

ELECTROMAGNETIC GENERATOR DESIGN FOR MEMBRANE MICRO STIRLING ENGINE

Fabien Formosa*, Adrien Badel, Emmanuelle Aroyo

SYMME - Université de Savoie BP 80439- 74944 ANNECY LE VIEUX CEDEX – FRANCE

*Presenting Author: fabien.formosa@univ-savoie.fr

Abstract: From previous analysis, a membrane microStirling engine has been proposed. The preliminary designs lead to a millimetre size engine which piston strokes is 0.4 mm at 680Hz. Electromagnetic conversion is seen here as the most appropriate concept for integration as well as efficiency. Optimization goals differ from those of usual electromagnetic energy harvesters. Indeed, the leading requirement is that the electromechanical induced effect must match the load required for suitable dynamic stability. Numerical modelling and optimization strategy are used. As a result an integrated design is proposed.

Keywords: microStirling, electromagnetic, design, optimization

INTRODUCTION

A membrane microStirling engine has been developed through looking for a mean to fulfil the need for micro energy generation devices [1]. The external heat source, closed cycle features and the use of membranes instead of sliding pistons are some advantages regarding the micro engine miniaturization issues. Preliminary designs of this type of engine have been performed on a test case for which the heat source and sink temperatures are 400°C and 25°C respectively. A displacement of 100 mm³ would allow an electric output power of about 1.5 to 3 W_e assuming 50% electrical conversion efficiency. This case can be representative of automotive waste heat recovery applications. Moreover, the moderate high temperature allows using a wide range of material for realization.

Therefore, as a design guideline, the main requirement is that the electromechanical induced effect must match the dynamic load $F_{Lp} = c_{Lp} \dot{x}_p$ which leads to a suitable motion x_p of the compression diaphragm and the expansion diaphragm subsequently.

Electromagnetic conversion is chosen here as a favourable transduction principle. Indeed, electrostatic forces require high voltage and tiny accurate gaps. Piezoelectric materials have to be integrated within the compression diaphragm which increases design requirements and induces complex process.

Lorentz force can be obtained from magnetic flux variations in a closed loop of wire. Various architectures can be proposed but actuators like architectures provide high force to volume ratio. However, in such applications, efficiency is often of poor values. In this work, the transducer geometry will be optimized to seek a trade-off between high force to volume ratio and high efficiency. At the same time, the output power criteria will be evaluated to offer easier comparisons with related works.

Loudspeaker based architecture presented in Fig. 2 was proven to deliver the maximal power output compared to equal volume other configurations [3, 4]. We chose to use the definition number from the work of Spremann [4]. Therefore, these first two geometries are denoted VI and VII and are chosen as a favoured basis for the membrane Stirling engine generator design. We propose here another architecture denoted VIII in Fig. 2.

In a first part, a finite element model and the associated analytical post treatment are detailed. An optimization strategy is then presented and used to compare the different architectures within a similar representative size constraint. Neodymium magnet is used whereas non linear behaviour of the back iron material is taken into account in the computer model. As already mentioned damping effect derived from the calculated magnetic flux is chosen as the optimization criteria for the dimensions of the magnet, back iron and coil.

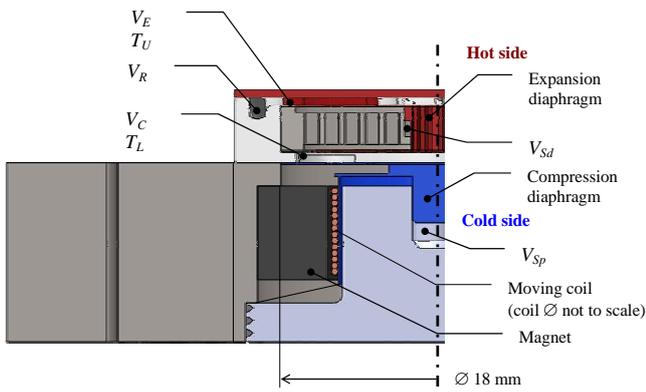


Fig. 1: MicroStirling architecture.

The flexural compression diaphragm motion which is a characteristic of the developed engine (see Fig. 1) leads to natural similarity with inertial energy harvester issue. The operation of the engine stems on dynamic characteristics of the diaphragms and related chambers (V_{sp} , V_{sd}) which act as gas springs. It turns out that a Hopf bifurcation has to be reached [1, 2]. As a consequence, the damping effect associated to the electromechanical transduction at the compression diaphragm must be tuned.

In a second part, the dimensions of the retained architecture are optimized. Two Stirling configurations depending on the used working fluid (*i.e.* air and helium) are considered. The geometric parameters of coil, magnet and back iron to reach the force criteria for a minimized volume and given efficiency are sought.

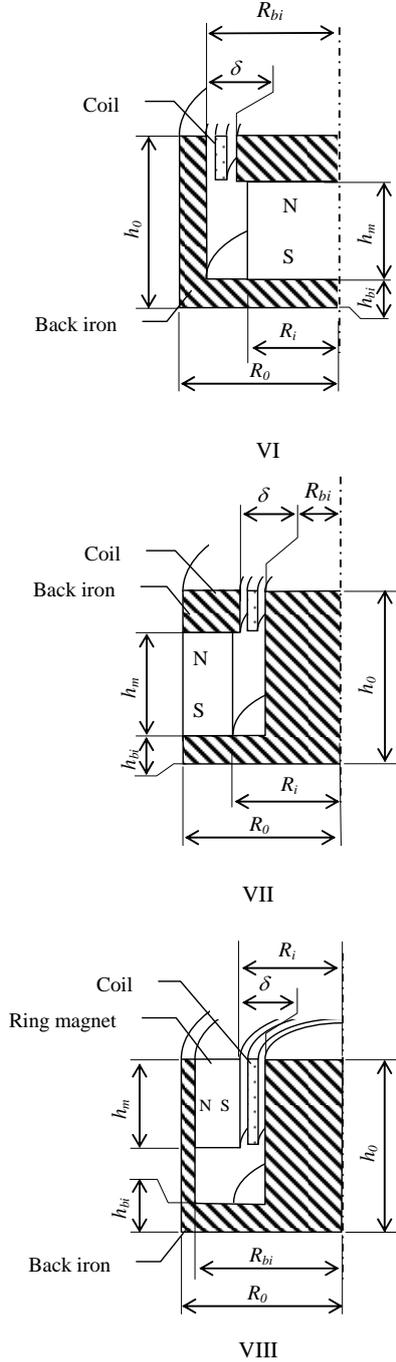


Fig. 2: Schematic of the three considered architectures.

ARCHITECTURE COMPARISON AND OPTIMIZATION

Model description

For a given architecture, the magnetic flux is evaluated using a finite element model (FEM) of the structure.

Because of the optimization purpose of the model non linear effects needs to be taken into account. Numerical evaluation allows taking into account any magnetic saturation within the back iron.

From the numerical results, the magnetic field within the air gap shows a linear variation along the longitudinal axis. As an example, the magnetic flux evaluated from the FEM is presented in Fig. 3 for architecture VI. The coil is supposed to be immersed in the air gap. Consequently, the expression of the electromagnetic force can be easily expressed as:

$$F_{elec} = \beta i \quad (1)$$

In which, $\beta = N \Phi_{aa} / h_c$, Φ_{aa} is the maximal magnetic flux within the air gap, N the number of turns of the coil and h_c its length. The electric intensity is denoted i .

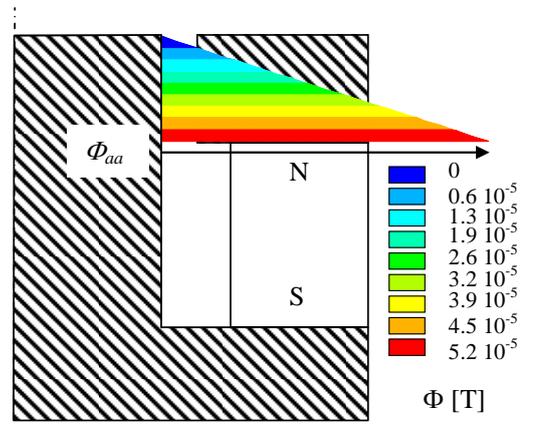


Fig. 3: Magnetic flux for architecture VI.

The windings and internal resistance of the coil can be approximated using Eq. 2 and 3 in which d_c and D_c are the wire diameter and the mean coil diameter respectively. α_c is the fill factor and ρ_c the electrical resistivity.

$$N = \frac{\delta h_c}{\alpha_c \pi d_c^2 / 4} \quad (2)$$

$$R_c = \rho_c N \frac{D_c}{d_c^2 / 4} \quad (3)$$

For a given electric load R_L and omitting the effect of the inductance, it is possible to express the value of the electric current as a function of the velocity of the moving part \dot{x} and the conversion efficiency η_e defined as $\eta_e = R_L / (R_L + R_c)$:

$$i = \beta \dot{x} (1 - \eta_e) \frac{1}{R_c} \quad (4)$$

Thus, the damping effect pertaining to the electromechanical conversion can be defined as $F_{elec} = c_{elec} \dot{x}$. It turns out that the damping coefficient c_{elec} is only related to geometrical parameters for a given efficiency η_e :

$$c_{elec} = \beta^2 (1 - \eta_e) \frac{1}{R_{coil}} \quad (5)$$

Optimization procedure

The aim of the optimization procedure is to find the geometry which permits the required damping coefficient to be reached for the higher efficiency and the smallest volume. The chosen geometric variables are the magnet radius and length (R_m , h_m) (see Fig. 2) and the back iron internal radius and thickness (R_{bi} , h_{bi}). In a first step, the efficiency is set at a value of 50%. A random method is used to sweep the variable space. In the vicinity of the best point a gradient method is then performed. The objective function is chosen as $1/c_{elec}^2$.

The optimization strategy is illustrated in Fig. 4. For the architecture VI, each dot stands for a simulation result. Blue dots of Fig. 4 are sets of values (R_m , h_m , h_{bi}) and purple dots are sets (R_{bi} , h_m , h_{bi}). The big dots are the geometric parameters values for which the objective function is the smallest.

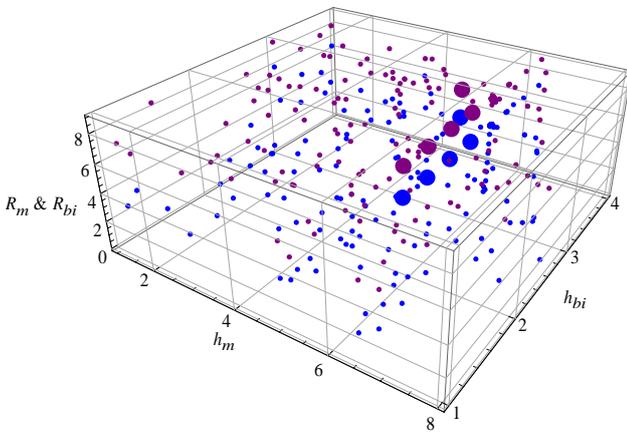


Fig. 4: Optimization results for architecture VI.

The procedure has been performed for the three architectures. From the preliminary Stirling generator design, the available cylindrical volume is of 20 mm diameter and 10 mm height. The electrical efficiency is set at the same value for each architecture.

The obtained optimal geometries are presented in Fig. 5. It can be seen that the highest damping coefficient is obtained for the architecture VIII which is finally retained for the engine generator.

Test cases design

A new optimization is achieved for the retained architecture VIII. It consists in reaching the highest electrical efficiency value whereas the required damping coefficient is matched as well. The design is achieved for two test cases: (i) air, (ii) helium based membrane microStirling. The operation characteristics of the engine are given in Table 1.

Table 1: Test cases dynamic characteristics.

Case	Frequency [Hz]	Comp. diaphragm stroke [mm]
(i) air	290	0.8
(ii) Helium	665	0.9

For size constraints consideration, the external diameter of the iron is limited to 20mm. Unlike the previous studies, the global height of the convertor is added as a new optimization parameter.

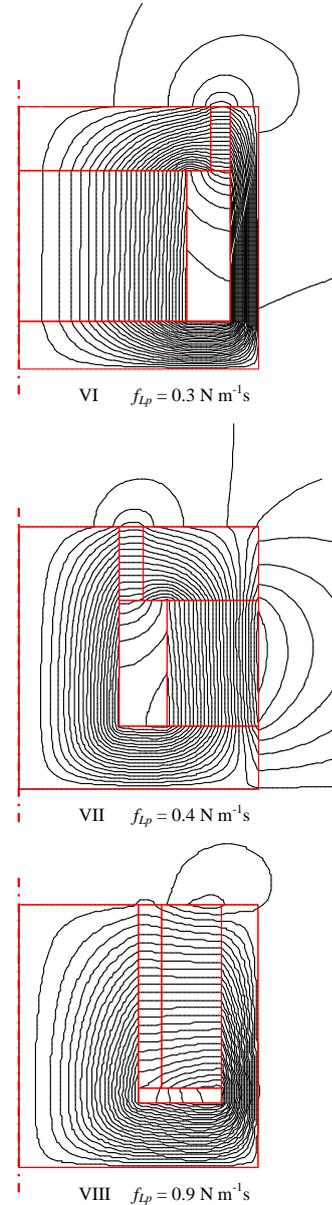
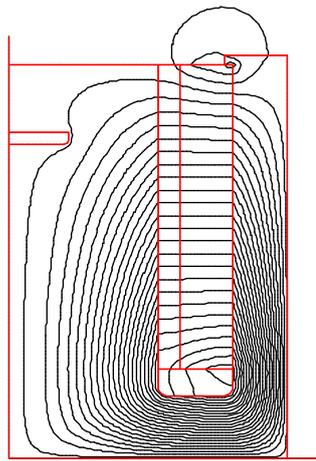


Fig. 5: Architectures comparison at optimal geometry.

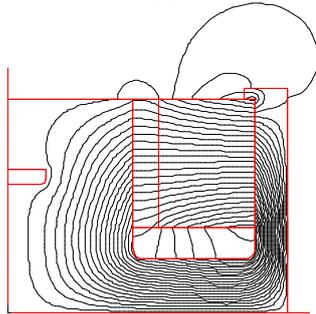
Geometric details are added. A diaphragm guiding (see Fig. 1) brings some discontinuity within the back iron material. The additional air gap (V_{sp}) promotes magnetic saturation. At the contrary, fillets allow the magnetic field to be smoother. The optimal geometry parameters are given in Table 2 and shown in Fig. 6.

Table 2: Test cases convertor geometry characteristics.

Case	(i) Air	(ii) Helium
Global volume [cm ³]	16	5.3
Radius R_{bi} [mm]	15.5	13
Global Height [mm]	22	10
Power [We]	0.63	1.49
Electric efficiency [%]	51	62
Voltage [V]	3.4	3.66



(i) Air



(ii) He

Fig. 6: Architectures comparison at optimal geometry.

Strong damping effect is required when air is to be used and a large height of the convertor is then required. In spite of the large volume of the convertor, its size can be used to enhance heat exchange at the cold side of the engine. By doing this, better thermodynamic efficiency can be reached. As the temperature of the compression cold chamber (V_c) would be modified by the enhanced heat exchange, the dynamic characteristics could be changed consequently. The convertor design would be finally checked and might be modified eventually.

Because of the different dynamic conditions associated with the use of Helium as a working gas, low damping coefficient is required in case (ii). The convertor volume is three times smaller than for case (i). It must be noted that the size could be reduced with lower efficiency. However, the retained values integrate the heat exchange purpose at the cold side. Figure 1 illustrates the microStirling generator in case (ii).

CONCLUSION

Three electromagnetic convertor architectures for a membrane microStirling have been proposed and studied. Using FEM and optimization strategy, we have shown that one configuration is best suited to match the specific requirements related to the engine dynamic. Thus, strong damping effect can be obtained whereas the efficiency remains at acceptable value. Then, the selected geometry is optimized taking into

account additional details for two test cases. A complete microStirling generator is obtained eventually.

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