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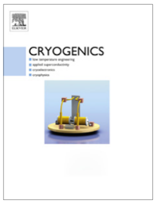

Research paper

Design, development and testing twin pulse tube cryocooler

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ABSTRACT

The design and development of Twin Pulse Tube Cryocooler (TPTC) is presented. Both the coolers are driven by a single Linear Moving Magnet Synchronous Motor (LMMSM) with piston heads at both ends of the mover shaft. Magnetostatic analysis for flux line distribution was carried-out during design and development of LMMSM based pressure wave generator. Based on the performance of PWG, design of TPTC was carried out using Sage and Computational Fluid Dynamics (CFD) analysis. Detailed design, fabrication and testing of LMMSM, TPTC and their integration tests are presented in this paper.

1. Introduction

With the advancements in IR based remote sensing technology in space, such as earth observations systems and weather monitoring, the sensor systems are also getting evolved to provide more resolution and sensitivity [1]. To enhance their detection sensitivity and to increase the signal to noise ratio, it is essential to cool them to cryogenic temperatures [2]. The cooling requirement depends on the specific applications and ranges from several milli-Watts to 2–3 W [1]. Different types of cryocoolers are developed to meet these requirements. This includes single stage cryocoolers such as coaxial pulse tube refrigerators designed by SITP & CAS which achieved 173 K [3], 40 K single stage coaxial pulse tube cryocoolers to cool long wavelength infrared arrays [4] and 10 W/90 K single-stage pulse tube cryocoolers developed for space borne optics cooling [5].

Multi stage cryocoolers are also developed for achieving very low temperatures. Two stage pulse tube refrigerator system designed for 1.3 W @ 20 K [6], three-stage Stirling pulse tube cryocooler which reached 4.26 K with He-4 as working fluid [7] are some of the examples. Studies on a thermally coupled Stirling type two stage pulse tube cryocooler using 1-D CFD code [8] and thermally coupled three stage pulse tube cryocooler with U type configuration [9] are also reported. A comparitive study on the performance of pulse tubes with different pressure wave generators and two twin pulse tube operation in tandem mode is discussed in [10,11]. Thus, extensive research is going on to realize efficient, reliable, long life, lightweight & low vibration cooling systems qualified for space applications.

Efficient and consistent performance of the linear compressor associated with PTR is very important in achieving the required temperature and cooling load [12]. Various studies and experiments were conducted to improve the design and performance of the Pressure Wave Generator (PWG). Thermally actuated pressure wave generator for space cryocooler [13], Pulse tube Stirling machine with warm gas-driven displacer [14], analysis of PTR considering the dynamic behavior of PWG [12] are some of them. The design process involved to predict and reduce the losses associated with the permanent magnet linear motor compressor using various computational methods are described in the literature [12–16]. FEM analysis, used to determine the generated force required for specific ampere turns and flux density for different materials and geometries are also explained in detail [17–22].

Discussion of the design of a LMMSM based dual piston head PWG for driving a Twin Pulse Tube Cryocooler (TPTC) for net cooling of 1 W at 85 K is presented here. The compressor design involves magnetostatic analysis and force calculations for various configurations using FEM analysis followed by the experimental measurement of force and no load resonance frequency. The twin pulse tube cryocooler design is based on the compressor output using SAGE & Computational Fluid Dynamics (CFD). Finally, the integration and cool down test of TPTC at no load are presented.

2. Design of Pressure Wave Generator (PWG)

A dual piston head PWG was developed using LMMSM to drive TPTC. The design of LMMSM consists of four important

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components as shown in Fig. 1. They are, field winding (in this case; segmented arc permanent magnet rings), armature winding (enameled copper coil), stator (outer yoke, side limbs, bottom limb, and coil support) and mover (inner yoke, magnet rings, magnets, piston rod, piston heads and end caps). The complete mover assembly contributes to the moving mass of the system which weighs 600 g. These components consist of different materials. The outer yoke, inner yoke, and outer and inner magnet rings are made of mild steel. Coil support and piston rod are made of stainless steel. Coil consists of 16 SWG enameled copper wire with 270 turns. Mover is supported by spring steel C-type flexures of 8 mm bending radii. Design and fabrication details of C-type flexures were discussed elsewhere [23,24]. Aluminum piston heads were covered with rulon sleeve to enable close clearance between the piston and cylinder to reduce blow-by losses. Nd-Fe-B magnets are coated with silicon conformal coating. Detailed development of magnet rings and mover assembly using flux diversion technique was discussed elsewhere [25]. The measured average flux density of each magnet ring was 420 mT [26].

The mover of LMMSM consists of four magnet rings. The four magnet rings were positioned on inner yoke in different combinations leading to three different configurations as shown in Fig. 2. In each configuration, four magnet rings are arranged in NSSN pattern (The N and S represent the north and south magnets at the outer radius magnet rings). The difference being the spacing between the magnet rings (see Fig. 3).

Configuration-1 is NS– – – –SN where each – represents 5 mm spacer. Thus, between north and south magnets, there is no gap whereas there is 20 mm gap between south and south magnets. Similarly, configuration-2 is N–S– –S–N, which means that there are 5 mm gap between north and south magnets and 10 mm gap between south and south magnets. The configuration-3 is N– –SS– –N which means that 10 mm gap between north and south magnets and no gap between south and south magnets. The assembly for configuration-3 is very difficult in comparison to other two configurations. The assembly was done using the concept called flux diversion [25]. The magnet ring width is 15 mm.

The magnetostatic analysis was carried out for each of the configuration for 2700 A turns with inner yoke and magnets at neutral positions. The flux distributions for the configuration-1,2 & 3 are shown in Figs. 4–6 respectively.

Figs. 4 and 5 show the magnetic flux lines are densely concentrated in the air gap between magnet and coil for configuration-1 & 2. This concentrated lines indicate magnetic locking of mover with stator known as cogging. Cogging reduces the net generated force for the same input power. Moreover, it also effects the smooth motion of the motor. In Fig. 6, flux lines are less concentrated, thus causing reduced magnetic locking and higher reluctance path which increases the net electromagnetic force as Eq. (1) [27] where, $P_{em} =$ *Electromagnetic power*.

$V =$ *Applied Voltage*,
$E_f =$ *Field EMF*,
$delta =$ *Load angle between* V *and* E_f,
$X_D =$ *Direct axis reactance*,
$X_Q =$ *Quadrature axis reactance*.

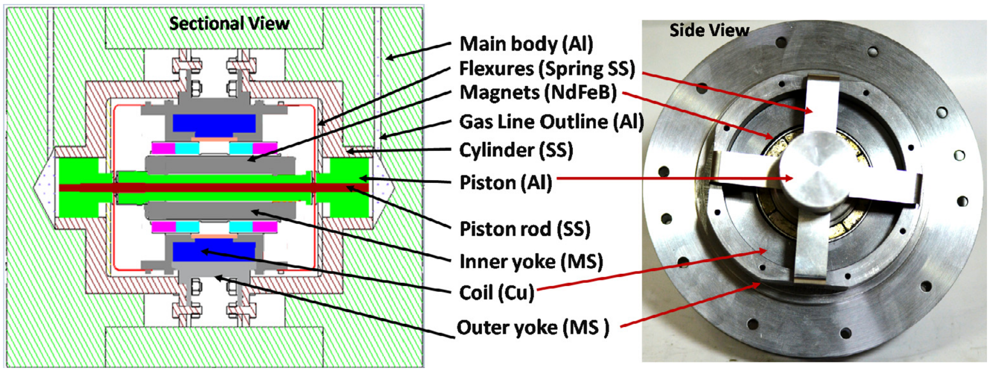

Fig. 1. Schematic of linear motor compressor components; magnets, coil, outer yoke, inner yoke, piston rod, piston heads, flexures and end cups.

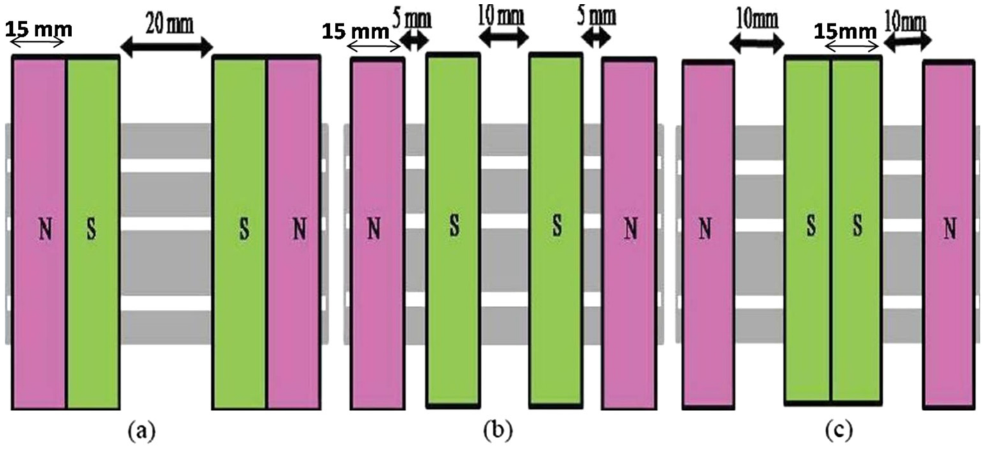

Fig. 2. Schematics of magnet assembly configurations (a) configuration-1 (NS– – – –SN), (b) configuration-2 (N–S– –S–N), (c) configuration-3 (N– –SS– –N).