Case Study of 767 Horizontal Stabilizer

• **Goals of this class**
  – Carry through the topics of this course on one product
    • Look in detail at a real aircraft structural assembly
    • Define and flow down KCs
    • Compare different assembly methods
      – conventional one based on fixtures
      – proposed one based on part-to-part mating features
    • Draw datum flow chains for them
    • Study the economics
History of 767 Horizontal Stabilizer Project

- Fast/Flexible Manufacturing Project 1996
- Coordinated Aircraft and Auto industry projects
- Vought Aircraft partner via LAI
- Vought’s goal: cut costs, earn more Boeing business
- Vought’s hypothesis: convert from fixed to flexible assembly tooling
- Vought’s focus of project: 767 H. S. upper wing subassembly
Our Challenge: How To Do This

• Available data
  – Existing tooling
  – No history, people, drawings
  – Evidence of errors in tooling

• Our process
  – Understand **goals** of existing process
  – Reverse engineer from the top down
  – Expand scope of study to complete horizontal stabilizer
  – Look up the supply chain to Boeing to get the requirements
  – Generate new process to achieve agreed goals
Structure of Horizontal Stabilizer
Top Level Key Characteristics

- **AERODYNAMICS**
  - (gap between skin and FTB & FTE)
  - (gap between skins)

- **STRENGTH**
  - (based on joining plus chords and ends of spars)

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HORIZ ASSY 2

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Horizontal Stabilizer Subassemblies
(current decomposition)

- UPPER SKIN ASSEMBLY
- FWD SKIN
- AFT SKIN
- FORWARD TORQUE BOX
- FORWARD SPAR
- RIB
- STRINGERS
- PLUS CHORD
- LOWER SKIN ASSEMBLY
- HORIZ ASSY 2
- STRINGERS
- FWD SKIN
- AFT SKIN
- PLUS CHORD
- REAR SPAR
- FIXED TRAILING EDGE
- STRINGERS
- LOWER SKIN
- PLUS CHORD
- STRINGERS
- LOWER SKIN
- PLUS CHORD

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PKCs for Horizontal Assembly

PKC #1: Joint Strength affected by alignment between plus chord ends and spar end fittings.

PKC #2 & #3: Aerodynamics affected by these skin gaps

PLUS CHORD

SPLICE STRINGER

FWD TORQUE BOX

FORWARD SKIN

AFT SKIN

FIXED TRAILING EDGE

SPAR END FITTINGS

JOINT STRENGTH PKC ACHIEVED

END FITTING

SPLICE PLATE

PLUS CHORD

SHIM NEEDED TO ACHIEVE JOINT STRENGTH PKC

END FITTING

SPLICE PLATE

PLUS CHORD (MISALIGNED)

SHIM

SPAR
Current Total Process

[Diagram of skin gap PKC, delivered by design of fixture to hold FTB and FTE, plus chord alignment to spar ends PKC, final assembly, skin gap PKC, delivered by skin gap AKC, plus chord alignment to spar ends PKC, skin subassembly, plus chord alignment to skins AKC, forward skin, splice stringer, aft skin, forward torque box, forward spar, ribs, rear spar, fixed trailing edge.]

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Top-Level KCs

Skin Gap & rib align KCs

Ribs

FKC #1

PKC #2

Skin Gap & rib align KCs

A Spar

FKC #2

PC

FTB

F Spar

FS

PKC #3

AS
Product Decomposition Based on Independent KCs
Based on Independent KCs

Decomposition/Subassemblies
Sob

Unfortunately,

these subassemblies are impossible!
If plus chords are assembled to spar ends before skins are assembled to plus chords, then it will be almost impossible to join skins and stringers to plus chords.
Actual Subassemblies

- FTB
- F Spar
- PC
- SS
- AS
- FS
- FTE
- A Spar
- Ribs
Type 1 and Type 2 Methods for One Subassembly - KC Flowdown Seems OK
Second Subassembly Has Lost Its KC Links to Higher Level Assemblies

- Any assembly process for this subassembly must provide proxies for the missing KCs, regardless of whether the subassembly is made as a Type 1 or Type 2
- These KCs will be coupled
- Note that no drawing of this subassembly could be found
Possible Assembly Strategies

ORIGINAL PKCs

ACHIEVE PKCs SEPARATELY (ASSEMBLY IMPOSSIBLE)

CURRENT METHOD USING FIXTURES

B1

B

ASSEMBLY POSSIBLE- (PKCs COUPLED)

TWO ALTERNATE METHODS REQUIRING DIFFERENT AKCs

B2

using fabricated edge features

B3

using fabricated hole and slot features

HORIZ ASSY 2

each part is placed against the fixture
Our Challenge

• Current assembly method relies on costly fixtures
• Can a process be devised that does not rely on fixtures other than for support against gravity?
• Can such a process achieve the PKCs?
• Would it be economical?
• What new worker skills would be needed?
• Can we figure out what the old process was doing so we can reproduce its objectives using new methods?
Diagram of Assembly Analysis Process

1. KC Flowdown
2. PKCs
3. AKCs
4. Assembly Sequence Generation
5. Prune into Families
6. Identify most promising family
7. Analyze Sequences
8. Propose Assembly Features
9. Equipment Requirements

Skin Gaps
Joint Strength affected by flange alignment.

PKCs
AKCs
Assembly
Feature AKCs
Plus Chord
aft hole &
forward slot
Aft Skin
aft hole &
inboard slot
Fwd Skin
inboard slot & fwd slot
Stringer #3
inboard holes
Stringer #3 holes

FORWARD SKIN
SPICE STRINGER
AFT SKIN
Liaison Diagram

- Str4-11
- Fwd Skin
- Plus Chord
- Str1-2
- Aft Skin
- Splice Str3
Current Skin Assembly Process

FIXTURE

Everything indexes off the fixture
Current Skin Assembly Process - 2
Assembly KC #1 & #2
Datum Flow Chain for Current Skin Process

EXPLICIT DATUM TRANSFER

CONTACT WITHOUT DATUM TRANSFER

KC
New Process #1: Fixtureless (Type 1)

FORWARD SKIN

AFT SKIN

SPlice STRINGER

PLUS CHORD

HOLES CHOSEN FOR LOCATION
SLOTS CHOSEN FOR LOCATION, THERMAL & SHOT PEEN GROWTH ACCOMMODATION
ALL SLOTS DRILLED OUT TO FULL SIZE
HOLES AT FINAL ASSEMBLY

BIGGEST THERMAL DIFFERENCE

SMALLEST FULL SIZE HOLE

ASSEMBLY LEVEL DATUMS

PART LEVEL DATUMS

MATING FEATURE (SLOT)

MATING FEATURE (HOLE)
PKC Delivery Map for New Process #1

PKCs

AKCs

Assy features

Mfr features

PKC #1

PC aft hole & fwd hole

Aft skin aft hole & inbd hole

Fwd skin inbd hole & fwd slot

PKC #2

AKC #1

PKC #3

AKC #2

AKC #2

Str 3 inbd holes

Skins & str 3 holes & slots

Size/shape of PC and hole locations

Size/shape of skins

Hole/slot locations on skins & str 3

Coord. of slot length and hole size

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Datum Flow Chain for New Process #1

Note: in existing process, skin-plus chord is a contact. In new process it is a mate.
New Process #2
Assembly Features for Process #2

- PLUS CHORD
- FORWARD SKIN
- SPLICE STRINGER
- AFT SKIN

Legend:
- ASSEMBLY LEVEL DATUMS
- PART LEVEL DATUMS
- MATING FEATURE (HOLE OR SLOT)
- MATING FEATURE (EDGE)
Datum Flow Chain for New Process #2

Str4-11 → (6) → Fwd Skin

Plus Chord Angle AKC

T (2) → (1) → Skin Gap AKC

Str1-2 → (6) → Aft Skin

Splice Str3 → (6) → F

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KC Deliverability Map - Process #2

PKCs

AKCs

Assy features

Mfr features

PKC #1

PKC #2

PKC #3

AKC #1

AKC #2

AKC #2

PC aft hole

Hole & inboard surface

Fwd skin aft

Skin gap

tool size

Aft skin aft

inboard surf

Tool location

at fwd end of

plus chord

CNC

worktable

Part sizes &

hole locations
Rib-Spar as a Type 2 Assembly

Step 1: Put FTB and FTE in Fixture

Step 2: Put in ribs

FTB-Rib-FTE assy

Fwd Torque Box

Strength PKC

Fairness PKC

Fixed Trailing Edge

Rib
Rib-Spar Assembly - 2

Step 3: Add skins and adjust skin gaps and plus chord alignment to FTB and FTE
DFC for Rib-Spar as a Type-2
DFC for Wing Assembly as a Type 2

Two KCs in conflict

FTB

Skin Gap PKC

Str4-11

Plus Chord Alignment PKC

Fixture

RIBS

Plus Chord

Skin Gap PKC

Fwd Skin

Plus Chord

Skin Gap AKC

Aft Skin

Splice Str3

Plus Chord Angle AKC

SKIN GAP PKC

FTE

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Tolerance Analysis of KC Delivery Using VSA

- VSA was used to on each candidate new process
- Results show that process 1 is unable to deliver AKC & PKC 1 all the time because the holes in the splice stringer can’t be placed accurately enough
- This also hurts PKC 2 and 3
- Process 2 is able to deliver all 3 PKCs 100% of the time
Matlab$^{\text{TM}}$ Analysis

- Assumed assemblers could maneuver the wing skin laterally and angularly
- Assumed smaller variation in hole and slot placement
- Assumed that the rest of the wing was error-free
- Determined that only a few assemblies would fail
Parts and Their Frames

AFT SKIN

FORWARD SKIN

SPLICE STRINGER

AFT SKIN

FORWARD SKIN

Parts and Their Frames
Parts Assembled and Frames

- STRENGTH KC
- AERODYNAMIC KC

END FITTING

FORWARD

RIBS

AFT

FTE

FORWARD SKIN

SPLICE STRINGER

AFT SKIN

END FITTING

FTB

G1

G2

P2

S1

PLUG CHORD

G3

G4

P4

H1

S2

STRENGTH KC

AERODYNAMIC KC

P3

0.045"

0.045"

63"

351"

INBOARD

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OUTBOARD

INBOARD 2004
Sample Space for Tolerance Analysis

[Diagram showing a sample space for tolerance analysis with annotations indicating adjustments possible by translation and rotation.]

Adjustment possible by translation and CW rotation.

Adjustment possible by translation.

No adjustment needed.

Adjustment possible by translation.

Adjustment possible by translation and CCW rotation.

Adjustment possible by translation and CW rotation.

0.015 * 5.25 / 29.25 = 0.0027
Matlab\textsuperscript{(TM)} Results

fixture and FTB-ribs-FTE modeled as ±0.008 and plus chord modeled as ±0.01

~120 out of 10000 fall outside
## Pros & Cons of Proposed Processes

<table>
<thead>
<tr>
<th></th>
<th>Current Process</th>
<th>Proposed Process #1</th>
<th>Proposed Process #2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td></td>
<td>• Delivers all AKCs and PKCs repeatably</td>
<td>• Delivers all AKCs and PKCs repeatably</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Delivers AKC #2 and PKC #3 repeatably</td>
<td>• Completely flexible method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Completely flexible method</td>
<td>• No dedicated fixtures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Uses existing fab equipment</td>
<td>• Uses existing fab equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Least costly</td>
<td>• Least costly</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Controls critical interfaces</td>
<td>• Controls critical interfaces</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td></td>
<td>• Inflexible fixtures</td>
<td>• Fails to deliver AKC #1 on a few assemblies</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Variation absorbed at stringer-plus chord interface</td>
<td>• PKC #1 &amp; #2 not delivered on those same assemblies</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>• Requires higher-functionality tack fixture (higher cost)</td>
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<tr>
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<td></td>
<td></td>
<td>• Requires a limited number of small fixtures</td>
</tr>
</tbody>
</table>
Rib-Spar as a Type 1 Assembly

Step 1: Put FTE on Support
Step 2: Add ribs
Step 3: Add FTE
DFC for Rib-Spar as a Type-1
DFC for Wing Assembly as a Type 1

- FTB
- Skin Gap PKC
- Plus Chord Alignment PKC
- Str1-2
- Plus Chord
- Str4-11
- Fwd Skin
- Aft Skin
- Splice Str3
- Skin Gap AKC
- Plus Chord Angle AKC
- RIBS

Two KCs still in conflict Fwd Skin

figs for designing assemblies
“Impossible” as a Type 2

FTB

KCs do not conflict

Fwd Sk

Skin Subassembly

Skin Gap PKC

Skin Gap PKC

Plus Chord

Alignment PKC

Plus Chord

Alignment PKC

Skin Gap AKC

FTE

Seam

Gap AKC

Fixtures

RIBS

Skin Subassembly

Str4-11

Splice

Str3

Aft Sk

Skin

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“Impossible” as a Type 1

KCs do not conflict

Fwd Skin

Skin Subassembly

Splice Str3

Skin AKC

Str1-2

Skin Gap PKC

Plus Chord Alignment PKC

RIBS

SKIN GAP PKC

SKIN PKC

FTE

FTB

Skin Gap PKC

Str4-11

Plus Chord

Meets

Skin Subassembly
Cost Analysis -1

- The basis for analysis was the KC-driven Precision Assembly (PA) process for the 767 horizontal upper skin assy.
- PA time and cost were estimated for the 767 skin.
- The 767 cost/time analysis was scaled for the remaining 747 & 767 assemblies Vought makes for Boeing.
- PA assumed to be accomplished in three distinct cells: Tack, CNC Auto-Rivet, Final Assembly.
- These cells all require new investment.
Cost Analysis - 2

• Baseline times for each step were taken from Vought’s estimates for its process.
• Required cell time for MIT’s processes was estimated based on Vought’s times and a distribution of realization factors applied to obtain an assembly time for each cell.
• A computer simulation was conducted to determine the necessary capital equipment.
Simulation Scenarios

- Three PA processes were developed and analyzed.
  - The 3 processes are “Vought,” “MIT 1,” and “MIT 2”
  - “Vought” is Vought’s proposed PA process
  - “MIT 1” uses holes and slots. It was derived from “Vought” by applying the KC flowdown method. “MIT 2” uses NC tack cell

- Three scenarios were studied:
  - All Boeing assemblies, all programs
  - Four representative assemblies
  - Introduction of a new assembly
    - New assembly would require new fixed tool but not new PA equipment

- One and Two shift operations
Results - 1

• PA estimated to reduce process time by approximately 50%. At current demand this results in approximately XX hours saved annually.* Value of flexibility, “image,” and freed-up floor space not included.

• Annual savings = $X Million (assumes all assemblies converted to PA at a rate of $XX/hour.)
  – VOUGHT TO BE = 54% OF AS IS TIME
  – MIT 1 = 43% OF AS IS
  – MIT 2 = 42% OF AS IS
  – *ACTUAL NUMBERS ARE PROPRIETARY
Results - 2

- Estimated equipment investment to implement PA (example for MIT 1)

<table>
<thead>
<tr>
<th></th>
<th>All Parts</th>
<th>4 Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>One Shift</td>
<td>$21.4M</td>
<td>$14.1M</td>
</tr>
<tr>
<td>Two Shifts</td>
<td>$14.1M</td>
<td>$7.3</td>
</tr>
</tbody>
</table>

(assumes cost per cell is Tack $2M, A-R $4.8M, Final Assembly $0.5M)
Results - 3

• Current economics did not justify the new process
• The new process becomes economical if Vought gains new business for which it can use the new cells, thus saving the cost of new hard fixtures
• Training and cultural issues remain to be evaluated
  – Adjusting by hand becomes adjusting via computer
  – Ad hoc process becomes a preplanned and designed one requiring more manufacturing knowledge during design
  – More communication between fab and assembly shops needed