Manufacturing Cost Considerations in Compressor Design

Joseph Orosz
Torad Engineering
• Brief History of Compressors

• Compressor Manufacturing
  » Yesterday and Today
  » Enabling Technology Changes in Manufacturing

• Design Considerations
  » Performance
  » Cost
  » Future Trends
A brief History of Compressors and Market Drivers over the last 30 years
History of Compressors

What types of compressors existed prior to 1955?

Reciprocating
Open Drive
Semi – Hermetic
Hermetic

Centrifugal
History of Compressors

- Reciprocating Compressors
  - Applied in comfort cooling up to 250 tons
  - Refrigeration Applications
  - Best fit for applications with variable compression ratios
  - All systems requiring
    - Direct Expansion air handlers
    - Remote air cooled units
    - Evaporative condensers
History of Compressors

- Centrifugal Compressors
  - Applied in comfort cooling greater than 150 tons
  - Limited operating range
  - Low pressure refrigerants – R11, R12
  - High Efficiency
  - Cost effective in large sizes
Market Forces

Market dynamics of the Mid 70’s

• The oil Crises
• Increased Regulations
  • DOE
  • ASHRAE
  • ARI
• Increased energy cost
Appliance Market

New United States Refrigerator Use v. Time and Retail Prices

Source: David Goldstein
Central A/C

Average 7.0 SEER in 1975

Average 13.5 SEER in 2010
Large Water Chillers

Example of HVAC Historical Product Efficiency Improvements for Large Centrifugal Chillers

ASHRAE 90.1 MINIMUM WATER CENTRIFUGAL CHILLER EFFICIENCY REQUIREMENTS >=300 AND <600 TONS

61% Improvement in Full Load Since 1977 on top of losses in cycle efficiency for changes in refrigerant from CFC to HCFC to HFC
Industry Drivers

What did the demand for increased efficiency and reduced cost look like over the last 30 years?

<table>
<thead>
<tr>
<th>Product</th>
<th>Selling Price</th>
<th>Energy Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domestic Refrigerators</td>
<td>-60%</td>
<td>+70%</td>
</tr>
<tr>
<td>Large Tonnage Chiller</td>
<td>-22%</td>
<td>+61%</td>
</tr>
<tr>
<td>Residential A/C</td>
<td>-24%</td>
<td>+68%</td>
</tr>
</tbody>
</table>

Cost and Efficiency improvements required new compression technologies
Manufacturing Technology of the past
Piston Compressors

What can we say about the manufacturing attributes of these two machines?

Piston Compressors

Easy to seal - Piston in a housing bore!
Capitalized on the existing Automobile supply chain
Rings, Pistons, Crankshafts, Rods, Blocks
Easy to Measure features
Experienced high volume production supply chain
How did we manufacturer reciprocating parts?

Capital Equipment based on Automotive

Prior to CNC equipment most manufacturing was done by breaking down operations into discrete features and producing those on individual machines.

The automobile industry was producing machines to make all these parts.

After all a piston compressor is an engine running in reverse!
Piston Compressors

Piston Bore Feature Generation

- Cast Bore
- Rough Bore – Boring Bar
- Semi-Finish – Boring Bar
- Finish – Fine Boring Bar
- Finish Hone
- Measure for size
- Scan for Cylindricity
Centrifugal Compressors

What can we say about the attributes of these machines?

Centrifugal Compressors?

No Seals!
Large capacity and high speed
Well suited for high capacity chillers
Due to large internal clearances and the use of non-contacting high speed blades these machines could be made using the same equipment as other steam turbine equipment turbo equipment of the day.
How did we manufacture centrifugal parts?

Capital Equipment?

Production was based on the steam turbine business which developed in the early 20th century.

Compressor were produced in low volume so cost was not the major issue.

Machine process was slow with hand fitting of parts.
New Compressor Technologies
New Technologies

What types of compressors evolved post 1950’s

Twin Screw

Mono-Screw

Rotary Vane

Scroll

Rolling Piston
What can we say about the attributes of these machines?

Positive Displacement
High Speed
Rotating Motion
Complex Geometries
Difficult to Manufacturer
Difficult to Measure
Hi Capital Equipment Cost
Enabling Manufacturing Technology
Enabling Technology - Machining

Old Machine Tools
Multi Step Process
Hard Tooling
Fixed Speeds
2 Dimensional
Non flexible
Long Set ups
Limited feature Geometry

Design Limitations
Holes
Lengths
No Complex Forms
Limited Surface Finish Control
Extra Processing
Limited Design flexibility
Enabling Technology - Machining

New Machine Tools
Flexible CNC Machines
Many features in one machine
Variable speed for improved cutting conditions
2d and 3D contour milling

Design Opportunities
Additional features for low cost
2D and 3D Contours
Improved Surface Finishes
Improved form
Squarness
Perpendicularity
### Enabling Technology - Measurement

<table>
<thead>
<tr>
<th>Old</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameters</td>
<td>Coordinate Measuring Machines</td>
</tr>
<tr>
<td>Lengths</td>
<td>Manual</td>
</tr>
<tr>
<td>Locations – Time Consuming</td>
<td>CNC</td>
</tr>
<tr>
<td>Form – Expensive</td>
<td>Scanning</td>
</tr>
<tr>
<td>No in process measurement</td>
<td>In Process Gaging</td>
</tr>
<tr>
<td>2D complex Curves</td>
<td>Optical Measurement</td>
</tr>
<tr>
<td></td>
<td>In Machine probing</td>
</tr>
</tbody>
</table>
Metrology Evolution

Manuel Transfer Gage (1960’s)


CNC High Speed Scanning Measurements 2000
Carl Zeiss IMT
Scroll Measurements

- Scan scrolls in minutes.
- This process used to take over an hour.
Design Considerations for Compressor Manufacturing
Design Considerations

- Feature Control
  - Size
  - Location
  - Form
- Tolerances vs Cost
- Design Influence
  - Manufacturing
  - Measurement
- Volume Effects
Design Considerations

- Feature Control diameters and lengths
  - Features have a none linear cost structure
  - > +- .005 Size Tolerance – Process Capable – Tooling inexpensive with long tool lives
  - > +- .001 Size Tolerance – Process Capable – Tooling Reasonable
  - > +- .0005 Size Tolerance – Process can be capable – tooling and machines expensive
  - < .0005 Size Tolerance – Process typical incapable
    - In process controls
    - Continues auditing adds cost
Design Considerations

- Form Control
  - Roundness
  - Flatness
  - Cylindricity
  - Straightness
  - Profile

- Form is not your friend!
  - Complex 2D shapes – Scroll
  - Complex 2D shape non constant Z – Twin Screw
  - Complex 3D Shape – Mono Screw
Why is form so difficult?

- It is typically a refinement of a feature – i.e., Bore size with a roundness of .0002"
- Need high level of data to evaluate correctly
  - Diameter Measurement - 2 points with a dial bore
  - Roundness Evaluation at .0002” Tolerance – for a 3” bore would need about 1,000 points
- Non Standard Measuring tools
  - Roundness Tester
  - Scanning CMM’s –
    - 100mm/sec with an acquisition rate of 4000 points/sec
Design Considerations

<table>
<thead>
<tr>
<th>Part Tolerance</th>
<th>Gage Repeatability*</th>
</tr>
</thead>
<tbody>
<tr>
<td>.005” (.127 mm)</td>
<td>0.0000175” (.0045mm)</td>
</tr>
<tr>
<td>.001” (.0254mm)</td>
<td>.000035” (.0009mm)</td>
</tr>
<tr>
<td>.0005” (.0127mm)</td>
<td>.000018” (.00046mm)</td>
</tr>
</tbody>
</table>

The Accuracy statement for the gauge is only PART of the answer. Remember.. numbers we are looking at are the AVERAGE REPEATABILITY of the GAUGE. This includes variation as a result of fixturing, probe flexing, thermal fluctuations, vibration influences, etc. So the gauge accuracy number is only a portion of the consideration.

*Average repeatability that is needed to assure .10% manufacturing tolerance is lost to the gauge.
The Cost Hierarchy of Feature Generation

1. Size – Diameters, lengths
2. Location – X, Y
3. 2D Form - Squareness Flatness, Roundness
4. 3D From – Profiles, Cylindricity
Volume and Experience
Volume Effects

● Volume and the Experience Curve
  » Volume effects are real
  » The higher the complexity the higher the experience curve
  » First cost estimates are always high
  » Low volume products move slowly along the curve – don’t over-estimate the cost evolution
Volume Effects

- Experience Curves

![Diagram showing experience curves for unit cost versus cumulative output. The curves indicate a decrease in cost as output increases, with different slopes representing 90% and 70% experience curves.]
Volume Effects

- Experience Curves

40% Cost Reduction 1960-2008

- Refrigerators
  - Time period: 1964-2008
  - \( R^2 = 0.87 \)
  - LR = 13 ± 3%; PR = 87 ± 3%

- Upright freezers
  - Time period: 1970-2003
  - \( R^2 = 0.69 \)
  - LR = 15 ± 5%; PR = 90 ± 5%

- Chest freezers
  - \( R^2 = 0.93 \)
  - LR = 9 ± 4%; PR = 91 ± 4%

- Specific price in EUR/100 volume

- Cumulative global production in million refrigerators

- Energy efficiency index

- Specific price in EUR/100 volume

- Cumulative global production in million freezers
Cost Drivers
Manufacturing Cost Drivers

- The “Z” is free concept!
  - What is the lowest cost dimension?
  - Along the axis of the compressor
    - Lengthening the stroke of a piston compressor
    - Scroll Involute height
    - Screw rotor length
  - Limit to exploiting the length is process capability

- Stay inside the motor diameter
  - Minimize enclosure dimensions
  - Give flexibility on the design
Manufacturing Cost Drivers

● Minimize the interfaces
  » Lower Cost
  » Better Geometric control
  » Easier assembly
  » Less defects

● Control vs. Adaptation
  » High volume selective assembly can make sense
  » Lower volume can employ other methods
    – Part adjustment
    – Shimming
    – Sacrificial coatings
Future Trends and Practical Limits
Future Trends

● Cost Requirements – Direct/Indirect and Capital
  » The winners will have a lower total cost
  » Reduce material
  » Reduce processing time
  » Reduce capital outlay
    – Rapid implementation of new designs
    – Allow for recapitalization of the product to assure performance requirements are met throughout the life of the product.
Future Trends

- Efficiency requirements
  - They will continue to be stretched
  - Due to unit requirements compressor variability must be minimal
  - This means improved manufacture
  - This means more tolerant designs
  - Designs must be robust enough to allow consistent manufacture of the compressor at reasonably cost
Future Trends - Efficiency

- With compressor Overall Isentropic Efficiencies over 70% how far can we go?
- Mature technologies will see only incremental improvement
- Large Chillers market is pushing hard for a more holistic approach to building efficiency as discrete efficiency gains from equipment are limited
- Efficiency gains still available in smaller sizes.
- Low cost compressor design will benefit by making dollars available for energy reducing technologies to be applied at better cost points, variable speed drives, controls etc.
Final thoughts

Increased design focus on Manufacturability

Design Determines about 50% of the manufacturing cost