CAD in the Aerospace Industry

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My biography is pretty straightforward

• Born in Wisconsin in 1958
• Received a B.S. from Yale in 1981
• Studied under Carl de Boor and received a Ph.D. at Wisconsin in 1985 for “Computing with Simplex Splines”
• Have worked for Boeing since 1986
Boeing has three main business units:

- **The Boeing Company**
  - Boeing Defense, Space & Security
  - Engineering, Operations & Technology
  - Boeing Commercial Airplanes

- **SSG**
- **BCC**

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**Boeing Defense, Space & Security**

- **68,000** employees

**Engineering, Operations & Technology**

- **18,000** employees

**Boeing Commercial Airplanes**

- **61,000** employees

**Research and Technology**

- **4,000** employees
The Applied Math group is organized by technical specialty

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- About 60 scientists, most with advanced degrees, about 2/3 PhDs
- One Senior Technical Fellow, 7 Fellows, 14 Associate Fellows
- Roughly 150 projects per year - Boeing programs, external customers, applied R&D
Who pays us for what?

Example: Develop targeting algorithms for the B-1 Lancer and Joint Direct Attack Munition

Example: Write a C++ geometry software library for the US Navy

Example: Develop a Boeing-standard design optimization system
First “CAD” in aerospace is due to Liming, 1944

- Liming presented a vision for CAD in his 1944 book, *Practical Analytic Geometry with Applications to Aircraft*
  - “While a graphic solution represents an approximate answer to a problem, the mathematical solution represents an exact answer; hence, the latter method is indispensable to securing accurately established data in a basic lofting development.”
  - “Furthermore, as soon as fundamental basic data have been calculated and established by a system of analytic geometry techniques, a compactly organized body of basic equations is available for all subsequent calculations. A coordinated body of dimensional data is assured at all stages of the calculation process.”
  - “The nature of lofting calculations is such that analytic geometry is ideally adapted to the resolution of lofting problems. At the same time, since the loft represents a permanent source of master dimensional authority, analytic equations and formulas, systematically charted, constitute an easily established permanent source of such dimensions.”
  - “. . . the algebraic difficulties [in solving a 5 x 5 linear system of equations] are insurmountable from a practical point of view.”
The value of interactive CAD is overstated

- Simpson’s 2004 study has profound implications*
  - Involved 35 Boeing test subjects
  - Interactive delays had no effect on subjects’ performance
  - Quality of answer correlated inversely with confidence of designer
  - Quality of answer correlated inversely with number of times designer examined graphical display of design
  - Quality of answer had no correlation with experience of designer

Aircraft design is typically accomplished in three stages

Three design stages

- **Phase I: Conceptual Design**
  - Knows
    - Basic mission requirements
    - Range
    - Altitude
    - Speed
    - Basic material properties
    - $\sigma / \pi$ $E / \pi$ $\$/LB
  - Results
    - Geometry objectives
    - Airfoil type
    - $R$
    - $l / c$
    - $\lambda$
    - Cost goals

- **Phase II: Preliminary Design**
  - Knows
    - Aerelastic requirements
    - Fatigue requirements
    - Flutter requirements
    - Overall strength requirements
  - Results
    - Basic internal Arrgmt.
    - Complete external config.
    - Camber, twist distributions
    - Local flow problems solved
    - Major loads, stresses, deflections

- **Phase III: Detail Design**
  - Knows
    - Local strength requirements
    - Productivity
    - Functional requirements
  - Results
    - Detail design
    - Mechanisms
    - Joints, fitting & attachments
    - Design refinements as results of test & oper.

**Manufacture**
- Geometry
- BOM
- Material Req

**Assemble**
- Plan/Schedule
- MFGing Plans
- NC Files
- Inspection
- Parts
- Final Product
The first phase is conceptual design

- Mission requirements determine design objectives

- Conceptual design problem: Determine best combination of shapes and sizes to meet these requirements

- Vehicle Capability Goals
  - Range (km) 14400
  - Passengers 468
  - Cruise speed (Mach) 0.9
  - Altitude (m) 11000
  - Take-off field length (m) 3100
  - Cost / seat mile (US $) 0.065
  - Flight control electric
  - Noise footprint -53%
  - Emissions (NO$_x$) -75%
  - Emissions (CO$_2$) -50%
Modern jet transports are all similarly configured...
. . . but other design solutions are proposed all the time

Military designs have even more variability
Conceptual design requires balancing a lot of different design objectives

- Lots of historical data and empirical rules
- Rules are usually configuration specific
- Analysis can provide rough ideas of sizing, weight, performance, wing sweep angles, etc.
- Shape often does not play a role in the analysis
- Make best educated guess of what will work best, taking all the quantifiable and non-quantifiable objectives into account.

Difficulty: Topological design exploration is hard
The output of conceptual design is a configuration.
A significant trap occurs by placing too much value on initial guesses and existing baselines

- Human behavior relies on “anchoring.”*
- Anchoring occurs whenever estimates based on incomplete or inaccurate information are made
- Human nature discourages adequate adjustments to anchor points
- Awareness of the anchoring bias does not eliminate its effect**

The original 737 re-engine project demonstrates this
Preliminary design follows conceptual design

Three design stages

- **Phase I: Conceptual Design**
  - Known
    - Basic mission reqmts.
    - Range
    - Altitude
    - Speed
    - Basic material properties
    - σ/p
    - σ/E
    - $$/lb
  - Design objectives
    - Basic internal arqgmt.
    - Complete external config.
    - Camber, twist distributions
    - Local flow problems solved
  - Results
    - Major loads, stresses, deflections

- **Phase II: Preliminary Design**
  - Known
    - Aerelastic reqmts.
    - Fatigue requirements
    - Flutter requirements
    - Overall strength reqmts.
  - Geometry
  - BOM
  - Material req
  - Plan/schedule

- **Phase III: Detail Design**
  - Known
    - Local strength requirements
    - Productivity
    - Functional reqmts.
  - Manufacturing plans
  - NC files
  - Inspection
  - Parts
  - Final product

- Manufacture
  - Geometry
  - BOM
  - Material req

- Assemble
  - Plan/schedule
  - MFGing plans
  - NC files
  - Inspection
  - Parts
  - Final product
Preliminary design refines the basic shapes and sizes

- The output at this stage includes
  - Complete external shape definition (OML = outer mold line)
  - Complete wing definition
  - Major structural boxes and components
  - Basic internal arrangement
  - Other considerations

- Cost is mostly locked in at this stage, so preliminary design needs to be done very carefully
Traditional preliminary design isn’t competitive in the 21st century

Geometric Model

Grid

This is very hard!

Change geometry

Too much drag

Engineering Analysis
Worst of all, it is impossible to know if design objectives are even feasible, let alone how to achieve them?
Multidisciplinary design optimization (MDO) offers a more systematic approach

- Design Parameters
  - sweep camber twist max thrust crown ht length ...

\[ \begin{pmatrix}
  x_1 \\
  x_2 \\
  \vdots \\
  x_n
\end{pmatrix} \]

- MDA
  - Geometry Generator
  - Analysis Code

\[ \begin{pmatrix}
  y_1 \\
  y_2 \\
  \vdots \\
  y_m
\end{pmatrix} \]
MDO-hardened geometry generators have stringent requirements

1. Provide input to analysis codes
2. Support multiple engineering views
3. Maintain parametric configuration
4. Satisfy known engineering requirements and principles by integrating physics with geometry
5. Satisfy geometric shape requirements
6. Provide differentiability of morphing
7. Produce analytic sensitivities
8. Satisfy known continuity requirements
9. Parametrize complex shapes with relatively few parameters
10. Provide integration with upstream and downstream CAD processes
(1) Provide input to analysis codes

- **Analysis** geometry and **Build** geometry are not the same
- **Analysis** geometry requires no gaps or overlaps, even when they are present in the actual product.
(2) Support multiple engineering views

- Create appropriate geometry for each analysis code
- Use “sole source” data to create discipline-specific views

Aerodynamics view

Structures view

Weights view
(3) Maintain parametric configuration

Parametrizations should always maintain sensible configurations

This is a good parameterization
It always produces a good wing plan form

This is BAD
(4) Satisfy engineering requirements and principles by integrating physics with geometry

Example: Isentropic high speed inlets

The engine should capture all the compression waves without spillage

Flow speed decreases and pressure increases as it turns

Direction of flow

Shock and Mach wave angles increase as flow speed decreases

Cowl lip point
(5) Satisfy geometric shape requirements

- No unwanted inflection points
- Satisfy component specific geometry requirements
- Control of curvature distribution

Parametric variants of this nacelle are also nacelles

+ Additional curve shaping parameters

Exit angle

Hilite radius

Hilite curvature

Nacelle crown

Nacelle keel, MHB

Section must match crown aft of here

+ Additional curve shaping parameters
(6) Provide differentiability of morphing

- Small changes in design parameters should not produce large changes in geometry
- “Open source” algorithms required to create program specific workarounds to inevitable problems
Phenomenon can easily be demonstrated...

- Small change (0.0001") causes curve to flip over

Curve is about 5" long
in any CAD system one chooses
Morphing discontinuities introduce discontinuities in analysis results

Center of Gravity

![Graph showing discontinuity in Z component of CG vs Position of Pad]

Source Vadim Shapiro:
http://sal-cnc.me.wisc.edu/Research/parametric/limits.html

We don’t want this!
(7) Produce analytic sensitivities

- One promising approach due to Chen, Freytag, and Shapiro works for all analysis functions of the form

\[ F(b) = \int_{\Omega} f(b, v) dv \]

- Key idea: Make use of solid modeling and track all changes through primitives

The math works even in the presence of topology changes!
How would one compute the derivative of the center of mass with respect to wing sweep?
Chen, Freytag, and Shapiro’s main result:

\[
\frac{dF}{db} = \int_\Omega \frac{\partial f}{\partial b} + \sum_{k \in \mathcal{A}(b)} \int_{\partial \Omega_k} f \left\| \nabla \Phi \right\| \frac{\partial \Phi_k}{\partial b}
\]

In terms of parametric loft components, this becomes

\[
\frac{dF}{db} = \int_\Omega \frac{\partial f}{\partial b} + \sum_{k \in \mathcal{A}(b)} \int_{S_k} f \frac{\partial S_k}{\partial b} \cdot N_k
\]

derv = 0.0
for face in Aofb:

Skwrtb = . . .
derv += Skwrtb.Flux (face)

The center of mass will move aft 1.4662” for every additional degree of wing sweep.
Much more work is needed to make this accessible

- What about analysis quantities that are not of the form

\[ F(b) = \int_{\Omega} f(b, v) dv \]

- How should one compute

\[ \frac{\partial S_k}{\partial b} \]

- How does one account for the discretization of the analysis codes?
- What geometric modeling tools will be needed to support this?
(8) Satisfy known continuity requirements

Example: Curvature continuity for fillets and blends needed for electromagnetic applications
(9) Parametrize complex shapes with relatively few parameters

- Strings of input points are not effective parameters
- Large changes in any one contributes undesirable, high-frequency changes
(10) Provide integration with upstream and downstream CAD processes
Geometric models are almost always built with splines

• Splines are piecewise polynomial functions

\[ \sum \left( \begin{array}{c} \mathbf{z} \\ \mathbf{z} \end{array} \right) \]

• The linear space of functions they live in is called $\mathcal{S}_{t,z}$
CAD geometry is built using splines

\[
\begin{pmatrix}
  u \\
  v
\end{pmatrix} \rightarrow \begin{pmatrix}
  x(u, v) \\
  y(u, v) \\
  z(u, v)
\end{pmatrix}
\]
B-splines are used to represent splines

• Any function in $\mathbb{S}_{k,d}$ can be represented as

$$s(x) = \sum_{j=0}^{n} \alpha_j B_{j,k}(x)$$
B-splines make excellent finite elements

- Given a differential equation

\[ L(u) = f(u, x) \]

- Compute an approximation solution

\[ \hat{u}(x) = \sum_j \alpha_j B_j(x) \]

- Advantages include
  - High order accuracy
  - Smooth approximation
Boeing’s B-spline ODE solver has a long history

**Major improvements**
- 1988 – First FORTRAN version [Grandine]
- 1989 – Autogeneration of Gauss points [Epton]
- 1991 – Improved adaptivity algorithm [Bieterman]
- 1995 – LAPACK’s banded solver instead of SolveBlok [Klein]
- 2001 – Code rewritten in C [Pierce]
- 2004 – Improved Newton convergence [Ettinger]
- 2009 – Leveraged decoupling for IVPs [Klein]

**Many minor improvements along the way, too**
- 6 formal revisions since January, 2009
- 37 formal revisions since 2001
- Current version dated 10 February, 2010
Our method of choice is de Boor – Swartz collocation

• Use B-splines as finite elements

\[ u''(\theta) = f(\theta, u(\theta), u'(\theta)) \]

\[ u(\theta) \approx \sum_j \alpha_j B_j(\theta) \]

• Approximate ODE solution by solving

\[ u''(\theta_i) = f(\theta_i, u(\theta_i), u'(\theta_i)) \]

\[ \theta_i \] are the Gauss-Legendre points over each polynomial piece
Earliest and most extensive use has been solving contouring problems

- The contouring problem is a DAE of index 2:
  \[ x'(u) \cdot x''(u) = 0 \]
  \[ f(x(u)) = 0 \]

Curve intersection

Horizon line determination

Curve projection

Envelope calculation

Rolling ball filleting

Variable radius filleting

Tool path determination

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Curves can be parametrized in terms of curvature

- Desired curvature distributions can be integrated

\[
\begin{pmatrix}
  x'' \\
  y''
\end{pmatrix}
= \kappa(s)\begin{pmatrix}
  -y' \\
  x'
\end{pmatrix}
\]

... can be integrated to produce ...

Nacelle Created
But not Displayed

Centerline Section Lengthened
Nacelle Displayed
Some high speed inlets need to satisfy a “shock on lip” condition

Example: Isentropic high speed inlets

The engine should capture all the compression waves without spillage

Flow speed decreases and pressure increases as it turns

Direction of flow

Shock and Mach wave angles increase as flow speed decreases

Cowl lip point
An implicit differential equation describes inlet to capture isentropic compression waves

\[
\tan \mu = \frac{y_{lip} - y - y'(x_{lip} - x)}{x_{lip} - x + y'(y_{lip} - y)}
\]

\[
M = \frac{1}{\sin \mu}
\]

\[
\nu(M) = \sqrt{\frac{\gamma + 1}{\gamma - 1}} \tan^{-1} \sqrt{\frac{\gamma - 1}{\gamma + 1}} (M^2 - 1) - \tan^{-1} \sqrt{M^2 - 1}
\]

\[
f(x, y, y') = \nu(M) - \nu(M_0) + \tan^{-1} y'
\]
B-spline finite elements can be used to correct lofts for computed deformations

- Solutions to the linearized structural analysis problem introduce unwanted stretching of material
- The combination of the two different discretizations sometimes leads to noisy computed deflections on the aero mesh
- Updating the mesh instead of the loft sometimes produces invalid deformed meshes
How can we reacquire some of the lost nonlinearity?

- **Basic idea:** Merge the deformations together with the intrinsic geometry of the undeflected curve

\[
q'' = \frac{q' p'^T + q'_\perp p'_\perp}{\|q'\|\|p'\|} (p'' + d'')
\]

- **Where**
  - \( p \) = Original curve
  - \( d \) = Computed deflections
  - \( q \) = Corrected, deflected curve
The model can be extended to surfaces
B-spline finite elements can be used to loft waveriders

- A waverider is a lifting surface which rides on the shock wave created by its own leading edge in supersonic flight
  - First developed by Terence Nonweiler in 1951
  - Only production design to use waveriders was XB-70 in 1960s
The Taylor-MacColl equation models conical flow

- Start with the Navier Stokes equation
- Assume
  - Inviscid flow
  - Circumferentially symmetric flow
  - Irrotational flow
  - Steady flow
- In spherical coordinates:

\[
u''(\theta) = \frac{\gamma - 1}{2} \left( 1 - u^2 - (u')^2 \right) \left( u + u' \cot \theta \right) - u
\]

\[
\left( u' \right)^2 - \frac{\gamma - 1}{2} \left( 1 - u^2 - (u')^2 \right)
\]
Generate streamline by solving another ODE

\[ \theta = \arctan \frac{y}{x} \]

\[ y'(x) = \frac{y(x)u(\theta) + xu'(\theta)}{xu(\theta) - y(x)u'(\theta)} \]

\[ y(x_0) = y_0 \]

Note: All solutions are self-similar
Each streamline of the waverider is produced this way
Can also loft Busemann inlets by tracing streamlines
**Detail design is the most expensive design stage**

### Three design stages

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<td>PRELIMINARY DESIGN</td>
<td>DETAIL DESIGN</td>
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#### PHASE I
- **Known**
  - Basic Mission Reqs. (Range, Altitude, Speed)
  - Basic Material Properties (σ/ε, E/ρ, $\$/LB)
- **Results**
  - Geometry, Airfoil Type, Lift/Cruise, Drag Level, Weight/Goals (α, λ, Δ)
- **Design Objectives**
  - Basic Internal Arrangement, Complete External Configuration, Camber, Twist Distributions, Local Flow Problems Solved, Major Loads, Stresses, Deflections

#### PHASE II
- **Known**
  - Aerelastic Reqs. (Fatigue Requirements, Flutter Requirements, Overall Strength Reqs.)
- **Results**
  - Plan/Schedule
  - Geometry, BOM, Material Req

#### PHASE III
- **Known**
  - Local Strength Requirements, Productivity, Functional Reqs.
- **Results**
  - Manufacturing Plans, NC Files, Inspection, Parts

### Manufacture
- Geometry, BOM, Material Req

### Assemble
- Plan/Schedule
- Final Product

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Detail design is what most people think of as design

- Geometry models for the entire airplane are created in this stage
- Commercial CAD/CAM systems are preeminent
- Little scope for systematic design at the vehicle level remains, but individual components are frequently optimized
- Analysis of individual components is more common than system or vehicle level analysis
CAD has helped reduce the need for physical prototypes

**Then**

- B2707 Supersonic Transport (1966-1971)
- Prototype made out of wood!
- Cost: Several million US$ (in 1970)

**Now**

- Elimination of any physical prototyping
- Early interference detection
- > 50% reduction of engineering change requests, rework and error
- Alignment to within .023” versus .5” previously (20 x better)
Manufacturing and assembly will be covered later

- **Manufacture**
  - Geometry
  - BOM
  - Material Req

- **Assemble**
  - Plan/Schedule
  - MFG\(^{\text{ing}}\) Plans
  - NC Files
  - Inspection
  - Parts
  - Final Product
Challenge #1: Actual parts are not rigid

A floppy structure

Issues:
- Part growth during assembly
- Sagging
- As built shape is different from in-flight shape
- Thermal effects (several models to represent engine)
- Warpage due to internal stresses
- Current CAD technology does not model dynamic structures very well

The yellow thing is part of a wing
Note the person in the back

Warped
Challenge #2: What’s the best way to customize material properties?

Part is built up with tape and thread

Preheats, lays down, & cuts the material
787 fuselage sections are made this way

Tape is wound over a barrel

Then baked

Thermal effects/warpage after it cools

Note the discrete nature of the surfaces in this part.

Note the pad up ~50 layers.
Challenge #3: What is the best way to model composite materials?

Problem:

How to model what the part looks like after curing. What should the IML mold look like to get a smooth OML?

Current modeling systems have trouble handling this volume of data. Consequently, description is dispersed and includes text, 2D data and geometry.
The future may lie with direct manufacturing

Flavors:
- Layered manufacturing
- Additive manufacturing
- Rapid manufacturing (RM)
- Direct digital manufacturing (DDM)
- 3D Printing
- Generative manufacturing
- Rapid prototyping
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Fused Deposition Modeling (FDM)
- Electron Beam Melting (EBM)
- Stereo-Lithography Apparatus (SLA)
- Laser Engineered Net Shape (LENS)
- Laminate Object Manufacturing (LOM)

Lots of new methods being developed
Direct manufacturing is widely applicable

Complex parts

“Impossible” parts

Molds for complex casting

“Plastic” parts (Nylon, PEEK, …)

Metals

Biologicals (bone & bladder scaffolds, teeth, …)
Huge opportunities exist for direct manufacturing

- **Production:**
  - Eliminate non-recurring tooling costs
  - Lower recurring unit part costs
  - Faster part delivery times
  - Supplier flexibility
  - Direct fabrication (in some cases):
    - 50% Cost Reduction
    - 67% Cycle Time Reduction at Minimum

- **Product:**
  - Reduced part count and weight
  - Lower inventory and transportation costs
  - Improved Life Cycle Product Costs

- **Future**
  - Battle field spares
  - Heterogeneous materials
  - Sensor embedding

- **Challenge #4:**
  - Not as strong (yet)
  - Not as accurate (yet)
  - Not for high volume
  - Size limits

DM parts in F 18
New materials and manufacturing techniques continue to open up new challenges

- How to make best use of “engineered anisotropic material”
- How can we generate the optimal shape AND material properties?
- Also... want to certify the process to avoid non destructive testing ➔ repeatable & reliable processes

Optimal shape

...with...

Optimal microstructure
Huge challenges remain

- Geometric design is not a solved problem!
- How to best exploit new manufacturing processes?
- How to best exploit tailored materials?

Back to the future?
Our first “manufactured” materials: Wood & cloth!