Affordable Cryocoolers for Commercial IR Imaging

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ABSTRACT

High-end infrared imaging usually requires active cooling infrared detectors down to cryogenic temperatures, thus enabling long working ranges, short integration time, high spatial and temperature resolution. Unfortunately, high ownership costs prevent the wide deployment of cooled infrared technology in the price-sensitive and highly competitive commercial market. Uncooled infrared technology, although inferior in performance, is more affordable and, therefore, more prevalent.

CryoTech Ltd. is an Israeli startup company established in 2018 as a subsidiary of the Gevasol Group with focus on developing and deploying cost-effective, long-life, compact, light-weight, and energy-efficient cryogenic technology for commercial infrared imaging. The authors present the outcomes of the full-scale feasibility study, characterization, and initial optimization of a commercially affordable split Stirling linear cryocooler

INTRODUCTION

High-end infrared (IR) imaging for commercial uses such as security, surveillance, gas leak detection, advanced driver assistance, enhanced flight vision, and clinical thermography may require the use of actively cooled IR detectors enabling long working ranges, short integration time, high spatial and temperature resolution.

Advanced IR imagers usually rely on a cryogenically cooled Focal Plane Array (FPA) that is directly integrated with a cold finger of a mechanical (Stirling, typically) cryogenic cooler, thus forming a so-called Integrated Detector Dewar Cooler Assembly (IDDCA). Actively cooling and maintaining IR FPA at cryogenic temperature is imperative for reducing thermally-induced noise.

Despite the significant advantages of cooled IR detector technology, the market for commercial IR imaging is price-sensitive and competitive, and thus limited. Uncooled IR imagers, albeit inferior, are often used for commercial applications simply because of their lower price.

As long as cryocoolers remain the most expensive and unreliable component of the cryogenically cooled infrared imagers, further advances in this field will not be possible without the development and deployment of long-life, cost-effective, compact, light-weight, and energy-efficient cryogenic solutions.

Long life, low Size, Weight, and Power (SWaP) mechanical split type Stirling linear cryocoolers are typically used in advanced, military-graded IR imagers. They usually comprise an electromagnetically driven linear dual-piston compressor and a pneumatically actuated expander interconnected by a flexible and configurable transfer line, as shown in Figure 1. Such cryocoolers are manufactured in limited quantities and contain mechanical components which are made of exotic materials being machined to micrometer precision levels. These factors contribute significantly to their high prices.

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

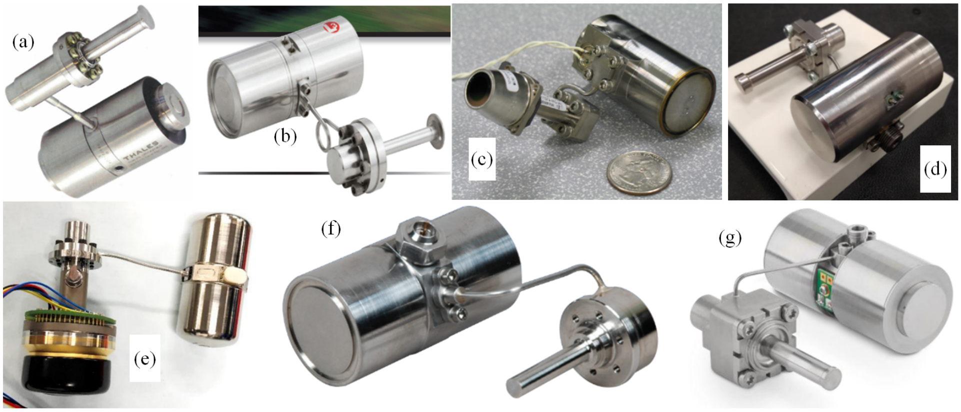


Figure 1. Low SWAP Stirling cryogenic coolers: Thales UP8197 (a), L3 L200 (b), DRS microIDCA (c), Ricor K588 (d), FLIR FL-100 (e), Cobham LC1076 (f), AIM MCC025 (g).

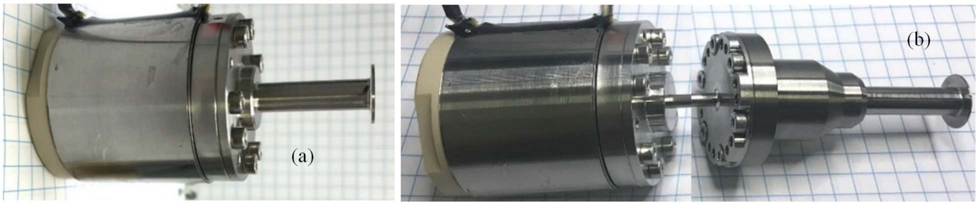


Figure 2. Integral (a) and split (b) prototypes (Ver.1)

Our primary goal is to reduce the cost of the cryogenic cooler to a three-digit figuree in a factory aggregate quantity of 10,000 units annually, without compromising lifespan, power consumption, compactness, weight, vibration/acoustic signature along with ease of assembly and integration [1]. The authors present the brief development history along with outcomes of a full-scale feasibility study, characterization, and initial optimization of the Ver. 3 split prototype.

INTEGRAL INLINE AND SPLIT PROTOTYPES

The initial prototyping began with integral and split topologies sharing a communal, low-cost single-piston linear compressor driven by the "moving magnet" actuator.

Figure 2 shows photographs of the Ver.1 integral (a) and split (b) prototypes. In the patent-pending integral topology, the resonant expander is driven by a mechanically actuated phase shifter, which is hidden inside the compressor housing. In the split topology, the patent-pending expander comprises a resonant pneumatic displacer, which is assisted by a failure-free spring.

The integral topology offers a more compact, lightweight, and power-saving solution. As a result of an inline placement of moving piston and displacer assemblies, such a cryocooler is free of harmful vibrational moments usually resulting in an harmful line of sight jitter. The residual vibration export may be easily controlled by an optional lightweight tuned dynamic counterbalancer [2]. The obvious disadvantage of this topology is the lack of flexibility in IR module packaging and increased size in the axial (optical) dimension.

Unlike integral, the split topology offers more flexibility in packaging the entire IR module. The penalties are higher power consumption, added weight, complex heat sinking, and vibrational moments resulting from usually side-by-side placement of compressor and expander units.

Figure 3 shows the CAD rendering and primary dimensions of the Ver.2 of split (a,b) and integral (c,d) prototypes, respectively. In the split configuration, the compressor weighs circa 200 gr, and the cold head (including Titanium cold finger) weighs 30 gr. In the more compact integral configuration, the total weight was circa 200 gr.

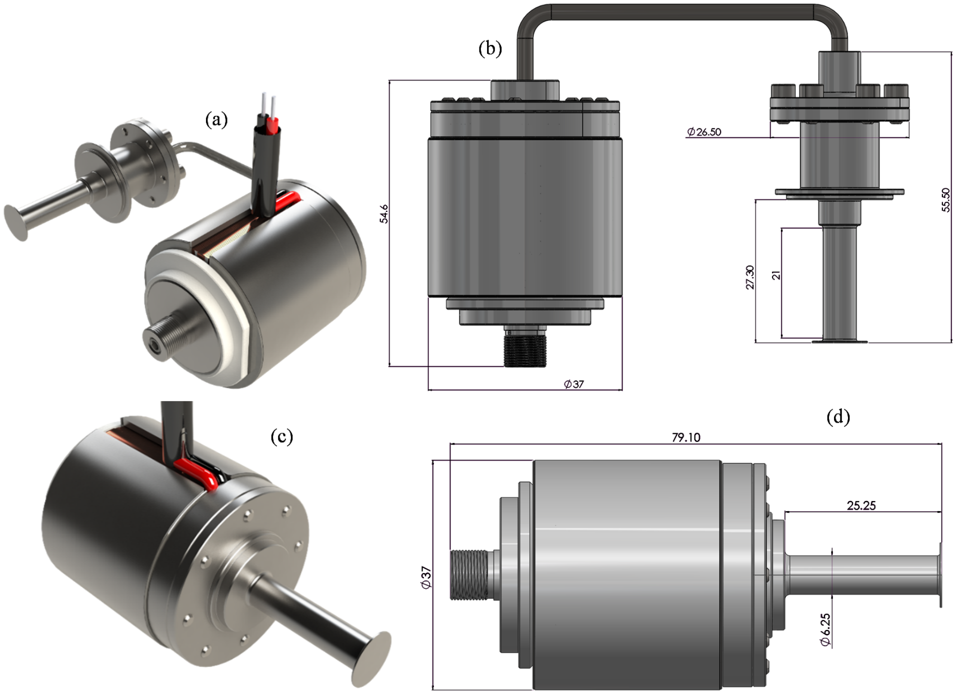


Figure 3. CAD rendering and outline dimensions of split (a,b) and integral (c,d) prototypes (Ver. 2)

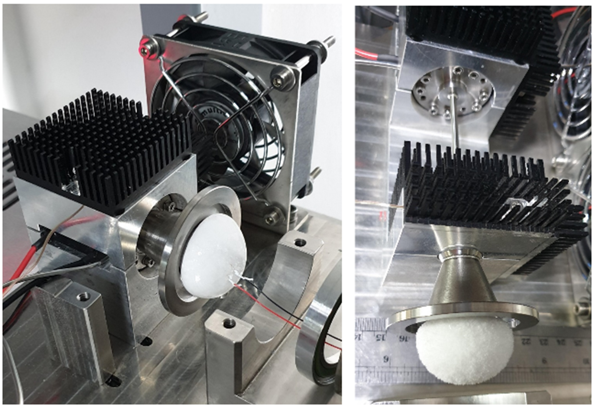


Figure 4. Frost build-up

FEASIBILITY STUDY

Figure 4 shows the frost build-up produced by integral (a) and split (b) cryocoolers after 24 hours of full-power operation with a cold fingertip exposed to the environment.

In Figure 4, the diameter of the frost ball reached about 40 mm while almost touching warm surfaces; it is worth noting that humidity in the laboratory room was as low as 35%. During this open-air testing, the split and integral prototypes reached 165K and 178K, respectively.

Upon completion of the open-air feasibility testing, the cold finger of a split cryocooler was integrated with dynamic simulation dewar, the high vacuum was maintained by an external vacuum pump. By manually adjusting the AC power supply, the cold tip temperature of 150 K was maintained with a power consumption as low as 1.85W AC; see the scope monitor in Figure 5. This initial study confirmed the feasibility of the design concept along with its essential cooling capacity.

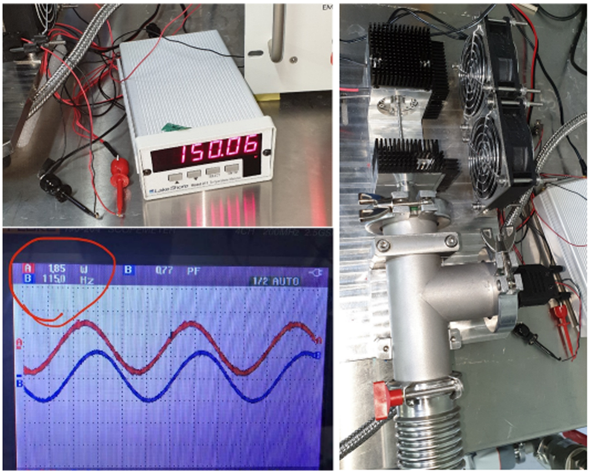


Figure 5. Integration with dynamic simulation dewar

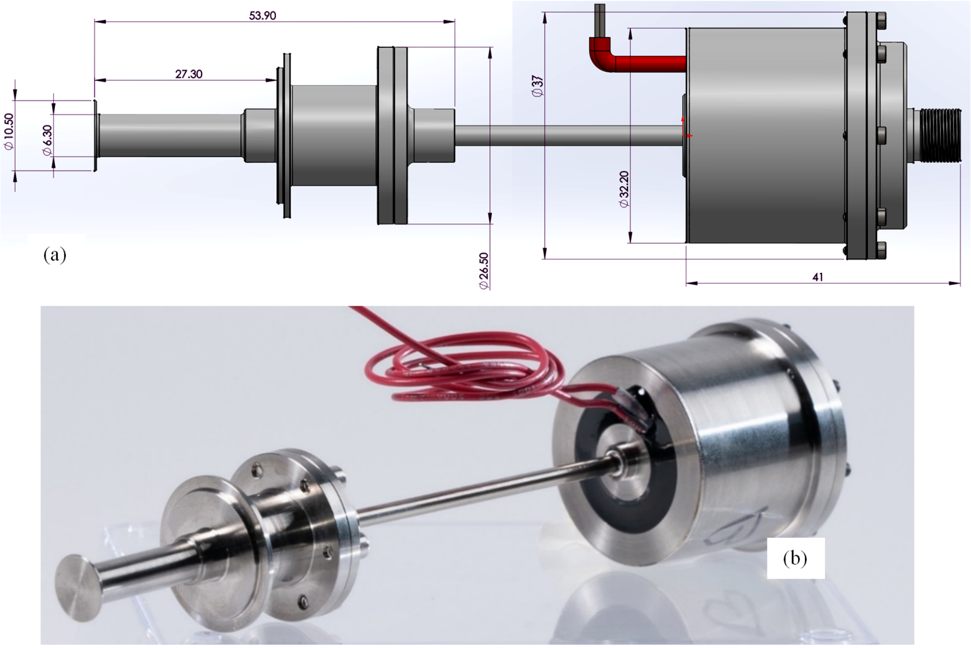


Figure 6. Split cryocooler Ver. 3

INTEGRATION WITH EVACUATED SIMULATION DEWAR

Upon completing the above initial feasibility study, the compressor of the split cryocooler was downscaled, and a cold finger was adopted for the evacuated simulation dewar. Figure 6 shows a dimensional drawing (a) and photograph (b) of Ver. 3 of the split cryocooler. In this design, the weight of the cryocooler was reduced to 140 gr, including a monolithic Ti-6Al-4V cold finger. Before the integration with simulation dewar, the cryocooler was subjected to a 1,000-hour full power burn-in test.

Figure 7 shows the split cryocooler integrated with an evacuated simulation dewar. The heat load of 200mW at 150 K & 23°C was evaluated numerically using proprietary software and further substantiated using multi-slope warmup calorimetry [3]. Such a high heat load may be explained by the length of the cold finger (21mm), wall thickness (150um), lack of cold finger polish, and lack of a cold shield.

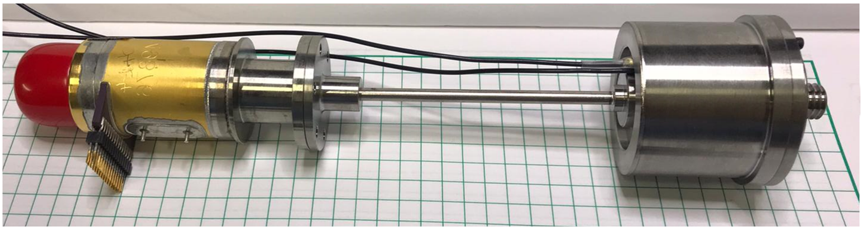
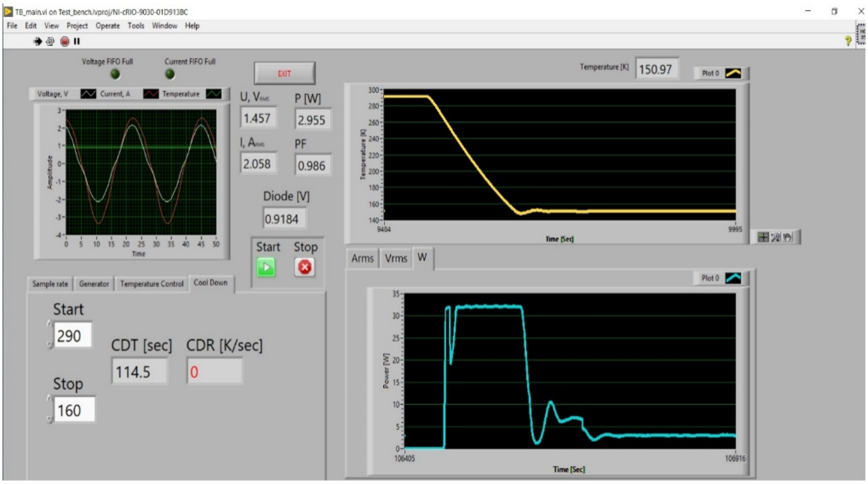


Figure 7. Integration with evacuated simulation dewar



U, V_{RMS}: 1.457
P [W]: 2.955
I, A_{RMS}: 2.058
PF: 0.986
Diode [V]: 0.9184
Temperature [K]: 150.97
Start: 290
Stop: 160
CDT [sec]: 114.5
CDR [K/sec]: 0

Figure 8. Cooldown from 300 K to 160 K

U, V_{RMS}: 1.3
P [W]: 1.72
I, A_{RMS}: 1.369
PF: 0.966
Diode [V]: 0.9183
Temperature [K]: 151.01

Master Sine Generator
Sine wave frequency (Hz): 82
Vpp (V): 10
Voffset (V): 0.1

Slave Sine Generator
Phase Offset (deg): 90
Vpp (V): 2
Voffset (V): 0

Figure 9. Temperature control mode at 150 K

Initial characterization was performed using a proprietary test bench allowing for driving and full control of the linear cryogenic cooler, including on-line driving frequency adjustment, tuning of PID temperature controller, temperature and applied heat load setup, soft start profiler along with cooldown rate monitoring, and cooldown timer. The Graphical User Interface (GUI) also includes graphic indication and data acquisition of the cold tip temperature, current, voltage, AC power, power factor, and added heat load.

Figure 8 portrays the entire cooldown process from 290 K to 150 K (a), whereupon time to image at 160 K is 115 seconds.

Figure 9 portrays operation of the cryocooler in a temperature control mode at 150 K. Accounting for the relatively high heat load of the simulation dewar, the power consumption is quite low – 1.7 W AC. The high power factor of 0.966 indicates the closeness to the resonant conditions.

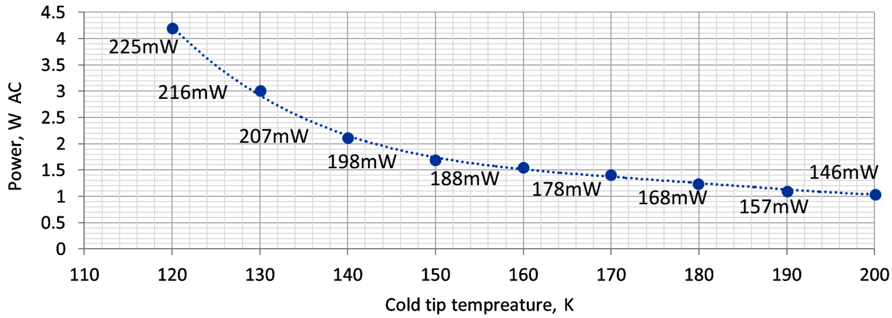


Figure 10. Power consumption at different cold tip temperatures

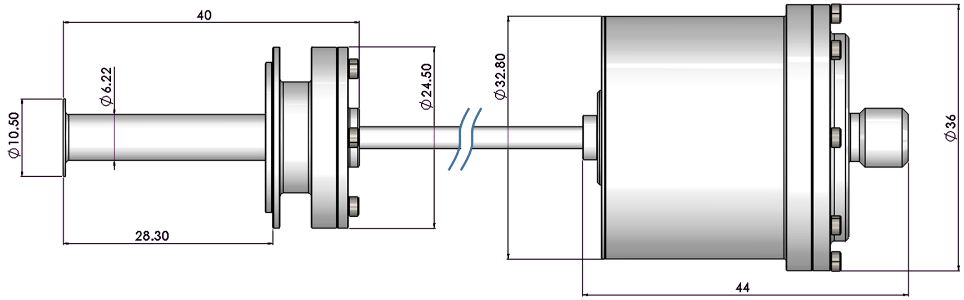


Figure 11. Cryocooler Ver. 3 updated design

It is very instructive to learn that this cryocooler can work over a wide range of temperatures starting from 120K. Figure 10 shows the dependence of power consumption on the cold tip temperature. Every data point is marked by the calculated heat load of simulation dewar at a given cold tip temperature at 23°C. The test was performed at a fixed charge pressure and frequency, which were optimized for operation at 150 K. Obviously, charge pressure and driving frequency may be optimized for every individual cold tip temperature, thus further improving attained performance.

FURTHER IMPROVEMENTS

Based on the outcomes of initial characterization, further improvements are expected due to:

- Minimizing the void volume in the expander's warm chamber
- Redesigning of the displacer's spring
- Increasing the active length of the cold finger from 21 mm to 27 mm
- Reducing the cold finger wall thickness from 150 µm to 120 µm
- Polishing the cold finger OD

Figure 11 shows a dimensional drawing of the next version. Due to the redesign of the warm side of the cold head, the overal length was reduced from 54 mm to 40 mm (compare with Figure 6), and the overall weight was further reduced from 140 gr to 120 gr.

VIBRATION CONTROL

As noted earlier, the cryocoolers under development rely on a single-piston compressor offering lower manufacturing cost, weight, and size along with higher efficiency as compared to dual-piston rivals. The obvious inherent disadvantage of the single-piston compressor concept is an essential vibration export resulting from the imbalanced motion of the piston assembly.

The residual vibration export was by design reduced down to levels which are adequate for heavy or rigidly mounted IR payloads. This was primarily achieved by using a lightweight moving piston assembly and shortening the working stroke.

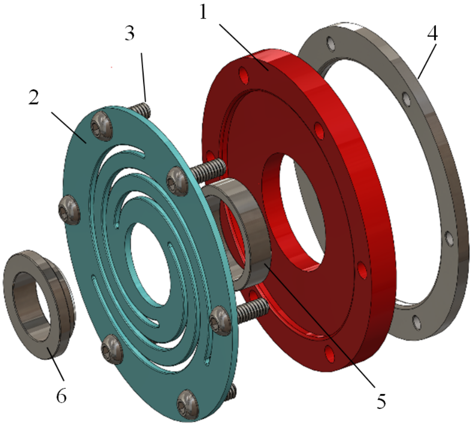
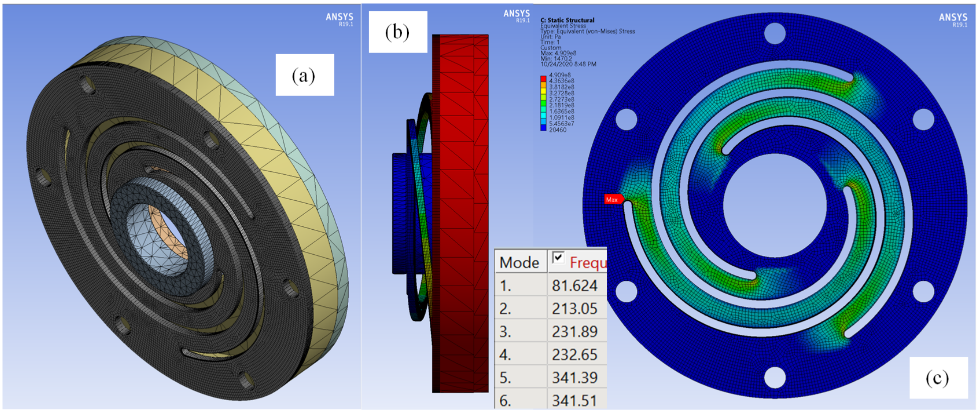


Figure 12. Exploded view of dynamic counterbalancer



Mode	☑ Frequ
1.	81.624
2.	213.05
3.	231.89
4.	232.65
5.	341.39
6.	341.51

Figure 13. Dynamic design of tuned dynamic counterbalancer: (a) – meshed model, (b) – modal shape, (c) - equivalent stresses

Low-weight handheld and gyrostabilized infrared imagers, however, are often sensitive to cryocooler induced vibration. Cryotech, therefore, is offering an optional tuned dynamic counterbalancer (TDC) designed in the form of an lightly damped "mass-spring" mechanical resonator, the frequency of translational mode of which is essentially tuned to the driving frequency (or vice versa). The frequencies of tilting, in-plane translations, rotation about the axis are well separated from the translational frequency [2].

With reference to Figure 12, the proof ring 1 is made of high-density material and is peripherally fastened to the circular planar flexural bearing 2 using screws 3 and threaded ring 4. Spacer 5 and nut 6 are used for anchoring the central hole of the flexural bearing upon the threaded charge port of the compressor. In this particular design, the designed mass of the proof ring is 46 gr, this is derived from constraints imposed on allowed dynamic stresses in flexural bearings developed during long-time operation in the temperature control mode and short-time cooldowns. The total added weight of such a TDC is 55 gr.

Because of the high radial stiffness of the flexural bearing and the symmetrical support of the proof ring, the frequency of the useful translational mode (82 Hz) is well separated from the other frequencies (rotation about counterbalancer axis, tilting modes, and in-plane modes). Figure 13 shows the outcomes of FEA. In particular, Figure 13a shows the meshed model, and Figure 13b shows the shape of the first translational mode at about 82 Hz; the rest of the frequencies are well distanced from the first frequency, see Table in Figure 13. Namely, the 2nd frequency 213 Hz corresponds to a rotation of the proof ring about its axis, the 3rd and 4th frequencies 232 Hz and 233 Hz correspond to the tilt modes, the 5th and 6th frequencies 341.4 Hz and 341.5 Hz correspond to the in-plane modes. Figure 13c shows the simulated

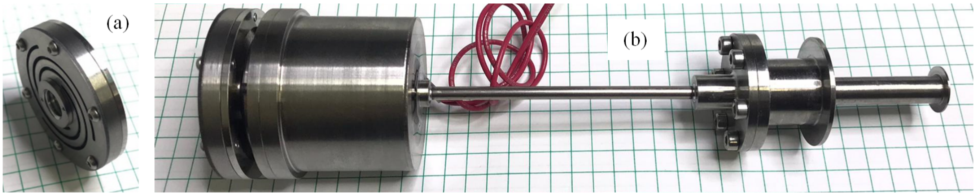


Figure 14. **P**ortrays the tuned dynamic counterbalancer (a) and cryocooler with a counterbalancer mounted upon the threaded charge port (b). It is important to notice that the overall length of the compressor did not change at all.

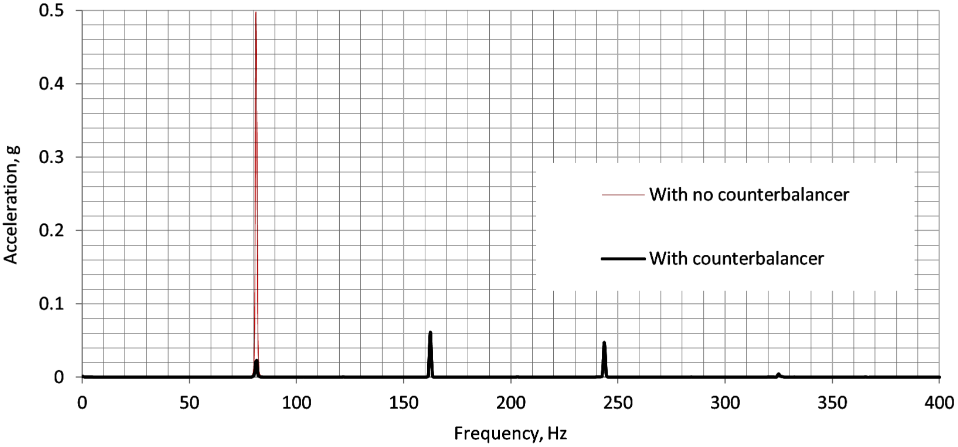


Figure 15. Cooler induced vibration with and without counterbalancer

distribution of equivalent Von-Mises stresses in the flexural bearing under maximum axial deflection as needed for counterbalancing the cryocooler working at full power. The observed maximum equivalent stress of 490 MPa is adequate for the fatigue safety limit for high-quality spring steels.

Figure 14 portrays the tuned dynamic counterbalancer (a) and cryocooler with a counterbalancer mounted upon the threaded charge port (b). It is important to notice that the overall length of the compressor did not change at all.

Figure 15 compares the spectra of cryocooler induced vibration in the 150 K temperature control mode with and without a counterbalancer; the cryocooler is mounted upon the base plate weighing 2kg thus mimicking the inertia of a typical hand-held imager. From Figure 15, the counterbalancer adding only 2.5% to the overall system weight results in 23-fold attenuation of the primary vibration component.

PROJECT STATUS

The authors continue the characterization and optimization of the presented cryocooler. The design is planned for freezing by the end of 2020. The first engineering series will be manufactured and assembled before March 2021. The accelerated life and environmental extreme (temperature, shock, and vibration) testing are scheduled to start before April 2021 and to complete before July 2021. The evaluation units will be available for potential customers by August 2021.

ACKNOWLEDGMENTS

The authors are thankful to Israel Innovation Authority for providing generous financial support for this project.

REFERENCES

1. Veprik, A., Tavori, A., Raviv Z., Zehctzer S., Refaeli R., Wise, A., “Low cost cryogenic coolers for commercial infrared imagers,” vol. 11002, *Infrared Technology and Applications XLV* (2019), p.1100203.

2. Veprik, A., Babitsky, V., “Ultra-light weight undamped tuned dynamic absorber for cryogenically cooled infrared electro-optic payload,” *Cryogenics*, vol. 83 (2017), p. 22-30.

3. Veprik, A., Shlomovich, B., Tuito, A., “Multi-slope warm-up calorimetry of Integrated dewar-Detector Assemblies,” vol. 9451, *Infrared Technology and Applications* XLI (2015), p. 945122.