MAXIMISING FILL FACTOR

A SHIPS PROJECT ASSIGNED BY ROLLS-ROYCE

PROF. FRANGI'S TUTOR GROUP

LAWRENCE CARSLAKE, DAN HINES, LEONARD OBENG, YANG FAN, LI ZHONGWANG

Outline

Introduction

Aims

Context

Fill factor

Research

Current methods

Portland Electric

Sheffield UTC

Our ideas

Brainstorming

Slot shape

Wire types

Hand/Machine

Insulation

Proposed design

Semi-closed slot

Band construction

Hexagonal litzs

Enamel insulation

Conclusions

Novel vs. tested

Future work

Aims

Suggest improvements to current winding techniques to improve slot fill factor of motor-generators

- How do manufacturers wind power dense coils?
- Constraints motors have to work around?
- Novel solutions vs trialed methods?

Context

- Assigned by the **Electrical capabilities group** of **Rolls-Royce**
- The motors are used within a jet engine to provide **electrical starting** and **power generation when in flight**
- They must generate **50MW** at a low voltage (**<230v**)
- Temperatures can vary between **-50°C and 150°C**
- Pressure can vary between 1atm at sea level to **0.16atm** at 43,000ft
- **Weight savings** and **Reliability increases** are the main design factors

Rolls-Royce

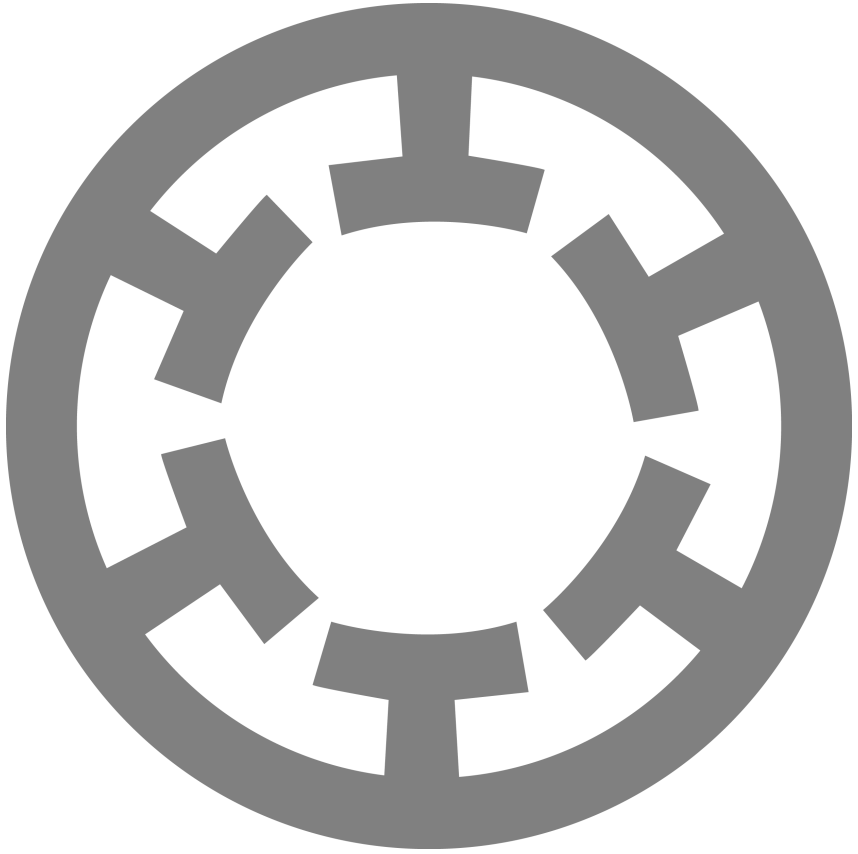
- Focus on **integrated propulsion** for Land, Sea and Air
- **50% Market share** in wide body aircraft market
- Worldwide operations with head offices in **Derby**
- Working on **more electric aircraft** such as the **787 Dreamliner**
- Larger electrical requirement necessitates **larger generation capacity**
- Our project aims to minimise the size of the generators while maintaining the generating capacity

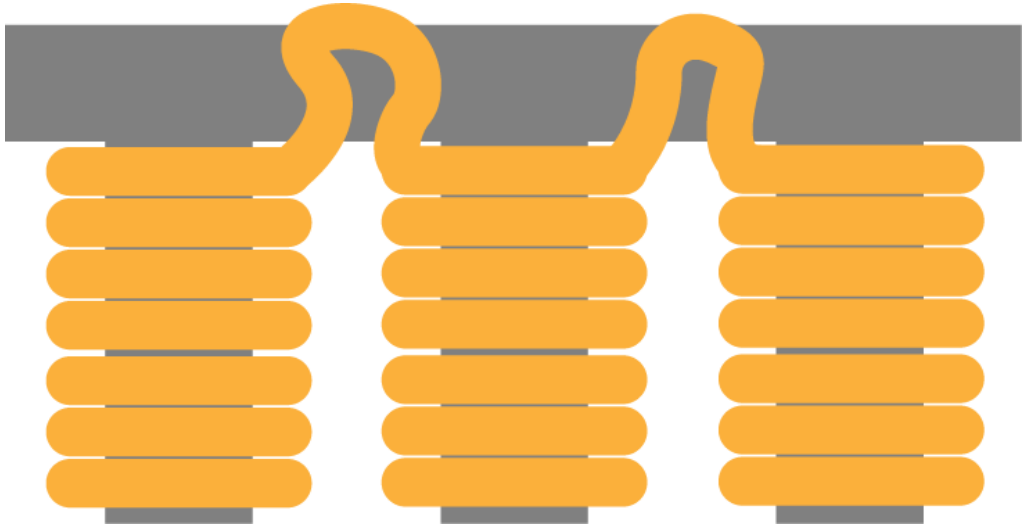
What is slot fill factor?

The ratio between the cross-sectional area of the conductors in a slot to the total area.

- Lower fill factors are often caused by airgaps between wires or production techniques
- Typical values for large motors are **0.4-0.6** however it is higher for smaller lower power coils
- If fill factor is increased, the motors can be **smaller and lighter** for the same conductor current density and heat density

Slot fill factor





Current methods of winding

- We've been in contact with coil winding companies around Sheffield to find out how they wind coils
- **Portland electrical** repair the windings of one-off machines
  - Mostly use **hand winding**
  - Hand winding can take over **30 hours** for large jobs but can achieve a higher fill factor
  - Don't design machines so have no control on fill factor
  - Serve businesses such as Rolls-Royce

Current methods of winding

- **Sheffield University technology center** (UTC)
  - Rolls-Royce working with **researchers from the university**
  - Utilise rectangular litzs and circular copper wire.
  - Typically a **40% fill factor**
  - Designing for **aerospace** applications
  - Cost **£25,000** for a single prototype motor
  - Use a physical prototyping approach
  - Aiming for a **MTBF of 30,000-100,000 hours**

Brainstorming

- Solution creation
- No ideas are judged
- Preparation, generation, consolidation, evaluation and exploitation phases.
- Generated ideas such as:
  - Coil compression
  - Band shaped construction
  - Novel stator construction
  - Hand and machine winding

1. Slot shape & Stator construction

- Open
  - **Easy to wind** and often used in large machines
  - Often used where ease of winding is more important than weight and volume.
- Semi-closed/Semi-open
  - Reduced air gap between teeth
  - **Harder to wind** due to smaller gap
  - Can be constructed through the band method
  - Is being currently used
- Edge
  - Very easy to wind
  - Not very often used

2. Type of wire

- Circular
  - Can be compressed
  - Lowest fill factor
- Profiled (Rectangular/Hexagonal)
  - Requires specialist machinery to wind
  - Poor reaction to skin effects
- Litzs
  - Made up of smaller gauges of wire to build up a larger shaped wire
  - Low skin effects due to individual conductor
  - Can be twisted to reduce proximity effects however reduces fill factor
- Coil casting
  - Novel solution, Useful for high current applications

3. Hand or Machine winding

- **Hand**
  - Better for single jobs and prototyping
  - Can easily cope with changes in wire profile
  - May be changes between each winding due to human input
- **Machine**
  - Is much faster after machines have been setup
  - Cheaper for a large run of coils
  - Very little variance between coils
  - Not many machines compatible with different profiles of wire

4. Wire Insulation

- **Enamel**
  - Applied as a very thin layer to the outside of the wire
  - Can be easily used on different profiles
  - Available in multiple layers and can have different temperature ratings
- **PVC/Rubber/Silicone**
  - Large compared to the size of the wire
  - Difficult to use at very small sizes
- **Aluminum oxide**
  - Untested research based idea
  - Very thin
  - Requires use of Al wires which have a higher resistance

Proposed design

Semi-closed slot

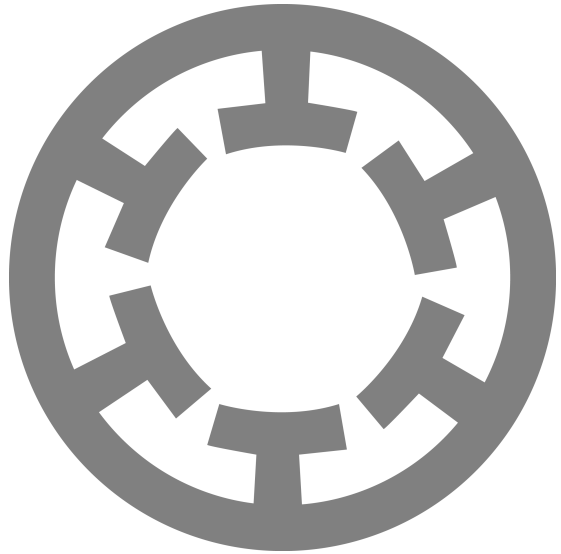
Jigsaw method with ”band” construction for stator

Compressed hexagonal Litzs wire made from circular wire

Enamel varnished

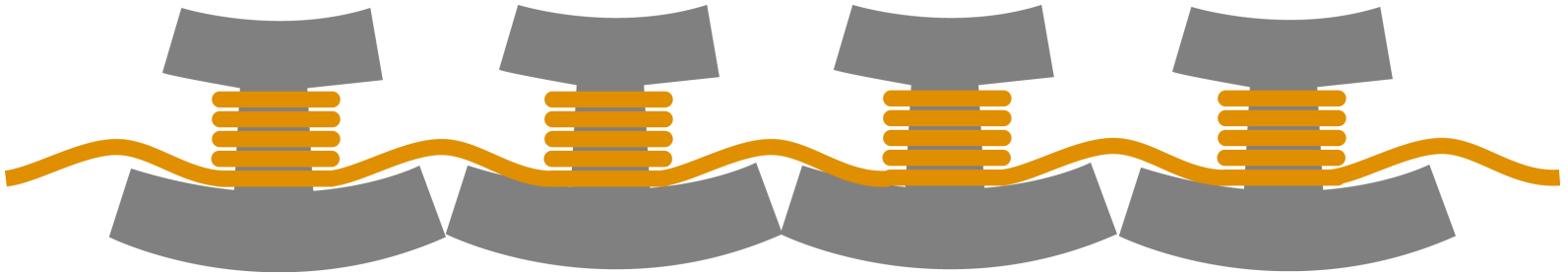
Why we chose a semi-closed slot

- Currently used in motor-generators
- Tested solution with many years in service
- Allows winding through the gaps
- Larger flux density before saturation than an open slot



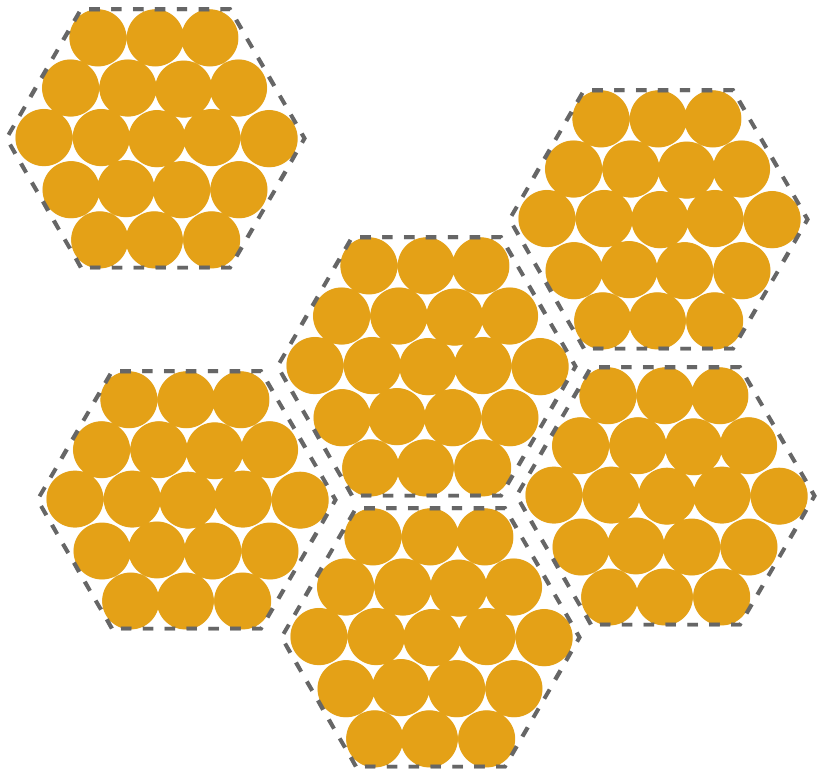
Why we chose a band construction

- Minimises the number of **terminations and connections** within the motor
  - Terminations having greater losses to skin effects and contact resistance
  - Increase the current density without increasing heat density
- **Ease of winding**
  - There is a large amount of space to get tools in or to allow machines to operate
- Minimises the length of **end winding**
  - Not ideal, still longer than winding directly onto circular stator



Why we chose a hexagonal litzs wire

- Litzs wire reduces skin effects due to being made up of individually insulated wires
- **Compression reduces airgaps** between the circular wires and if this is performed before winding there is no risk of damaging the stator
- Hexagonal shape is **self locating** and if produced in the ideal shape are no air gaps
- Would require **new machinery** to be able to control the rotation of the wire when winding



Why we chose enamel insulation

- Thinnest viable solution
- Very good temperature ratings (up to 250°C) so suitable for use within engine cowling or core
- Can have self bonding characteristics if desired allowing for greater mechanical stability within the coils
- Lubricant can be applied during coil winding to allow it to pass through the machine easily

Conclusion

- Overall, our solution uses a mixture of novel and tested design content
- Tested idea allow it to be quickly implemented
- Novel technology requires months/years of testing
- For further work:
  - Calculate the fill factor our proposed design
  - Effects of compression on insulation
  - Proximity effects
  - Physically prototype solution

Thank you for watching

A SHIPS PROJECT ASSIGNED BY ROLLS-ROYCE

PROF. FRANGI'S TUTOR GROUP