COLLEGE OF ENGINEERING
KEVIN T. CROFTON DEPARTMENT OF
AEROSPACE AND OCEAN ENGINEERING
VIRGINIA TECH.

AOE 4144: Applied CFD

A Lecture Series on ACA

Reflections on Applied Computational Aerodynamics

How we got to where we are today.
How we get to where we must be tomorrow.

"My journey on a long and winding road for more than five decades!"

Pradeep Raj, Ph.D.
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Director, Lockheed Martin (Retired)
Deputy Dir., Technology Development & Integration
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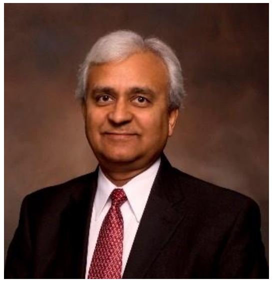
Advanced Development Programs
LOCKHEED MARTIN

The 1st of 12 lectures

Lecture 1: Introductory Remarks

ABOUT THE AUTHOR

Pradeep Raj



https://www.aoe.vt.edu/people/faculty/raj/personal-page/curriculum_vitae.html

- **Virginia Tech, Blacksburg, VA – Professor (2012–present)**
  - ○ ***Teaching:*** **Capstone Air Vehicle Design and Applied CFD**
  - ○ ***Research:*** **Applied Aerodynamics and Aircraft Design**
- **Lockheed Martin**
  - ○ ***Technical (1979–2000):*** **Aeronautics Co., California/Georgia**
  - ○ ***Leadership & Management (2000–2011):*** **Advanced Development Programs, Skunk Works®, Palmdale, California**
- **UMR*, Rolla, Missouri**
  - **– Asst. Prof. (1978–79)**

**now Missouri S&T University*

- **ISU, Ames, Iowa**
  - **– Res. Asst. Prof. (1976–78)**
- **GT, Atlanta, Georgia**
  - **– Ph.D. Aerospace Engineering (1976)**
- **IISc, Bangalore, India**
  - **– M.E. Aeronautical Engr. (1972)**
  - **– B.E. Electrical Tech. (1970)**
- ***AIAA Fellow* (2011), *FRAeS* (2016), and *FIAE* (1991)**

Image Source: Internet

Why join VT after retiring from LM?

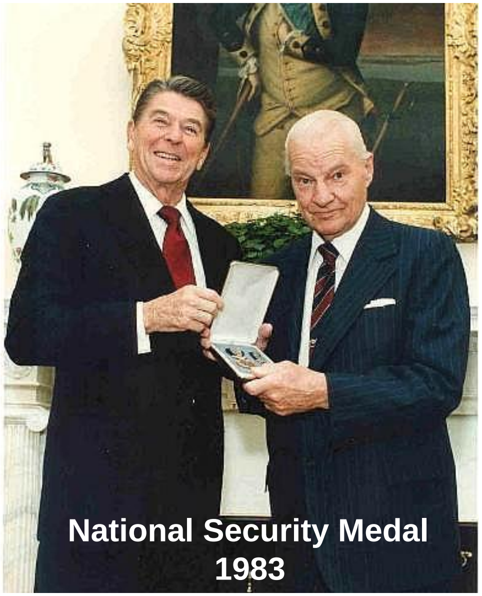
Kelly's Rules for Happy Retirement

1. *Retirement is like a job and must be approached as such*
2. *Don't travel too much, you want to establish a daily grind*
3. *Don't think about living someplace new, that's why God created hotels*
4. *Drive till you can't remember where you parked*
5. *Be pleasantly reckless - but if you have never done it before, now may not be the time to start*
6. *Don't hang with the children too much - visit , give presents and then move on*
7. *Maintain your bad habits, but never get drunk more than once a day. You're not a kid anymore*
8. *Hang with young people; they mostly have it right*

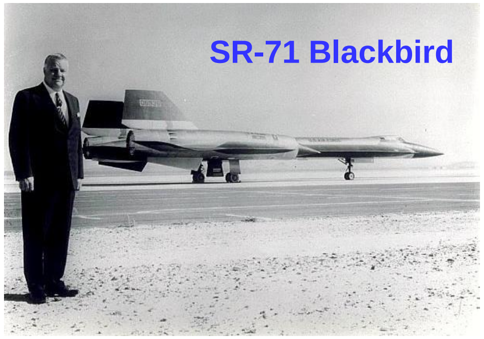
Clarence Leonard "Kelly" Johnson (1910-1990)

Legendary Aircraft Designer

Founder of World-renowned Skunk Works®



National Security Medal
1983



SR-71 Blackbird

"Hang with young people; they mostly have it right"

ABOUT THESE LECTURES

In these lectures, the author shares his personal reflections on the evolution of Applied Computational Aerodynamics, limited effectiveness of its current capabilities, and prospects for *fully effective ACA.**

The author places the evolution of ACA as well as its capabilities and shortcomings in a historical context, but it is NOT a history of ACA.

The lectures are a much expanded version of the Lead presentation
Applied Computational Aerodynamics: *An Unending Quest for Effectiveness*
Royal Aeronautical Society Applied Aerodynamics Conference
The Future of Aerodynamics, Bristol, U.K., July 24-26, 2018

URL to access the current version:
https://www.aoe.vt.edu/people/faculty/raj/personal-page/ACA.html

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**Fully Effective ACA ≡ ACA Nirvana* (a goal hoped for but apparently unattainable)!

DISCLAIMERS

The material contained herein reflects the views, thoughts, and convictions solely of the author, and not necessarily those of the author's employers or other groups or individuals.

Being a perspective, the material reflects opinions shaped by author's knowledge, experiences, and biases.

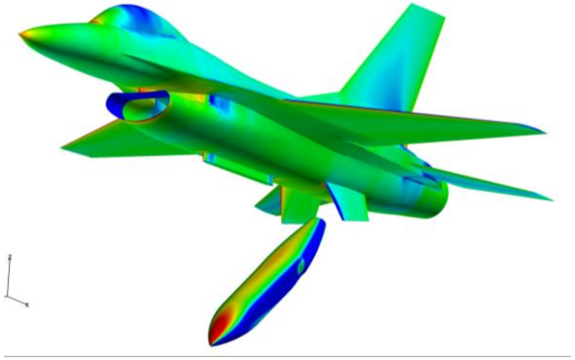
The author has gathered and compiled this material from publicly available sources and personal archives solely for educational purposes. Although a good-faith attempt has been made to cite all sources of material, the author deeply regrets any inadvertent errors or omissions.

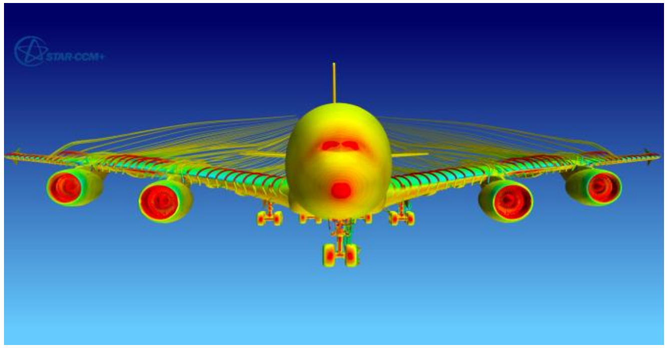
Contents

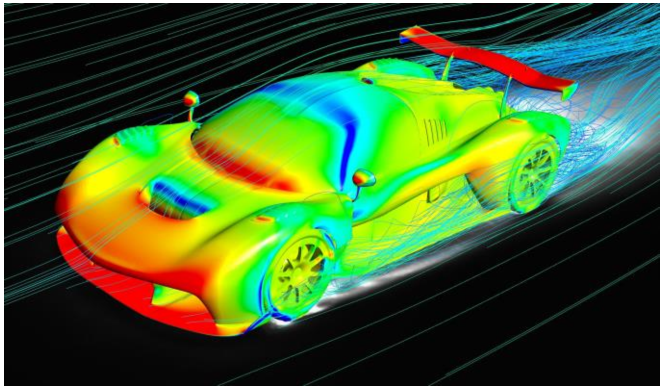
(7 Chapters)

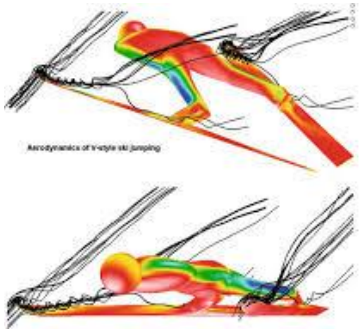
Applied Computational Aerodynamics (ACA)

ACA** is an engineering discipline that deals with the application of **C**omputational **F**luid **D**ynamics (CFD) to **analyze** and **design** arbitrarily shaped objects moving through the **air.









ACA is No Longer a Luxury, But a Necessity, to Support Engineering Design of All Types of Systems That Move Through Air

Image Source: Internet

Overarching Goal of ACA

The overarching goal of applied computational aerodynamics (ACA) is to deliver credible solutions of practical aerodynamic problems on time and on budget to support engineering design of systems that move through air such as, aircraft, by performing the necessary aerodynamic analysis and design using computational fluid dynamics (CFD).

Definition of Applied:

"(of a subject of study) having a practical use rather than being only theoretical"

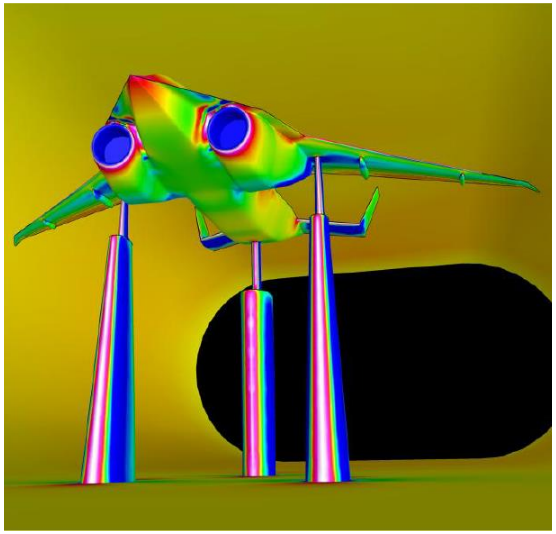
Source: https://dictionary.cambridge.org/us/dictionary/english/applied

ACA Puts CFD to Practical Use!

CFD and ACA are *NOT* Synonymous

CFD *Produces Data*.

Computational Fluid Dynamics (CFD) offers a powerful *means* of *generating aerodynamic data*, à la wind tunnels, for bodies moving through air.



Both use a 3-step process

1. Build a model

2. Blow air on it

3. Gather and interpret data

(Data include:
forces, moments, and
flow quantities—on and off the surface)

ACA Produces Solutions!

Applied Computational Aerodynamics (ACA) is all about using CFD to deliver credible *solutions of engineering problems* that designers face.

Solving Engineering Problems Needs Aerodynamic Data, But Don't Confuse Data with Solutions!

Image Source: Ref. 1.1

Don’t We Already Know a Lot About CFD and ACA?

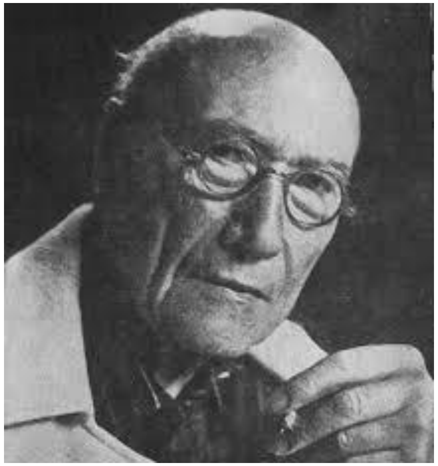
Yes, everything has been said in many books, reports, and papers!

Then Why Say It Again?

Source: Refs. 1.2 to 1.9

Everything has been said before, but since nobody listens we have to keep going back and beginning all over again.

André Gide



French author
Nobel Prize in Literature (1947)
22 November 1869 – 19 February 1951

- **It is extremely difficult, if not impossible, for any single book or report to do justice to multiple facets of CFD and ACA**
- **These lectures complement a large number of books and other publications that cover the subject from different vantage points including theoretical aspects of CFD and applications of CFD methods**

Source: Ref. 1.10

Motivation for These Lectures

To share a comprehensive yet concise perspective on

- ***the evolution of applied computational aerodynamics (ACA) for meeting flight vehicle design needs,***
- ***the impressive capabilities of today's ACA but its less-than-satisfactory effectiveness due to some serious shortcomings, and***
- ***the prospects for fully effective ACA capabilities,***

which reflects author's 50+ years of related experience in aerospace industry and academia.

So what?

"experience is knowledge or skill in a particular job or activity that you have gained because you have done that job or activity for a long time."

— Collins online dictionary

Más sabe el diablo por viejo que por diablo.

The devil knows more through being old than through being a devil.

You may not agree with everything this 'old devil' says, but he still has much knowledge to pass on to you!

More About Experience

"experience is direct observation of, or participation in, events as a basis of knowledge" **— Merriam-Webster dictionary**

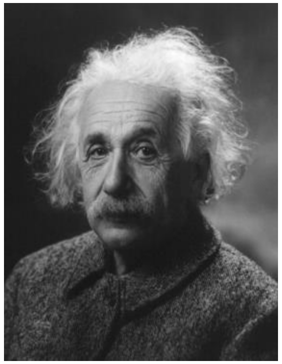
C.S. Lewis

29 Nov 1898 – 22 Nov 1963

"Experience: that most brutal of teachers. But you learn, my God do you learn."

"The only source of knowledge is experience."

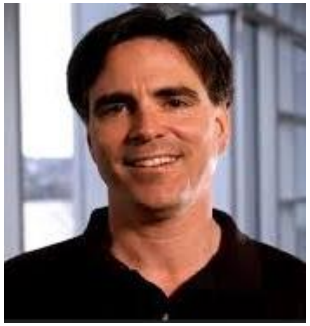
Albert Einstein



14 Mar 1879 – 18 Apr 1955

"Experience is what you get when you don't get what you wanted. And it can be the most valuable thing you have to offer."

Randy Pausch



23 Oct 1960 – 25 Jul 2008

Knowledge from experiences over time is crucial to developing wisdom you need to make good decisions; you can't get wise overnight from books alone.

"With age comes wisdom, but sometimes age comes alone."

-- Oscar Wilde

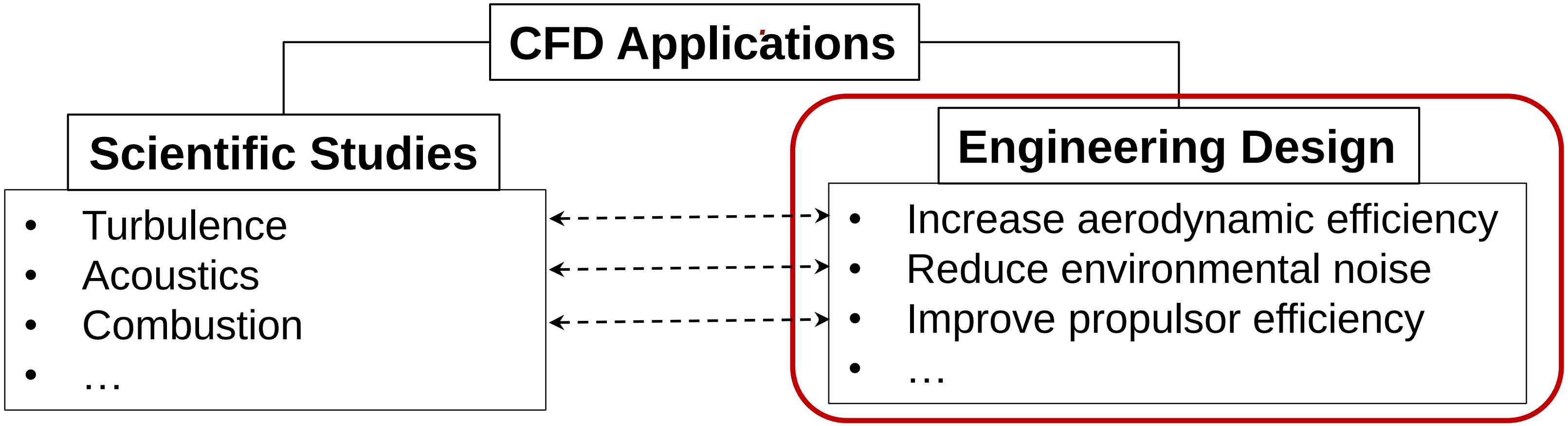
Image & Quotes Source: Internet

Scope of These Lectures

Discuss the ACA discipline in terms of how we got to where we are today, and how we get to where we must be tomorrow with ④ fully effective ACA to meet ③ engineering design needs of flight vehicle development.

Our focus is limited to examining application of ② CFD (computational fluid dynamics) to the aerodynamic problems in the engineering design of flight vehicles.

Since CFD is applicable to a broad range of problems in ① science and engineering, here is a highly simplified taxonomy of CFD applications to distinguish applications to scientific studies and to engineering design :



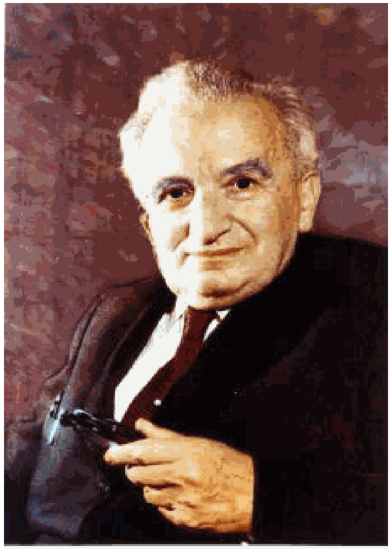
CFD Applications

Scientific Studies
- Turbulence
- Acoustics
- Combustion
- …

Engineering Design
- Increase aerodynamic efficiency
- Reduce environmental noise
- Improve propulsor efficiency
- …

1. “Engineering isn’t Science!”

"Engineering isn't Science!"



**<u>Scientists discover</u> the world that exists;
<u>engineers create</u> the world that never was.**

*Theodore von Kármán
1881-1963*

***<u>Engineering is</u>* in the end
<u>about making something</u>.**

*Eugene E. Covert, MIT
1926 - 2015*

***The Core Purpose of Engineering:
Apply Knowledge and Skills to Develop New Devices***

Image Source: Internet

"An engineer is *not* a scientist"

"Throughout my years in Cal Tech I like to believe that I gave **engineering education** a little push in the right direction and this helped subsequently in creating the kind of engineers needed in the United States. But eventually a strange thing happened. During those years I had emphasized the importance of physics and chemistry in the engineering curriculum and urged **closer cooperation of science and engineering**. I even suggested **social sciences for engineers** interested in management. So, many educators started to think that *if a little science is good for engineers a whole lot is better*. They gave students more physics and more chemistry, until now the pendulum seems to have swung the other way and **engineering education has become indiscernible from science education**."

"I am sorry to say that I do not like this trend. ***An engineer is not a scientist.*** ***In addition to basic technical knowledge he must have the creative capacity to design new hardware.*** Engineering schools that fail to recognize and encourage this dual role are remiss in their duty to the profession."

"Whether we call future scientists physicists or engineers is not important. ***What is important*** I think ***is to*** repair the imbalance in the scientific world and ***turn out people who not only understand fundamental phenomena but can use this knowledge for developing new devices***. This in turn will not only bring some glory to the engineer, but I think it will contribute substantially to the pace of progress."

-- **Theodore von Kármán (1881–1963)**
The Wind and Beyond, 1967, pp. 157 & 159

Note: Highlighting by the author.

Source: Ref. 1.11

“An Engineer’s Mentality”

“In essence, the current engineering education paradigm consists of giving the students all the data at the top of the page, and the solution (?) consists of rearranging the data on the bottom of the page and handing it in as a "worked" assignment. In many years in industry I never encountered anything even remotely close to this process. ”

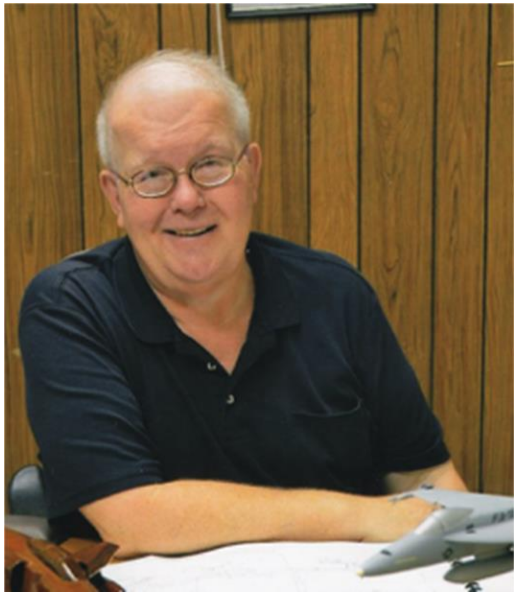
“In my experience, ***the overwhelming majority of the engineering problem is gathering information and interpreting results.*** *Although this is the engineering problem it almost never occurs in our science-based engineering education system*.”

“**Engineering design** may be the student's only exposure to this process. The student response in evaluations comes across as "problem statements too vague." If that's the case with these problems, we have not yet helped the students develop an engineer's mentality.”

William H. Mason
AIAA Paper 92-2661

Note: Highlighting by the author.

William H. Mason



Professor Emeritus, Virginia Tech
Co-author ACA textbook
Grumman Corp.
19 Jan 1947 - 27 Mar 2019

Source: Ref. 1.12

"An Engineer's Reality"

"One of the **characteristics of engineers which** I have frequently observed, and which **must be guarded against** is the ***search for exact answers***, and the feeling of frustration if the exact answer is not forthcoming. This probably stems from the many years of high school and college training where the answer is always to be found in the back of the book, and the feeling of elation which comes when, after trying several solutions, and looking furtively at the answer, the latest trial finally works.

Unfortunately, **in real life, there are no exact or final answers**. In a job, which must go ahead at a rapid pace, we cannot withhold judgment "until all the facts are in". Rarely is all the evidence at hand. Decisions must be made, and action taken, before complete knowledge can be acquired.

I have for some time thought that **a few of our present day ills stem from this childish faith in the existence of perfect answers**. It requires a degree of maturity to realize that all solutions are partial ones."

Adm. Hyman G. Rickover (1900–1986)

"Administering a Large Military Development Project"

Delivered to U.S. Naval Postgraduate School, Monterey, CA, 15 March 1954

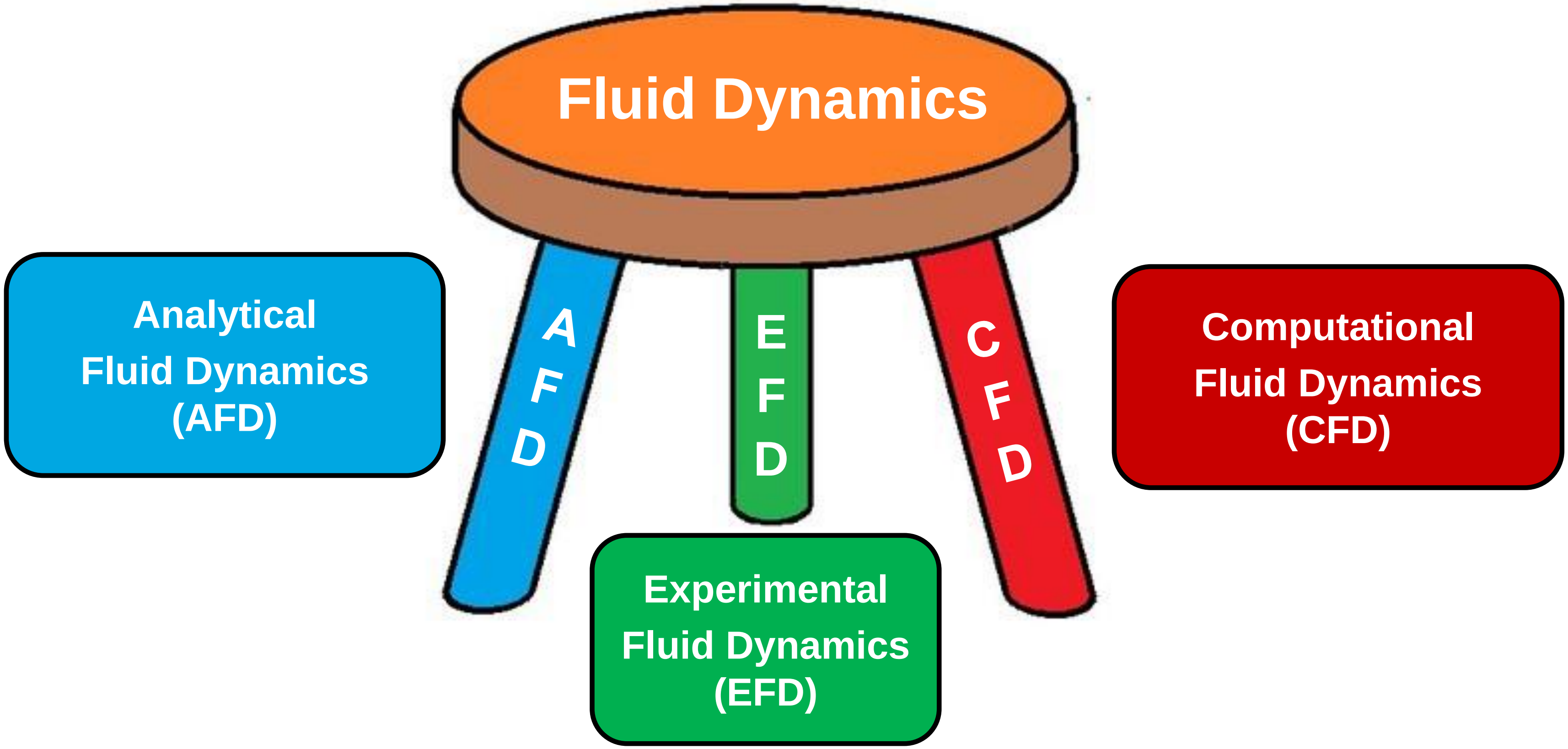
Note: Highlighting is done by the author.

Source: http://hdl.handle.net/10945/59370

2. Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD):
A Subdiscipline of Fluid Dynamics

Fluid Dynamics: The branch of applied science concerned with the movement of fluids (liquids and gases).*



Aerodynamics: *A subset of Fluid Dynamics with air as the fluid.*

Synergistic Use of AFD, EFD, and CFD is Essential for Comprehensive Understanding of Fluid Dynamics

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*American Heritage Dictionary definition

Four Key Ingredients of CFD

Governing Equations of Mathematical Models of Fluid Flow

(*Partial differential equations in continuous domain*)

Computer Platforms

(Digital computers to run computer programs, and for data processing & storage)

CFD

Numerical Models of Governing Equations

(*Difference equations in discretized domain*)

Computer Programs

(Software suite based on algorithms to solve the difference equations)

Today's CFD offers a powerful suite of numerical models, computer programs, and associated tools & processes for simulating fluid flows using digital computer platforms.

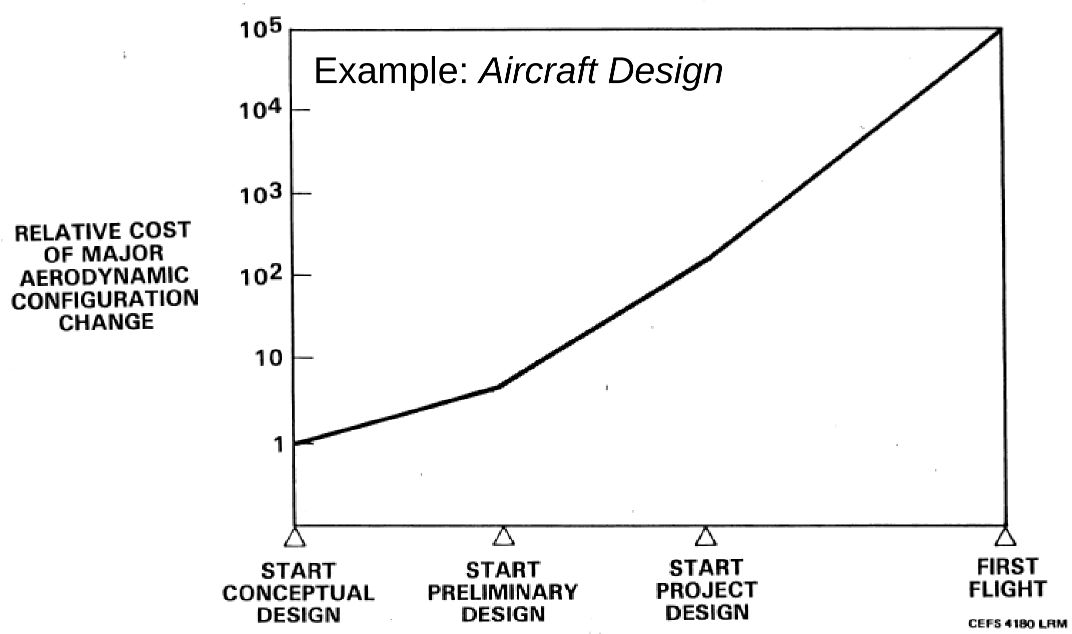
3. *Engineering Design*

Engineering Design

"Design is an iterative decision-making activity performed by team of engineers to produce plans by which resources are converted, preferably optimally, into systems or devices to meet human need."

T.T. Woodson
Introduction to Engineering Design, 1966

- **Successful design requires that quality decisions be made in a timely manner**
- **On-time quality decisions require <u>credible data</u> (*faithful replication of reality*) at the <u>right time</u> and the <u>right cost</u>**
- **The later a major configuration change is made, the higher the cost—*exponentially higher!***



Quality Decisions Early* → *Better Quality Affordable Product Later

Credible Data—On Time, On Budget—Are Key to Success

Image Courtesy of L.R. Miranda

EFD and CFD:

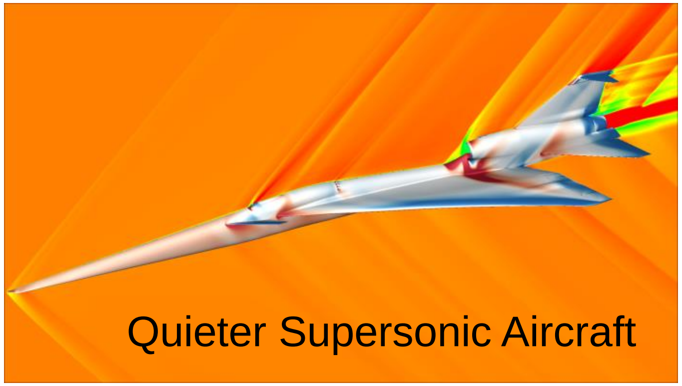
Two Primary Means of Generating Aerodynamic Data for Design Today

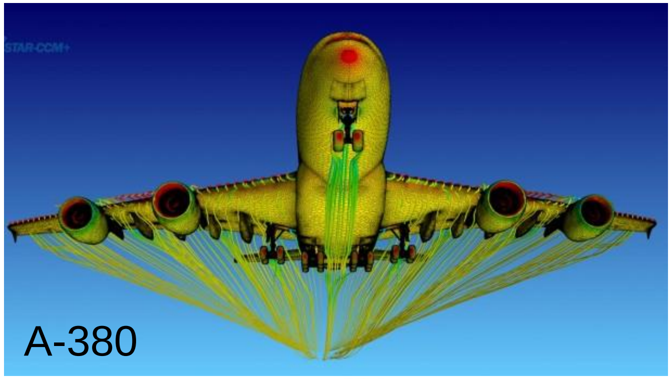
	EFD (Experimental Fluid Dynamics)	**CFD (Computational Fluid Dynamics)**
Strengths	• **Perceived as “Real”** • **Credible data** ▪ Quantified uncertainties • **Large excursions per entry**	• **Low cost** • **Quick turnaround** • **No scale effects** • **No wall interference effects** • **No support interference effects** • **Can model aeroelastic distortions** • **Applicable to *all* flight conditions**
Weaknesses	• **Higher cost, longer elapsed time** • **Scale effects** • **Wall interference effects** • **Support interference effects** • **Aeroelastic distortions** • **Not practical for *some* flight conditions**	• **Perceived as “Virtual”** • **Lack of credibility due to** ▪ Computational uncertainties caused by limitations or deficiencies in Numerical Models and Flow Physics Models

Highly Complementary Strengths

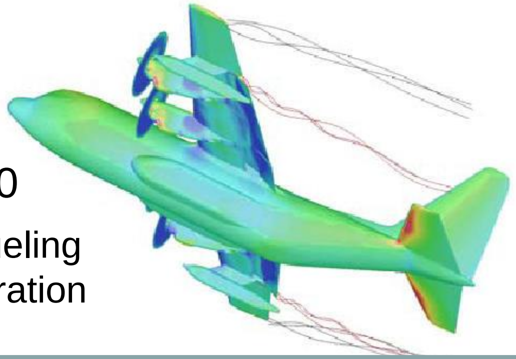
Role of CFD in Flight Vehicle Design

- **New Vehicles (“clean-sheet” designs)**
  - ○ *Outer Mold Line (OML) Design:* Forces, moments, and surface pressure distributions
  - ○ *Shape Optimization*: Sensitivity of aerodynamic data to design variables
  - ○ *Flight Performance Prediction:* Data to validate take-off, climb, cruise, maneuver, descent, landing
  - ○ *Airframe Propulsion Integration:* Data to minimize installation losses
  - ○ *System Integration:* Off-body flow field for safe carriage and deployment of stores & weapons
  - ○ *Structural Design*: Steady and unsteady flight loads
  - ○ *Flight Control System Design*: Stability & Control coefficients and rate derivatives
  - ○ Etc.
- **Derivative Vehicles (improvements, upgrades and/or modifications)**
  - ○ Aerodynamic data to assess impact of shape change on performance when integrating new or improved subsystems to upgrade current product or design a derivative


Quieter Supersonic Aircraft



A-380


KC-130

New Refueling
Pod Integration

Generate Aerodynamic Data for Flight Vehicle Design

Source: Refs. 1.13 – 1.18

CFD Plays a Crucial Role in Flight Vehicle Design

- **Generates Aerodynamic Data for Designing Flight Vehicles**
  - New Vehicles (“*clean-sheet” designs*)
  - Derivative Vehicles (*improvements, upgrades and/or modifications*)

- **Enables Multidisciplinary Analysis, Design & Optimization (MADO) Environments to Create Quality, Affordable Flight Vehicles**
  - CFD offers the *most practical* (probably the only?) *means* of producing data required for rapid design closure through extensive multidisciplinary trade-offs
  - CFD affords timely and cost-effective evaluation of the impact of geometric changes on performance, and of sensitivity of performance to *numerous* design variables
  - *CFD provides inverse design and shape optimization capability that most clearly differentiates it from EFD*

Success Hinges on Credible Data On Time & On Budget

Source: Refs. 1.13 – 1.21

4. Fully Effective ACA

Fully Effective ACA

Ability to deliver credible solutions* of aerodynamic problems using CFD on time and on budget to support engineering design

**how faithfully do the solutions replicate reality*

Luis R. Miranda

Manager
Computational Aerodynamics
Lockheed-California Co.

Miranda, in 1982, defined ACA Effectiveness as a product of two factors

$$\textit{Effectiveness} = \textit{Quality} \times \textit{Acceptance}$$

"Quality" *(how well the results represent reality?)*

- Credibility of the results of the computational aerodynamic simulation of flows about arbitrarily shaped configurations

"Acceptance" (*timeliness & cost of delivering results*)

- Ease of use and short turnaround time (elapsed time from go-ahead to delivery)
- Low cost (labor hours + hardware & software costs)

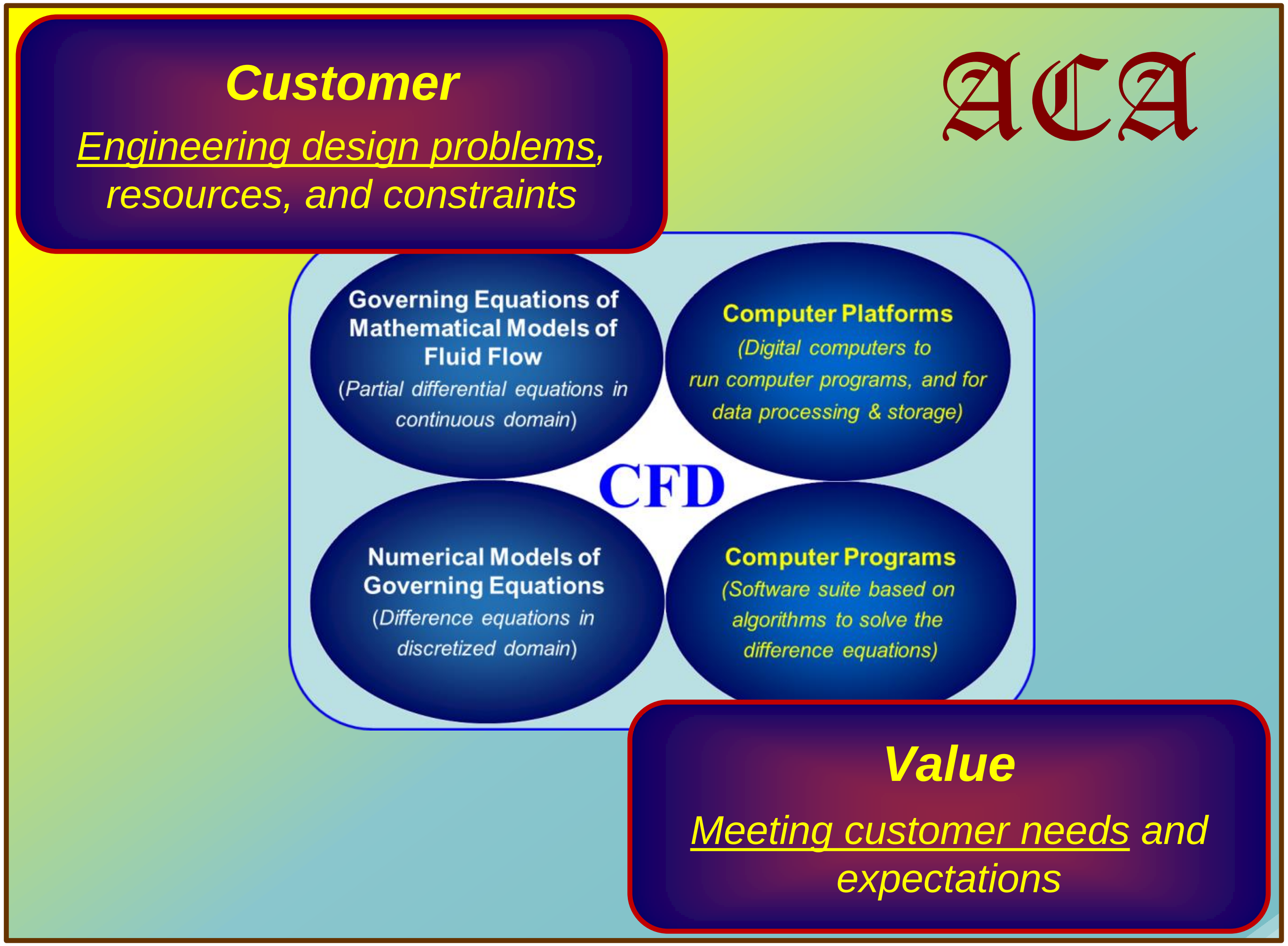
Fully Effective ACA Requires Simultaneous Maximization of Both Quality and Acceptance Factors

Pervasive Role of ACA in Engineering Design Drives the Pursuit of Fully Effective ACA

Source: Ref. 1.23

Relationship of CFD to ACA

ACA extracts Value from CFD for the Customer



Customer

Engineering design problems, resources, and constraints

ACA

Governing Equations of Mathematical Models of Fluid Flow

(*Partial differential equations in continuous domain*)

Computer Platforms

(Digital computers to run computer programs, and for data processing & storage)

CFD

Numerical Models of Governing Equations

(*Difference equations in discretized domain*)

Computer Programs

(Software suite based on algorithms to solve the difference equations)

Value

Meeting customer needs and expectations

CFD is to ACA as Airplane is to Air Transportation!

Lecture 1:
Overarching Takeaways

CFD Produces Data, ACA Produces Solutions.
Don’t Confuse Data with Solutions!

CFD is to ACA as Airplane is to
Air Transportation!

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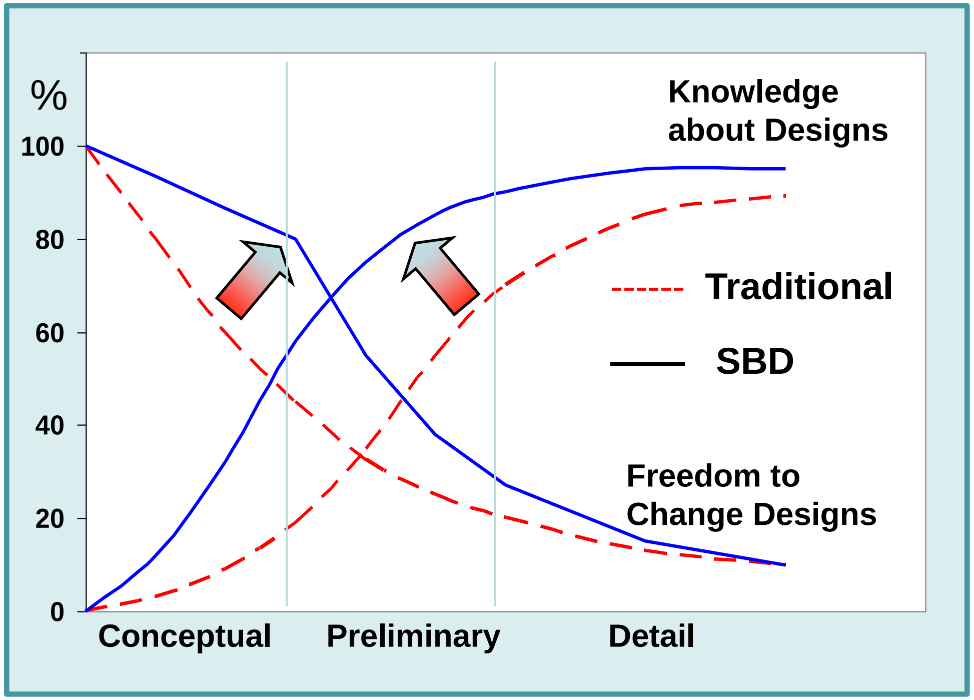
Backup Slides

Simulation Based Design (SBD)

A Paradigm for Designing Quality Affordable Vehicles

SBD exploits *Integrated Product & Process Development (IPPD)* concept and requires MADO environments for implementation

- **Employs integrated multidisciplinary models and computational simulations to develop *Virtual Prototypes (aka Digital Twins)***
- **Considers all aspects including manufacturing, operations and support simultaneously with all requirements and constraints from start**
- **Reduces chances of design changes in later stages**
- **Conducts cost/performance trade-offs *EARLY Using more Knowledge about designs***



SBD relies on computational methods as the primary means of all data required to make design decisions

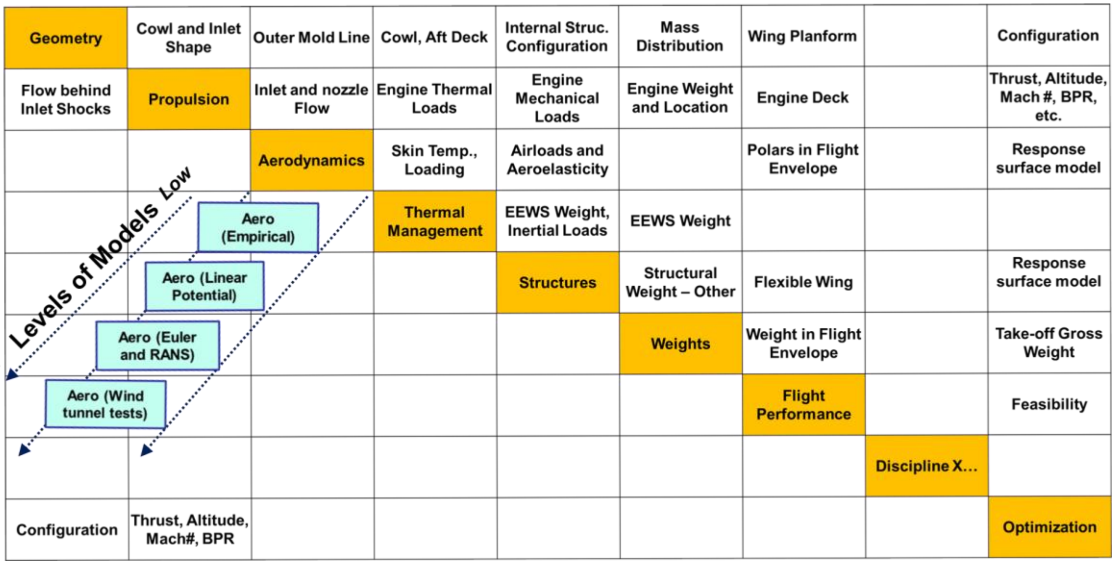
CFD is the Linchpin of Simulation Based Design!

Source: Ref. 1.21

Role of CFD in MADO Environment

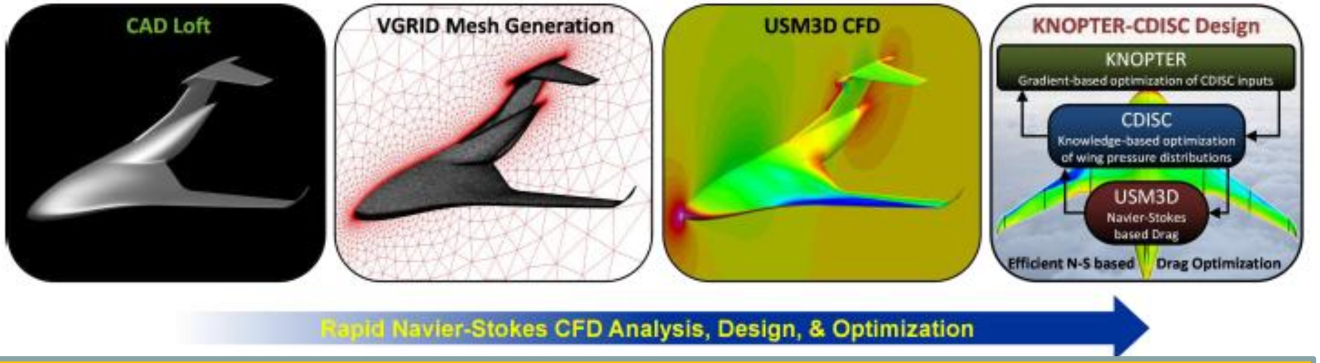
Enable Multidisciplinary Analysis, Design & Optimization (MADO) Environments to Create Quality, Affordable Flight Vehicles

- CFD provides aerodynamic data for timely and cost-effective evaluation of the impact of geometric changes on vehicle performance, and of the sensitivity of performance to *numerous* design variables
- CFD offers the *most practical* (probably the only?) *means* of producing data required for rapid design closure through extensive trade-offs



Geometry	Cowl and Inlet Shape	Outer Mold Line	Cowl, Aft Deck	Internal Struc. Configuration	Mass Distribution	Wing Planform		Configuration
Flow behind Inlet Shocks	**Propulsion**	Inlet and nozzle Flow	Engine Thermal Loads	Engine Mechanical Loads	Engine Weight and Location	Engine Deck		Thrust, Altitude, Mach #, BPR, etc.
		Aerodynamics	Skin Temp., Loading	Airloads and Aeroelasticity		Polars in Flight Envelope		Response surface model
			Thermal Management	EEWS Weight, Inertial Loads	EEWS Weight			
				Structures	Structural Weight – Other	Flexible Wing		Response surface model
					Weights	Weight in Flight Envelope		Take-off Gross Weight
						Flight Performance		Feasibility
							Discipline X...	
Configuration	Thrust, Altitude, Mach#, BPR							**Optimization**

CFD provides inverse design and shape optimization capability that most clearly differentiates it from EFD



Enable Extensive Trade-off Studies and Rapid Design Closure

Source: Ref. 1.22