Design and analysis of miniature free piston Stirling engine (FPSE) for on-board power production

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Abstract. Free piston Stirling engine integrated with linear alternator has high efficiency, quiet operation, long durability and long life. It is flexible to use any kind of potential heat sources such as chemical energy power sources and solar power. Size, mass and less total heat exchanger area than other power converters makes the FPSE attractive to space power requirements, as soldier borne power sources and cogeneration applications. The step by step design of 100 W power generating FPSE with helium as working fluid is done in the Sage software. To get an output power of 100W, the parental and child components were suitably arranged in the modeling section and then numerically solved in the software (Sage) with various input parameters and the decision variables were optimized to get the desired objective function. The engine uses heater head of 750K at 20 bar mean charge pressure, frequency of 50 Hz and getting overall efficiency of 32%. The design consists of a displacer and a power piston supported on flexure bearings. Non – contacting clearance seals are used between internal volumes. A linear alternator is designed, which converts the piston motion into electricity. Analysis to find the behavior of alternator using FEA is also done.

1 Introduction
Stirling engine have the same processes as any of the other heat engine, which are heating, expansion, compression and cooling. Helium gas, used as the working fluid will have cyclic compress and expands at different chambers and at different temperatures, as a result power is produced. Free piston Stirling engine (FPSE) is a variety of the Stirling engine in which there is no mechanical linkage between the displacer and power piston, which are resonating at same frequency and may at different stroke. To achieve the long life of the system, the piston and the cylinder surface contact should be reduced. A flexure bearing is used which will support of the moving components and oscillate, as there is no surface contact between piston and the cylinder surface friction inside is reduced. Flexure bearing are flat metallic discs having slots inside and have very high radial stiffness to axial stiffness ratio.

This paper includes the design of the free piston Stirling engine converter. To design, the model is subdivided into mechanical, thermal and electrical subsystems and designs these subsystems [1].

2 Design of FPSE
The engine part of the system is designed in Sage software. Based on the requirements, the basic model is designed in the Sage software. The model of the system in the software is shown in the fig 1. Values are provided to the user defined input parameters for each components and the model is solved to get
the results and behavior of the system are studied using mapping option in sage. Optimization of the design consists of three components, objective function, decision variables, and constraint. Objective function is the function that needs to be optimized. Efficiency is the only one objective function of the system and it is set as to maximize. The solution to the optimization problem is the set of values of the decision variables for which the objective function reaches its optimal value. Constraint is that restrict the values of the decision variables. The power output is the only constraint of the system and it is set as 100 W.

3 Design of linear alternator
A permanent magnet moving linear alternator is designed in the software. The components of the linear alternator are inner iron, moving permanent magnet, outer iron and coil. All fluxes generated by permanent magnets are expected to flow crossing the coils. The stator holds the cylindrically wound armature coil. The coil is compact since there is almost no space between wires. A low reluctance magnetic circuit material is required for the outer iron. Basic model made in the software is shown in the figure 2. User defined variables for each component is specified and the model is optimized.

The material chosen for the design are, for permanent magnet neodymium magnet and for the winding copper and for the inner and outer core silicon steel. Force analysis and magnetic field variation of the linear alternator is done in two dimensional and three dimensional FEA software and the results where compared.

4 Design of flexure bearing
Flexure bearing gives the frictionless non-wearing support for the reciprocating components of the Stirling engine. The flexure is allowed to deform by the applied load on the centre of it. Design includes and power piston flexure bearings. Finite element method is the tool to analyze the axial stiffness of the flexure. The basic specifications of the flexure bearings are given in the table 1.

| Parameters                  | Displacer piston |
|-----------------------------|------------------|
| Stiffness                   | 5630 N/m         |
| Outer Radius                | 21 mm            |
| Shaft connecting hole radius| 1 mm             |
| Fixing hole radius          | 1.5 mm           |
| Fixing holes pitch radius   | 18 mm            |
| Number of fixing holes      | 6                |

Archemedian equation is used to make the spiral slot profile of the flexure bearings. Different flexure designs with varying thickness and varying spiral angle are analyzed using FEM.

5 Results and discussion

5.1 Free piston Stirling engine

The optimized results are taken from the software, the specifications of the designed engine is given in the table 2. The optimized displacer amplitude is nearly the half of the amplitude of the piston that was fixed. The bore diameter of the displacer and piston is optimized to the same value. Length of the displacer is the sum of the heater and regenerator length.

| Parameter               | Value       | Parameter               | Value       |
|-------------------------|-------------|-------------------------|-------------|
| Working gas             | Helium      | Rejecter length         | 20 mm       |
| Charge pressure         | 20 bar      | Regenerator length      | 30 mm       |
| Frequency               | 50 Hz       | Regenerator porosity    | 0.9         |
| Heat input              | 308.5 W     | Regenerator matrix ID   | 32.01 mm    |
| Net power output        | 100 W       | Heater length           | 10 mm       |
| Efficiency              | 32.06 %     | Displacer length        | 50 mm       |
| Pressure wall ID        | 42.18 mm    | Displacer OD            | 29.8 mm     |
| Piston OD               | 30 mm       | Displacer amplitude     | 3.7 mm      |
| Piston length           | 30 mm       | Displacer drive rod diameter | 3.2 mm |
| Piston Amplitude        | 6 mm        | Displacer spring stiffness | 5.63 kN/m |
| Compression space length | 20 mm   | Expansion space         | 5 mm        |

5.2 Linear alternator

Linear alternator with the same frequency as that of engine is designed. The designed optimal values of the alternator are given in the table 3.

| Parameter               | Value       | Parameter               | Value       |
|-------------------------|-------------|-------------------------|-------------|
| Frequency               | 50 Hz       | Number turns in coil    | 650         |
| Working gas             | Ideal He    | Wire conductor material | Copper      |
| Alternator efficiency   | 93 %        | Wire diameter           | 1 mm        |
| Pole length             | 20 mm       | Power/FR loss           | 2 W         |
| Inner iron radius       | 31.75 mm    | Eddy current loss       | 0.1 W       |
| Magnetic gap            | 2.75 mm     | Hysteresis loss         | 0.1 W       |
| Outer iron radius       | 34.5 mm     | Poles separation        | 37.4 mm     |
| Coil height             | 29.7 mm     | Container length (Length) | 17.6 mm   |
| Inner iron thickness    | 3.95 mm     | Permanent magnet Number spatial cells | 12 |
| Coil outer radius       | 64.2 mm     | Embedded component length | 17.6 mm  |
| Outer iron inner thickness | 7.8 mm | Permanent magnet material | NdFeB 1.4T |
| Outer iron outer thickness | 8.5 mm | Reciprocating mass      | 350 g       |

The losses in the model are low as compared to rotary generator. Overall size of the linear alternator comes in 145.4 mm diameter and 53 mm height.

5.2.1 Analysis of linear alternator

The analysis of designed linear alternator is done in the Ansys Maxwell 3D software and Ansoft Maxwell 2 D software. The performance evaluation is done by giving excitation in the range of 650 ampere turns to 2350 ampere turns. Table 4 gives the overall force on the permanent magnet cylinder from the 3D analysis with the position.
Table 4. Force on magnet at various positions.

| Position of magnet from rest (mm) | Force |
|----------------------------------|-------|
| X (N) | Y (N) | Z (N) | Overall (N) |
|----------------------------------|-------|
| 0 | 2.55 | 260 | 9 | 260 |
| 1 | -4.8 | 250 | 4.25 | 250 |
| 2 | 1.2 | 235 | -0.4 | 235 |
| 3 | 3.8 | 224 | -4.5 | 224 |
| 4 | -5.6 | 205 | -6 | 205 |
| 5 | 0.4 | 188 | -5 | 188 |
| 6 | -3 | 175 | 1.6 | 175 |

5.3 Flexure bearing

The required stiffness of the power piston flexure bearing is 10,000 N/m. After various analysis and optimization of model, the design ended up with the parameter values given in the table 5. Total deformation of the power piston flexure bearing along axial direction and radial direction and equivalent stress distribution is shown in fig 3. The model gives a deflection in the axial direction of 0.39418 mm for 1N axial load, and then the stiffness is 2536.91 N/m. The required stiffness for the power piston flexure bearing is 10,000 N/m, a stack of four numbers of designed bearings can make the required stiffness. The maximum stress exerted on the flexure bearing is 13.8 MPa on maximum amplitude.

Fig 3. Total deformation in (a) axial direction (b) radial direction and (c) equivalent stress distribution.

Fig 4. Variation of stiffness of flexure bearing with percentage of void.
Table 5. Parameter values of displacer and power piston flexure bearing.

| Sl No. | Parameter                        | Displacer flexure | Power piston flexure |
|--------|----------------------------------|-------------------|----------------------|
| 1      | Thickness of spring              | 0.6 mm            | 1 mm                 |
| 2      | Spiral slot width                | 1 mm              | 2 mm                 |
| 3      | Spiral slot angle                | 540°              | 540°                 |
| 4      | Number of arms/spiral slot       | 3                 | 3                    |
| 5      | Spiral slot shape factor         | 0.03              | 0.03                 |
| 6      | Spiral slot starting radius      | 3 mm              | 5 mm                 |
| 7      | Spiral slot ending radius        | 16 mm             | 47 mm                |
| 8      | Axial Stiffness                  | 2772.15 N/m       | 2536.91 N/m          |

Variation of stiffness with the percentage of void volume in the flexure bearing is analyzed. Void volume is the sum of the volume of the slot void and inner rim volume. Percentage of void volume is the ratio of the total void volume to the volume of the flexure bearing. The total volume is the volume of flexure bearing assumed to be a solid disc with the outer diameter at the outer end point of slot. The variation of the designed flexure bearings with the percentage of void is shown in the fig 4.

6. Conclusion

The design of miniature 100 W generating free piston Stirling engine is designed. The design is based on the ideal conditions and it has an overall efficiency of 32.06%. The designed linear alternator has an efficiency of 93% and dimension is 72.7 mm × 53 mm. For the same excitation the alternator 2D software results shows the variation of 20 to 30% from the 3D software analysis results. For the power piston flexure bearing, stiffness of 3307 N/m with thickness of 1 mm designed, using stack of four flexure bearings the target stiffness can be reached.

References

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