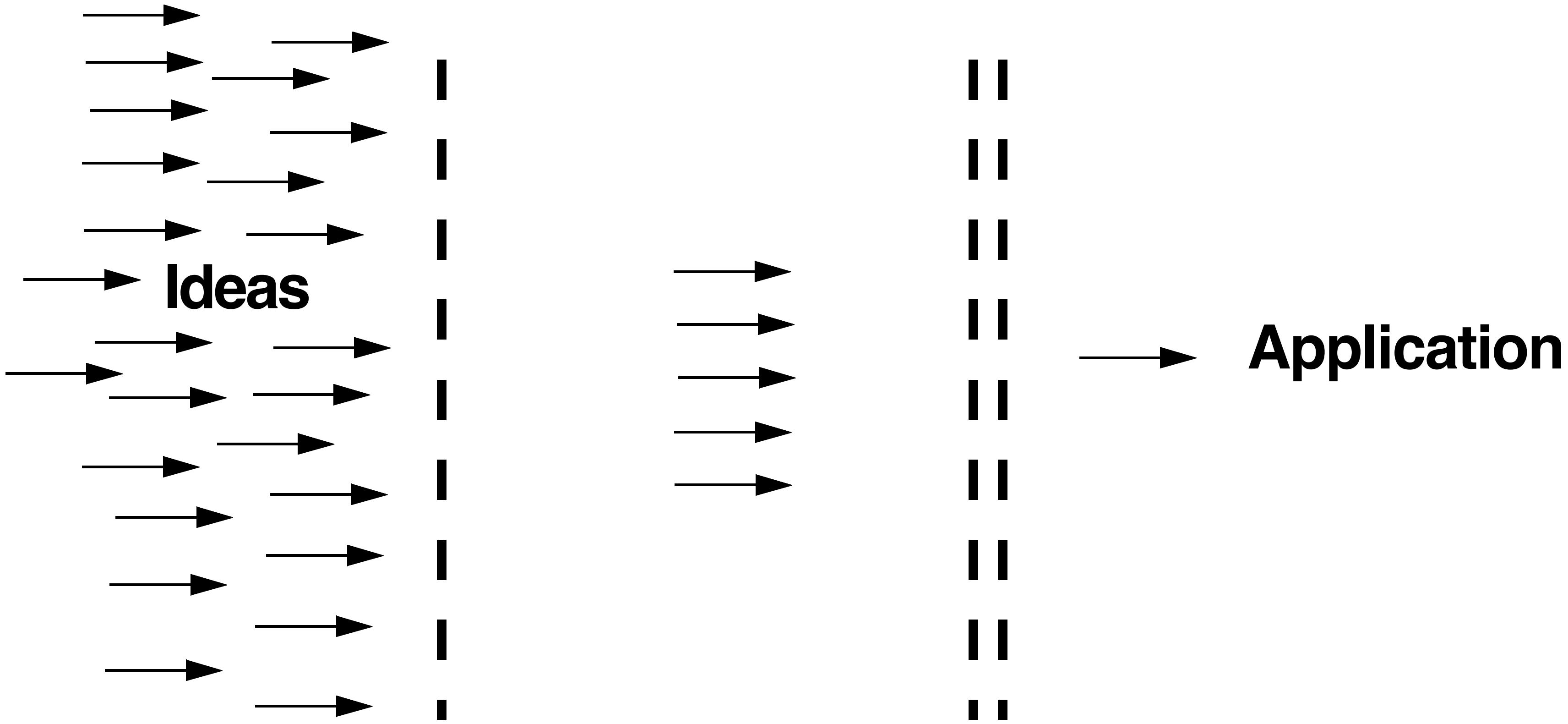
FIGURE 1: TAXONOMY OF DESIGNER FLUID MECHANICS

Application		*Type of Fluid*		*Type of Flow*		*Effector*		*Type of Control Logic*		*Phenomena Controlled*		*Purpose*
• Aeron. Vehicles **--Transports** **--Fighters** **--Missiles** **--Rotary wing** **• Ocean Vehicles** **--Surf. ships** **--Submarine** **--Torpedoes** **• Architectural Aerodynamics** **• Wind Engineering** **• Land Transport** **--Trains** **--Autos** **• Bio engineering** **• Pipeline Transport** **• Power Generation** **• Chemical Processing** **• Manuf. Processes** **• Industrial Fluid Dyn./ HVAC**	X	**• Gas** **• Liquid** **• 2-Phase** **• 3-Phase** **(Newtonian, non-Newtonian)**	X	**• Attached** **--Lam.** **--Turb.** **--Transitional** **• Separated** **--2-D** **--3-D** **• Vortical** **--Longitudinal** **--Transverse** **--Other** **• Free Shear Layers** **• Free Surfaces** **(steady, dynamic)**	X	**• Suction** **• Injection** **• Rigid Bodies** **• Body Forces** **--Magnetic** **--Electrical** **• Surface Motion** **• Energy Release (chem./ electrical)** **• Additives** **• Mass Permeability** **• Heating/ Cooling**	X	**• Passive** **• Active** **--Random phasing** **--Phase locked**	X	**• Wall Friction** **• Heat Transfer** **• Mass Transfer** **• Combustion** **• Acoustics** **• Pressure loading (static, dynamic)** **• Wave Drag** **• Particle Size** **• Electrostatic Fields** **• Erosion** **• Fluid Motion(s)**	X	**• Vehicle motion control/ enhancement** **• Environment (pollution, noise)** **• Sensor improv.** **• Performance** **--Drag red.** **--Payload increase** **--Size reduction** **--Range increase** **--Economics** **• Safety** **• Survivability (military)** **• Improved resource utilization** **• Propulsion improvement** **• Health improvement** **• Improved accuracy**

FIGURE 2: THE (SERIAL) “FILTERS” THROUGH WHICH AN IDEA/APPROACH/CONCEPT MUST PASS BEFORE UTILIZATION



<u>Technical/Scientific</u>
Filter (will it work?)

Market/Affordability/Safety/
Environmental/<u>ECONOMICS</u> etc. Filter
(does it make sense in the “real world.”)
can/will it “transition”

FIGURE 3: THE "CRUCIBLE" THROUGH WHICH NEW/DIFFERENT (CIVILIAN) AERONAUTICAL DESIGNS HAVE TO PASS FOR APPLICATION (ELEMENTS OF THE "TECHNOLOGY FILTER")

PART 1 - ENGINEERING

- **Producability/manufacturability**
- **Maintainabilty/supportability**
- **Reliability**
- **Flyability/airworthiness**
- **Inspectability**
- **Performance (aero, structural, propulsive)**
- **Flexibility (growth, Pax/cargo, variable production rate)**
- **Repairability**
- **Operability**
- **Durability/damage tolerance**
- **Airport compatibility**

PART 2 - ECONOMIC/BUSINESS

- **PROFIT (airframers/airlines)**
- **Fuel usage/"carbon tax"**
- **Size/weight/part count/material/complexity**
- **Ancillary/"side" effects**
- **Product liability**
- **Timeliness**
- **Protectability/ease of duplication/exclusive rights**
- **Criticality of requirement/novelty**
- **Regulatory issues**
- **Risk**
- **Distribution system**
- **Availability/productivity**
- **THE COMPETITION (product, approach)**

PART 3 - SAFETY/ENVIRONMENTAL

- **"Crashworthiness"**
- **Vortex hazard**
- **Weather (icing, microburst)**
- **Stall/spin**
- **Fatigue**
- **Emissions**
- **Engine and airframe noise**

FIGURE 4

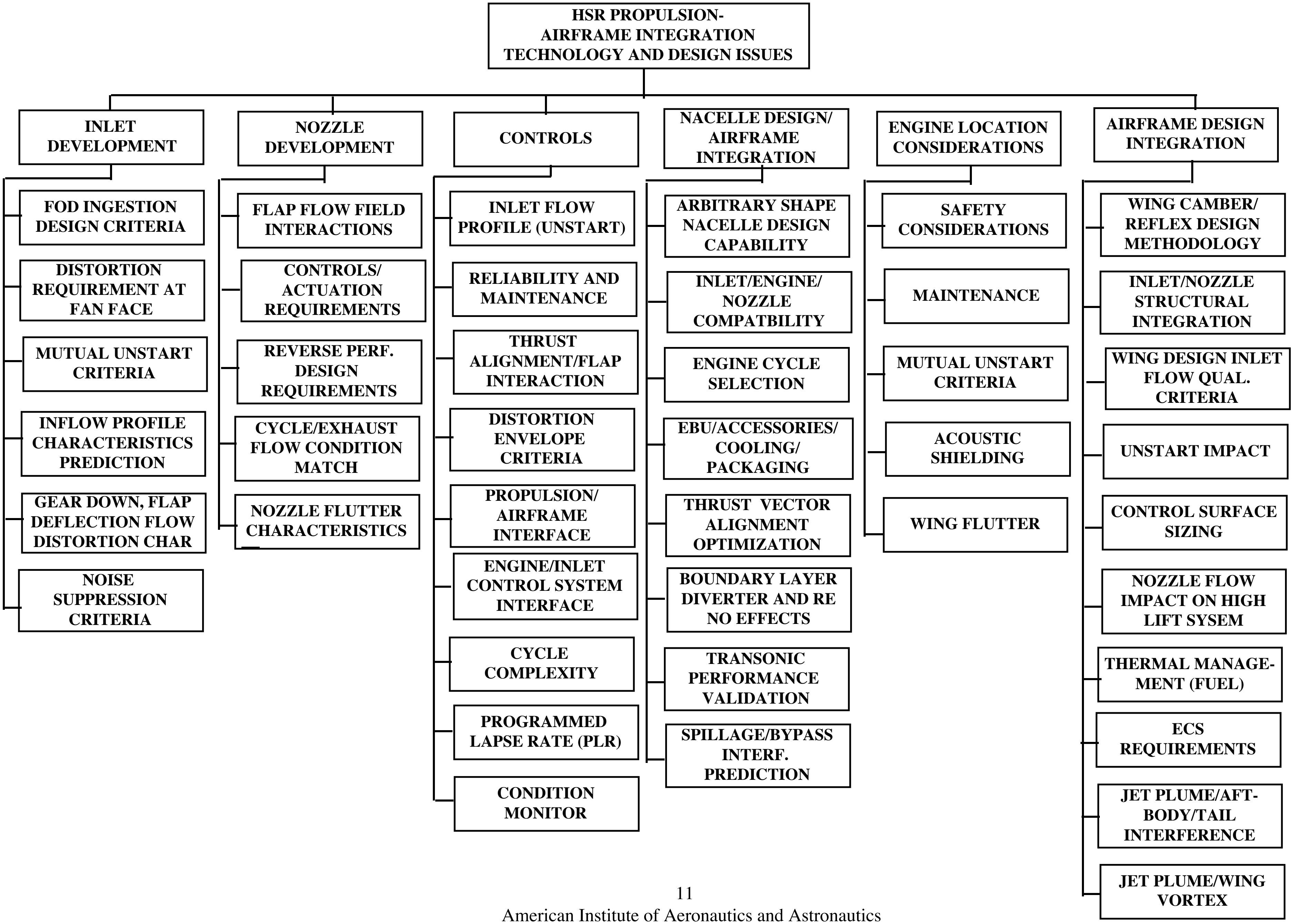

HSR PROPULSION-AIRFRAME INTEGRATION TECHNOLOGY AND DESIGN ISSUES
INLET DEVELOPMENT
FOD INGESTION DESIGN CRITERIA
DISTORTION REQUIREMENT AT FAN FACE
MUTUAL UNSTART CRITERIA
INFLOW PROFILE CHARACTERISTICS PREDICTION
GEAR DOWN, FLAP DEFLECTION FLOW DISTORTION CHAR
NOISE SUPPRESSION CRITERIA
NOZZLE DEVELOPMENT
FLAP FLOW FIELD INTERACTIONS
CONTROLS/ ACTUATION REQUIREMENTS
REVERSE PERF. DESIGN REQUIREMENTS
CYCLE/EXHAUST FLOW CONDITION MATCH
NOZZLE FLUTTER CHARACTERISTICS
CONTROLS
INLET FLOW PROFILE (UNSTART)
RELIABILITY AND MAINTENANCE
THRUST ALIGNMENT/FLAP INTERACTION
DISTORTION ENVELOPE CRITERIA
PROPULSION/ AIRFRAME INTERFACE
ENGINE/INLET CONTROL SYSTEM INTERFACE
CYCLE COMPLEXITY
PROGRAMMED LAPSE RATE (PLR)
CONDITION MONITOR
NACELLE DESIGN/ AIRFRAME INTEGRATION
ARBITRARY SHAPE NACELLE DESIGN CAPABILITY
INLET/ENGINE/ NOZZLE COMPATBILITY
ENGINE CYCLE SELECTION
EBU/ACCESSORIES/ COOLING/ PACKAGING
THRUST VECTOR ALIGNMENT OPTIMIZATION
BOUNDARY LAYER DIVERTER AND RE NO EFFECTS
TRANSONIC PERFORMANCE VALIDATION
SPILLAGE/BYPASS INTERF. PREDICTION
ENGINE LOCATION CONSIDERATIONS
SAFETY CONSIDERATIONS
MAINTENANCE
MUTUAL UNSTART CRITERIA
ACOUSTIC SHIELDING
WING FLUTTER
AIRFRAME DESIGN INTEGRATION
WING CAMBER/ REFLEX DESIGN METHODOLOGY
INLET/NOZZLE STRUCTURAL INTEGRATION
WING DESIGN INLET FLOW QUAL. CRITERIA
UNSTART IMPACT
CONTROL SURFACE SIZING
NOZZLE FLOW IMPACT ON HIGH LIFT SYSEM
THERMAL MANAGE- MENT (FUEL)
ECS REQUIREMENTS
JET PLUME/AFT- BODY/TAIL INTERFERENCE
JET PLUME/WING VORTEX

FIGURE 5: CRITICAL “END USE” METRICS

(from a survey of good technologists who are involved in “end product” R&D and speak “flow control”)

- **Low initial cost/favorable <u>overall</u> cost/benefit**
- **“Works” in presence of operational/real world conditions**
- **Demonstrated experimentally at large scale**
- **Favorable energistics or provides unique/valuable capability worth energy expenditure**
- **Manufacturability, reliability, maintainability, inspectability**
- **Enhances/improves a valuable metric**
- **Acceptable “side effects”**
- **ROBUST**
- **Acceptable from a legal/regulatory/safety standpoint (product liability/safety, environmental/acoustic “pollution”)**

FIGURE 6: “DEPLOYED” FLOW CONTROL DEVICES/APPROACHES

- **Blown flaps**
- **LEX**
- **“Natural” laminar flow**
- **L.E. notch/“snag”/ “vortilon” VG’s**
- **Vane VG**
- **NACA flush inlet**
- **Flow diverters**
- **Variable geometry (flaps, slats, var. sweep)**
- **Base burning**
- **Winglets**
- **Wing “fences”**
- **Inlet “bleed”**
- **Transition trips**
- **Screens/honeycombs**
- **Jet inj. TVC**
- **Spiral chimney bands**
- **Anti-noise**
- **Pipeline polymer D.R.**
- **Shelter belts**
- **Supercavitation**
- **MHD electrolysis/casting control for alum.**
- **Shaping/fairing**
- **“NOTAR” helo tail boom**
- **Spoilers**
- **Cyclone combustors**
- **Supersonic wing warp/twist**
- **Groomed runways/roadways/tires (anti-hydroplaning)**

FIGURE 7: FLOW CONTROL APPROACHES/ DEVICES “UP AGAINST” THE TECHNOLOGY FILTER

(*i.e., shown to “work” via computations/experiments/flight demonstrations*)

- **Trapped vortex diffuser**
- **Circulation control**
- **Suction /heating LFC**
- **Low profile VG’s**
- **Riblets**
- **Pneumatic/actuated strake forebody vortex control**
- **Compliant wall transition delay**
- **Passive porous surface shock--B.L. control**
- **Active mixing control**
- **TDR via slot inj.**

- **Spanwise blowing for vortex lift**
- **Phased active cancellation of linear waves (except anti-noise)**
- **Microbubble TDR**
- **Longit. wall motion for sep. control, TDR**
- **Suction sep. control**
- **Ship polymer D.R.**
- **Vortex flap**
- **Active compressor stall control**
- **Counter flow/fluidic thrust vectoring**
- **“Mission-adaptive” wing**
- **Several “tip treatments” (blowing, turbines)**
- **Jet VG’s**

FIGURE 8: "PRACTICAL" APPLICATION ISSUES--RIBLETS AND HLFC

Riblets

- **Application/removal time and cost (unit "out of service," not making money but still accuring expenses (loan/ lease service, taxes, etc.)**
- **Durability/maintainability**
- **Cost/benefit/tradeoff**
- **Substrate inspection**
- **Cosmetics/weathering**
- **Control/surface effectiveness/buffet**
- **Lightning strikes**
- **Fluids interaction**
- **Operational damage/clogging**

HLFC

- **Insects**
- **Lack of adequate ground testing capability (e.g.,high Reynolds Number low disturb. transonic tunnel) for certification and performance/stab. and control**
- **Complexity**
- **Leading edge high lift device effectiveness**
- **Cost/reliability/maintainability**
- **Manufacturability**
- **Fatigue life**
- **Risk/uncertainty**

FIGURE 9: VORTEX CONTROL APPLICATIONS

- **Submarine/surface ship improvement**
- **Improved architectural aerodynamics**
- **Wake vortex hazard reduction (civil aviation, airport/airspace utilization)**
- **Turbomachinery optim. (root, tip vortices)**
- **SST-ozone layer interacton/control**
- **Drag due to lift reduction**
- **Three-dimensional flow control**
- **Reduced buffet/wing rock**
- **Noise reduction**
- **Heat transfer augmentation/reduction, arc heaters**
- **Chemical engineering (reactors, separators, injectors, burners, condensers, dryers)**
- **Turbulence/free mixing control**
- **Interference drag reduction/reduced scouring**
- **Benthic oxygenation and sediment control**
- **Energy separation (e.g., Hilsque tube)**