High Efficient, Dual Poled Linear Motor (DPLM) for Cryocoolers

What is the proposed concept?

NASA seeks improvements to multistage low-temperature spaceflight cryocoolers [1]. Specifically desirable are system- or component-level improvements that improve efficiency while also reducing both complexity and cost. Therefore, the thesis of this Phase I is to study a new type of linear motor for use in cryocooling compressors toward the enhancement of cryocooler efficiency as well as reducing complexity and cost to advance NASA's ground base and in-space research missions requiring cryocoolers.

The compressor is critical to the enhancement of cryocooler efficiency, and a key component to the linear compressor is the linear motor. Research of literature and patents have deemed the moving coil linear motor to be the best choice, so not much change to the moving coil linear motor has occurred in many decades. The PI has been developing a new type of linear motor, called the Dual Poled Linear Motor (DPLM) [2], which has shown promise toward having increased efficiency, being less complex, and lower cost than state-of-art linear motors.

The DPLM design is more similar in look to a solenoid than that of state-of art moving coil linear motors, which allows for increased magnetic field strengths in a smaller package. The key innovation of the DPLM over state-of-art moving coil linear motors is its dual poled permanent magnet and use of multiple parallel coils to reduce resistance, combined with a high current pulsing (~2ms to ~4 ms) controller to produce an sinusoidal force on the moving coil at cryocooler compressor frequencies ($\sim 60Hz$ to $\sim 70Hz$).

The DPLM is based on the Dual Position Linear Solenoid (DPLS) technology [3-6] and is basically a single moving coil DPLS [2] composed of a moving coil section, a fixed permanent magnet section, flexure springs, pusher, and a controller that is a small variation of the DPLS controller [4]. The moving coil section is composed of a magnetic core encasing the coil. The fixed Permanent Magnet Section is composed of an outer and inner magnetic core about a toroidal and radially poled, permanent magnet. A pusher is attached to flexure springs and the moving coil section, extending through, and allowed to freely move through the fixed permanent magnet section; whereas in a cryocooler compressor would be attached to a piston that transfers the impulse power to high pressure helium gas, that is transposed through the cryocooler head by the piston movement.

What makes it exciting?

The DPLM is basically a higher oscillated DPLS and an $203\ mm\ (\sim 8\ inch)$ diameter DLPS for pumping fluids to 2000 psi, that demonstrated $>13kN\ (3000\ lbf)$ due to the permanent magnets at ~1 mm (0.004 inch) separation, under no power, was built and demonstrated by the inventor [2]. However, as the DPLM is a new and unreported technology (except in patents), to demonstrate the DPLM's feasibility toward use as a high oscillating linear motor, an ~63.5 mm (2.5 inch) diameter DPLM with an ~22.9 mm (0.9 inch) thick moving coil section and ~15.2 mm (0.6 in) thick permanent magnet section was built and tested. The magnetic core material used was low carbon steel. The permanent magnet was composed of N42 Neodymium permanent magnets assembled in a radial fashion about the central dual poled magnetic core. At ~1 mm (0.004 inch) separation and under no power, the magnetic attraction force between the moving coil section and the permanent magnet section was ~110 lbs. With an input voltage $V \sim 25\ V$ to the controller and within an optimum frequency range $f \sim 66\ Hz - 74\ Hz$, the movement distance was ~ 4 mm and the force swing was ~ 100 lbs. It is noted that this DPLM continued to operate down to ~15V with reduced movement distance.

The tests showed that the DPLM could produce sinusoidal movement of the moving coil section at the magnetic force of the permanent magnet, and that the controller could produce impulse power $(V \cdot I_{coil} \cdot f \cdot dt)$ to the coil ~3 times higher than the impulse power $(V \cdot I_{PS} \cdot f \cdot dt)$ supplied by the power supply (PS) during the impulse $dt \sim 2\ ms$; i.e., the coil current I_{cap} from the capacitor in the controller was approximately two times higher than the power supply current I_{PS}, during the impulse $dt \sim 2\ ms$, where during the impulse $dt \sim 2\ ms$, the coil current $I_{coil} \approx I_{PS} + I_{cap} \approx 3I_{PS}$.

Given that a DPLM can be driven in a sinusoidal fashion, as with state-of-art moving coil linear motors, they can be analyzed for use in cryocooler compressors in similar manner, with the exception that the method of the driving force $F_{LM}\,(\neq L_w IB)$ is different. I.E., the coil parameters length L_w and current I no longer apply as the driving force F_{LM}, as it is now (mostly) a function of the magnetic attraction force; whereby F_{LM} is proportional to the magnetic field (B), from the permanent magnets, squared times the pole area (A). Effectively, the magnetic field from the coil adds only enough magnetic force to cause initial movement of the moving coil section, with the back EMF preventing magnetic latching between the moving coil and permanent magnetic section.

Further, increasing the force of a DPLM entails increasing the permanent magnet size, which increases the coil size and the capacitor capacitance, without changing the input voltage. Therefore, a DPLM is mechanically scalable at the same voltage.

Is the concept unexplored?

The concept of using a DPLM as a linear motor in cryocooler compressors is Ground Breaking, as it has not been considered for cryocoolers previously.

Why is the concept credible and technically sound?

As previously discussed, a prototype DLPM has been built and tested to forces and frequencies needed in cryocooler compressors. Therefore, this exciting TRL 2 (Active research and development is initiated. Examples include components that are not yet integrated or representative) technology is ready to take the next step toward the development of efficient cryocoolers to advance NASA's ground base and in-space research ambitions.

As the DLPMs composition is very similar to other linear motors use in cryocooler compressors, there are no unforeseen technological issues.

Briefly, what do you plan to accomplish in the Phase I study.

Our initial Phase I effort will have two tasks:

1. Conduct an engineering study that addresses the reduce complexity and cost of a DPLM linear motor compressor in a pulsed tube cryocooler. Higher magnetic permeability and low coercivity materials to reduce the eddy current effects will be discussed.

2. Design and develop a dual DPLM linear motor gas compressor, for use in the engineering study, to demonstrate a dual DPLM linear motor compressor under relevant conditions and to bring the DPLM linear motor compressor to between TRL 3 – Proof-of-Concept Demonstrated, Analytically and/or Experimentally and TRL 4 – Component and/or Breadboard Laboratory Validated. Each DPLM will have double the force attained in the previous DLPM tests to show scalability of the DPLM.

Development of a helium pressurized, dual DPLM linear motor compressor, as used in cryocoolers, will be developed in Phase II and demonstrated on a pulse tube cryocooler head, to bring the technology to between TRL 5 – Component and/or Breadboard Validated in Simulated or Real space Environment and TRL 6 – System Adequacy Validated in Simulated Environment.

References

1. NASA 2022 SBIR. Focus Area 9 Sensors, Detectors, and Instruments, S16.07 Cryogenic Systems for Sensors and Detectors (SBIR), Scope Title: Low-Temperature/High-Efficiency Cryocoolers.

2. Robertson, G. A., Dual Poled Linear Motor (DPLM) as described in US patent application 1767146, Feb. 19, 2022.
3. Robertson, G. A., Divergent Flux Path Magnetic Actuator with Reciprocating and Rotatable Shaft, US Patent 9,136,052, Sep. 15, 2015.
4. Robertson, G. A., Energy Efficient Bi-Stable Permanent Magnet Actuation System, US Patent 9,343,216, May 17, 2016.
5. Robertson, G. A., Power Versatile and Energy Efficient Electric Coaxial Valve, US patent 9,702,477, July 11, 2017.

Robertson, G. A., Dual Acting Solenoid Valve Using Bi-Stable Permanent Magnet Activation for Energy Efficiency and Power Versatility 10,024,453, July 17, 2018.

High Efficient, Dual Poled Linear Motor (DPLM) for Cryocoolers

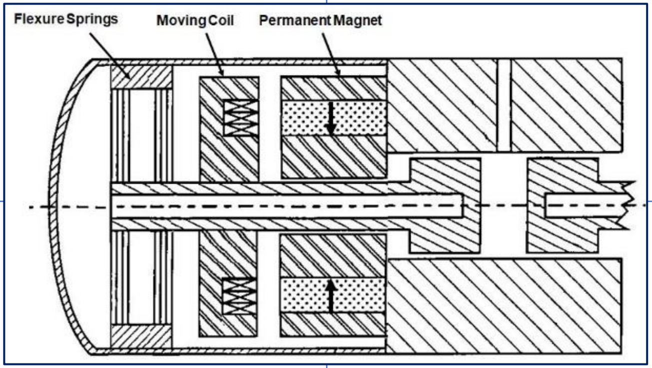
What is it?

DPLM

- A new linear motor for cryocooler compressors
- Consistent with Modern Physics
- <TRL 2, preliminary lab experiments conducted

How can it be used?

The DPLM can replace linear motors in cryocoolers to make them more efficient, less complex, and cost less.



Potential & Benefits

- The DPLM can be operated at cryocooler frequencies and forces at lower power with less complexity and cost.
- Scalable mechanically at same voltage.

Study Approach

1. Conduct an engineering study that addresses the reduce complexity and cost of a DPLM linear motor compressor in a pulsed tube cryocooler.
2. Design and develop a dual DPLM linear motor gas compressor for use in the engineering study and to bring the DPLM linear motor compressor to between TRL 3 and TRL 4.