Directly measuring thrust from a superconducting applied field magnetoplasmadynamic thruster

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Benjamin P.P. Mallett,* Celine Jane† and Emile Webster‡
Robinson Research Institute, Victoria University of Wellington, Lower Hutt, Wellington, 5010, New Zealand

Jens Schmidt§
Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, Germany

Superconducting magnet technology can significantly improve the system-level performance of electromagnetic thrusters by reducing the size, weight and power of the magnet module. However, a superconducting magnet poses some unique challenges to accurate and direct thrust measurement, a key performance metric of any thruster. The Robinson Research Institute (Robinson) in New Zealand and the DLR Institute of Aerodynamics and Flow Technology (DLR) in Göttingen, Germany, are working together on a project to directly measure thrust from a kW-class applied-field magnetoplasmadynamic thruster (AFMPDT) with a conduction-cooled superconducting magnet for its applied field module. This paper presents results of the characterization and modification of the thrust stands at DLR and Robinson to meet the additional challenges of stray magnetic fields, cryocooler vibrations and thermal gradients associated with the superconducting magnet system. We find that after some modifications to thrust stand parts and data analysis methods, the stray magnetic field and vibrations of a cryocooler, although large at approximately $1g$ peak acceleration, should have negligable impact on accuracy of thrust measurement. Moreover, the vibrations may improve the quality of the measurement by reducing hysteresis arising from bearing stiction. A variety of methods will need to be carefully employed to reduce sensitivity to temperature, particularly to an uneven temperature distribution across the pivot axis. As such, we deem it feasible to make direct thrust measurement in our facilities of a flight-like superconducting AFMPDT accurate to within a few mN. The key next stage of this project involves comparative measurements of a superconducting AFMPDT planned for 2025.

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[*] Senior Scientist, Robinson Research Institute, ben.mallett@vuw.ac.nz
[†] Junior Scientist, Robinson Research Institute, celine.jane@vuw.ac.nz
[‡] Senior Engineer, Robinson Research Institute, emile.webster@vuw.ac.nz
[§] Research Associate, Department of Spacecraft, jens.schmidt@dlr.de

I. Introduction

The use of superconducting magnets with electric propulsion systems, such as applied-field magnetoplasmadynamic thrusters (AFMPDTs), presents opportunities to study the relevant physics and scaling relationships[1,2] to higher magnetic fields as well as improving the feasibility of using such thrusters on spacecraft due to a potential size, weight and power reduction of the magnet system.[3] A critical characterization of an electric propulsion system is its thrust, favoring a direct measurement to reduce uncertainty and thus improve measurement accuracy.[4] A superconducting magnet subsystem will present several additional challenges to this already difficult task. For a superconducting magnet to operate correctly it needs to be kept at cryogenic temperatures (<80 K) and although liquid cryogens, such as liquid nitrogen, can effectively cool magnets,[5,6] we wish to build capability to measure potential space-bound systems that will need to use mechanical cryocoolers. The vibrations from such cryocoolers, combined with the stray field from a magnet operating at much higher fields than conventional AFMPDT magnets, will impact the thrust measurement apparatus.

The Robinson Research Institute (Robinson) undertakes fundamental and applied superconductivity research and has recently embarked on an AFMPDT research program.[7] The project involves an in-space demonstration of a superconducting magnet subsystem,[8] and the development of a ground-based, kW-class superconducting AFMPDT[9] with applied fields of 1 T along with the establishment of ground test facilities.[10] At the DLR Institute of Aerodynamics and Flow Technology in Göttingen (DLR), electric propulsion is tested for commercial and scientific customers which includes the development of electric propulsion diagnostics as well as thrusters. Test facilities include multiple thrust stands,[11,12] one of these stands is an inverted double-pendulum based on a set of quartz glass rods, which has been used to measure different thrusters.[13]

This paper relates to a collaborative project between Robinson and DLR to develop direct, accurate thrust measurement capability of superconducting AFMPDT. The project will also cross-validate measurement systems at our respective facilities and quantify the impact of vacuum-chamber size and background pressure. The project culminates in thrust measurements throughout 2025 of the full AFMPDT system at both Robinson and DLR facilities across a range of operating parameters. The paper describes initial results from characterization and modification of the thrust stands at DLR and Robinson to meet the additional challenges of associated with a superconducting AFMPDT. We take the approach of quantifying individually the impact of stray magnetic fields, vibrations and thermal gradients ahead of the integration of a complete AFMPDT system. This approach allows rapid testing of mitigation strategies with smaller subsystems, with the thruster development proceeding in parallel.

II. Thrust stands at DLR and Robinson

A thrust stand, see Figure 1(a), has recently been designed and built at Robinson to support its AFMPDT research program. It is a simple hanging pendulum that is currently operated in a free-swinging configuration. The pendulum pivots over a set of full-ceramic ball bearings. Motion of the pendulum is measured by an optical displacement sensor. A set of calibrated weights, that can be loaded and unloaded *in-situ* inside the vacuum chamber, is used to relate the measured displacement to force. The platform of the thrust stand, onto which the thruster is mounted, is a black-anodized aluminium optical breadboard. A custom made chiller plate is attached to the bottom of the platform and which supports a flow of approximately 2 L.min^{-1} coolant water. Details of the design and performance of the thrust stand, and accompanying test facilities, will soon be presented in a separate paper.[10]

DLR-Göttingen has multiple thrust stands, but this project uses the DEPB thrust stand as described in Ref.[12,13] and shown in Figure 1(b). It is an inverted double-pendulum that uses a set of quartz glass rods as flexure bearings. Force is measured by a commercial Sartorius WZA224-N load-cell and is calibrated against a set of weights that can be loaded and unloaded *in-situ*. An eddy current break, comprising of a sheet of copper in between two permanent magnets, is installed to dampen oscillations of the stand.

III. Results

A. Magnet field

Figure 2(a) shows the calculated magnitude of the radial stray magnet field for two indicative operational points of the superconducting magnet; a 0.3 T central field (blue curve) and a 1 T central field (green and

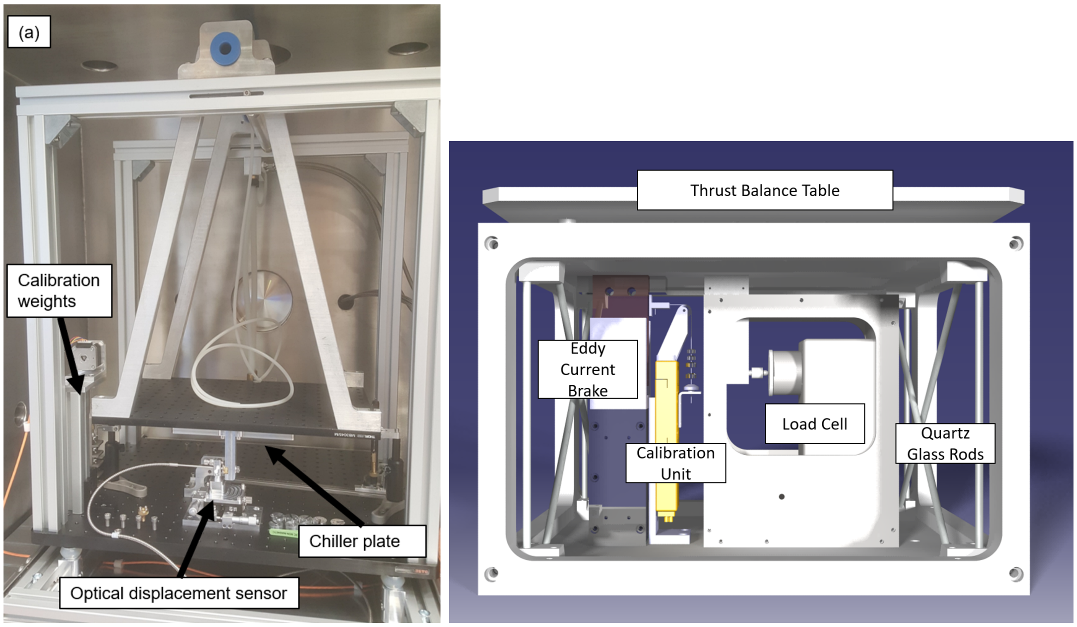

Figure 1. (a) The thrust stand at Robinson. (b) The DEPB thrust stand at DLR (shown here as a render without side cover to better highlight its various components).

orange curves). Vertical dashed red lines indicate the inner and outer radii of the magnet. This magnetic field, which is essentially a DC-field, could have a noticeable impact on thrust measurements by exerting a force on magnetically susceptible, e.g. strongly paramagnetic or ferromagnetic, components of the thrust stand.[14] Examples in our case include steel components (such as bolts), the load-cell or electric motors used as part of the force calibration systems.

The magnitude of the stray field expected at critical components of the thrust stands was determined to be up to 50 mT for our AFMPDT operating at 1 T. Nd-Fe-B permanent magnets were fully characterized and then used to simulate the stray field at those components of the thrust stand at DLR and Robinson. By using permanent magnets, we could test the sensitivity of individual components on the thrust stands more easily. On the other hand, using a superconducting magnetic would have introduced significant heat flux and vibrations from its cryocooler, and a conventional magnet would have been impractically large, heavy and require significant power to operate.

Several magnetically susceptible components were found on the thrust stands that impacted the force calibration when subjected to the magnetic field. We replaced as many of these sensitive parts as possible with aluminium parts, for example the micrometer screw used to tension the load-cell on the DLR thrust stand. Figure 2(b) shows force calibration measurements as a function of the orientation and proximity of the permanent magnet to the micrometer after its magnetic parts had been replaced. The data show relatively minor changes in thrust stand behavior, even at the maximum field of 150 mT and 35 mT (for the two field directions respectively) shown in the figure. Similar results were found on the thrust stand at Robinson, but work is still underway to replace or remove some parts found to be magnetically susceptible.

These encouraging results will be checked with the full superconducting magnet operating on the thrust stands, however, by far the more significant impact of the magnet will be the vibrations and heat flux from the cryocooler that is used to cool the superconducting magnet.

B. Cryocooler vibrations

A CryoTel CT mechanical cryocooler from SunPower is operated in various orientations on the thrust stands and fitted with an accelerometer to monitor the exported vibrations. The 3.1 kg cryocooler is powered by up to 180 W, which ultimately ends up as heat flux, and is capable of cooling the AFMPDT's superconducting magnet to its operational temperature. Duplicate compact high-power loudspeakers that mimic the vibrations of the cryocooler have also been developed for comparative testing at both Robinson and DLR facilities, and whose frequency can be swept to experimentally identify resonances of the thrust stand.

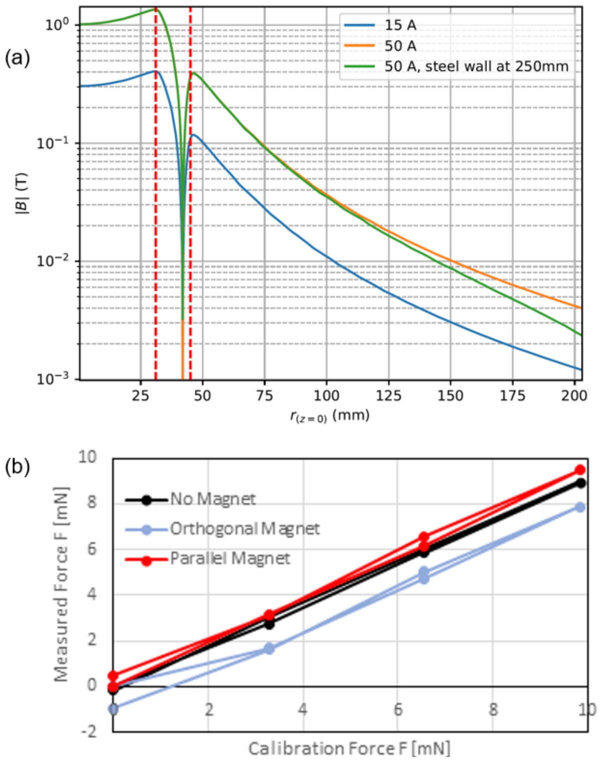

Figure 2. (a) magnitude of the calculated stray field in the radial direction from the superconducting magnet at two operating points, and (b) after modifications to the thrust stands, the stray magnetic field will have only minor impact on thrust measurements. Results shown for its impact on the DLR thrust stand. See text for details.

Figures 3 and 4 show results from operating the cryocooler on the thrust stands at Robinson and DLR. Vibrations from the cryocooler have an amplitude of $1.5g$ (14.7 m.s^{-2}) at steady state in the axis of the cryocooler's motor denoted (the Z-axis in this case), and $0.3g$ in the orthogonal axes. During start up of the cryocooler however, the acceleration can exceed $3g$ as shown in Figure 3(a) and we found it necessary to stabilize the calibration setup to avoid some of the weights being knocked out of their holders! The vibrations peak at the 60 Hz driving frequency of the cryocooler's motor and its harmonics, as shown in Figure 3(b).

Figure 4(a) shows the impact of these vibrations on the measurement of a set of calibration weights at Robinson. In this case, the cryocooler's motor is orthogonal to the thrust-direction of the thrust stand. The vibrations cause the oscillations in the raw data when loading a weight, which are damped over several seconds. Nevertheless, filtering of the raw data allows measurements accurate to less than 1 mN. Similarly, although an initial offset and significant oscillations appear in the raw data from DLR's thrust stand, shown in Fig. 4(b), simple filtering of the data allows meaningful measurements to still be made. We are mindful that with loading of the thrust stand with the AFMPDT, we may shift a vibrational resonance of assembly into the cryocooler's frequency bands. In this case, we can take active measures to dampen or shift that resonance.

An unintended, and somewhat positive, consequence of the vibrations is to lessen the severity of stiction at the bearings. We believe stiction to be the leading cause of hysteresis in weight calibration measurements (a difference between the force/displacement measured whilst loading compared with unloading of the calibration weights that cannot be accounted for by baseline drift), and with the cryocooler operational hysteresis in the weight calibration measurements is effectively removed.

These preliminary results also show that temperature change on the thrust stand caused by the cryocooler have just as big an impact as the vibrations themselves. For example, note the baseline drift in the raw data of Fig. 4(a) that became prominent once the heat generated by the cryocooler's was sunk to the thrust stand platform. Experimental studies to quantify and mitigate these thermal effects are explored further in the following section.

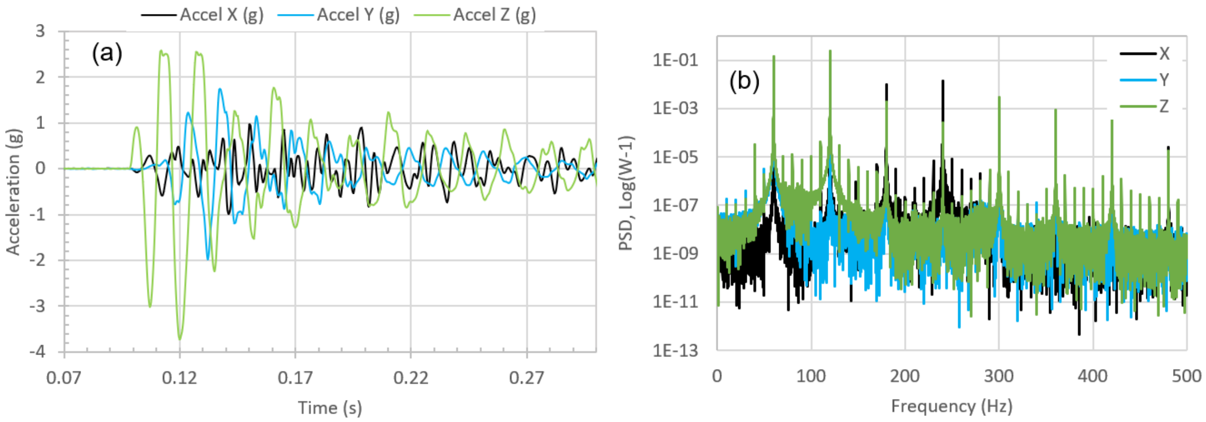

Figure 3. (a) Acceleration vs time during the start-up, at 0.1 s, of the cryocooler used to cool the superconducting magnet on the AFMPDT. For this experiment, "Y" corresponds to the thrust direction. (b) Power spectrum of the vibrations from the cryocooler in steady state operation at 140 W.

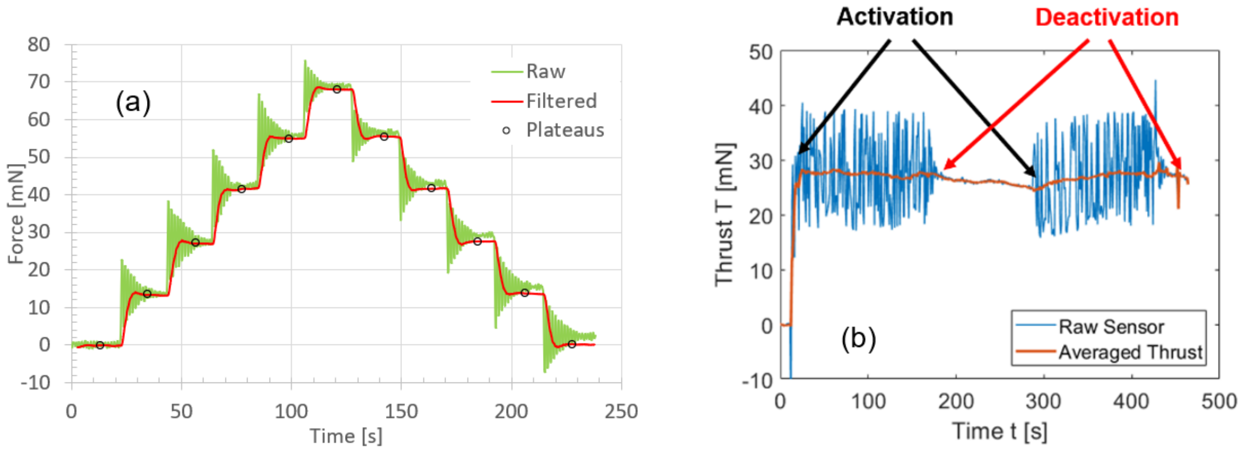

Figure 4. (a) Loading then unloading calibration weights on the thrust stand at Robinson with the cryocooler operating at 60 W input power. (b) Operating the cryocooler on the thrust stand at DLR.

C. Thermal effects

We have undertaken investigations into the temperature sensitivity of the thrust stands. The superconducting AFMPDT will have two main sources of heat flux into the system, up to 180 W from the cryocooler and potentially up to a few kilo-Watts from the thruster. In principle, the associated temperature variation can impact the thrust measurement via; materials properties (e.g. stiffness of flexure bearings or cables), sensitivity of sensors, and structural distortions that lead to a change in the centre-of-mass (CoM) on the stand. Ahead of integrated thruster testing, we have therefore undertaken a series of experiments seeking to assess and better understand the thermal sensitivity of the devices at DLR and Robinson.

To study the thermal sensitivity independently, multiple electrical heaters and temperature sensors are mounted on the thrust stands and operated to produce temperature variations and gradients. Calibration-weight and cold-gas thruster measurements are used to assess the impact on the force measurement. For the tests on the DLR thrust stand, four 12.5 W heaters were placed in the corners of the stand's moving platform and Pt100 temperature sensors placed either end of the platform, and on the fixed base of the stand. The passive thermal insulation between the platform and its instrumentation below on the fixed base was removed, to maximize the sensitivity to temperature of the platform. Sample data from these experiments are shown in Figure 5.

The temperature of the vacuum chamber used in this experiment is not actively stabilized, and so varies over the course of a day. That temperature variation is observed on the thrust stand also, as approximately 0.5 $\mathrm{K.hr^{-1}}$ in this case. Concurrently, the output of the load-cell monotonically drifts at a rate of approximately -18 $\mathrm{mN.hr^{-1}}$. Combining these results gives a sensitivity of -36 $\mathrm{mN.K^{-1}}$, although we note that doing so might imply the drift in the load-cell is caused by the temperature change.

Once the heaters are energized to 50 W, at 13:45 in Figure 5, the temperature variation of the thrust stand increases to 24 $\mathrm{K.hr^{-1}}$, and there is a rapid variation in the baseline of the load-cell output also. However, the interspersed calibration-weights and cold gas thruster measurements, one of which is highlighted in the inset to Figure5(b), returned consistent force measurements before and after activation of the heaters, once the variation in the baseline had been accounted for. This encouraging result means accurate thrust measurements can still be made outside of thermal stability of the thrust stand.

Despite the rapid variation in the baseline load-cell reading due to actively heating the thrust stand, when expressed as a temperature sensitivity at -9 $\mathrm{mN.K^{-1}}$, it is significantly lower than unforced variation case discussed above. This suggests that none of the monitored temperatures are the relevant ones, if indeed a single temperature is the relevant variable. For example, it may be that the spatial temperature distribution is more significant as it shifts the centre-of-mass on the thrust stand. We have started to investigate these hypotheses further in subsequent studies on the thrust stand at Robinson.

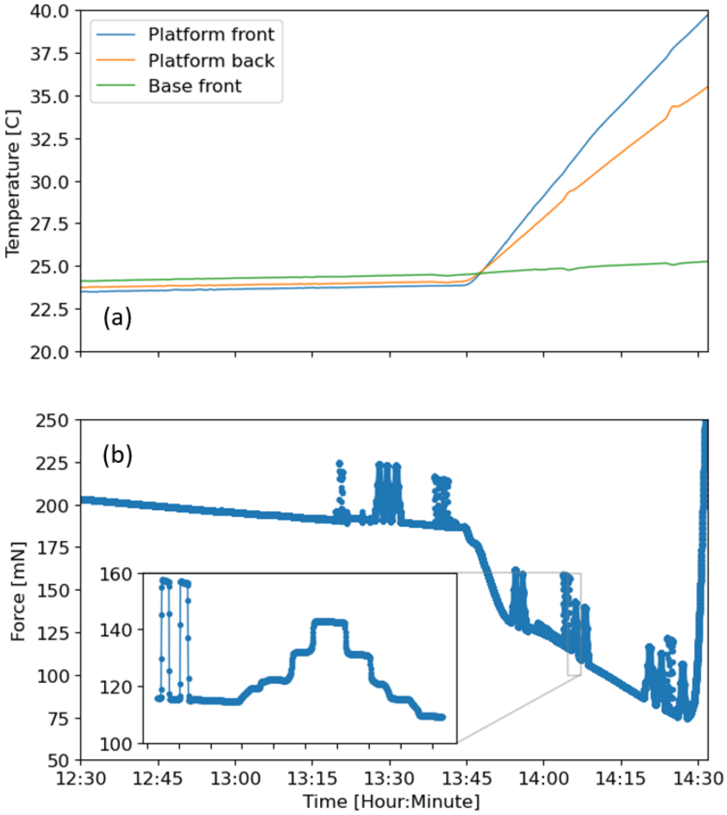

Figure 5. Temperature sensitivity studies of the thrust stand at DLR. Panel (a) shows temperatures measured at two locations on the movable platform, and one location on the fixed base of the thrust stand. Panel (b) shows the load-cell reading over the same time period. Gold-gas thruster and calibration weight measurements are run intermittently, as highlighted by the inset.

A similar set of experiments were undertaken at Robinson. It is not our intention to directly compare thermal-drift performance, as might be captured by the $\Delta F/\Delta T$ metric used above. The experiments at DLR were testing a 'worst-case' scenario whereby there was no active and minimal passive (e.g. multi-layer insulation) temperature control, on an inverted pendulum thrust stand. On the other hand, the thrust stand at Robinson is operated as a simple, free-swinging pendulum that is actively water-cooled and which therefore will be less sensitive to heat loads. Rather, these studies seek investigate the cause of thermal sensitivity, its mitigation and assess its potential impact on the measurement of our kW-class thruster.

Figure 6 shows a selection of results from these temperature sensitivity studies at Robinson. In the top row of the Figure, a 90 W heater is located in the centre of the thrust stand and turned on intermittently, as indicated by bars along the time-axes. Panel (a) shows the temperature measured either side of the pivot axis, as indicated by the inset schematic. In this case, both temperatures at ‘C1’ and ‘D1’ show an approximate 5 K peak-to-peak variation. At the same time, the measured force varies by approximately 1 mN, although it does not seem to be a result of the ΔT. The ‘random’ drift of the force measurement is a similar magnitude to this, at approximately 1 mN.hr^{-1}. This relative insensitivity of the thrust stand to temperature variation is however lost as soon as the pendulum is locked in place and no longer free to swing. When locked, or preloaded with 180 mN, there is a clear correlation between the temperature and measured force, at about 3 um.K^{-1}.

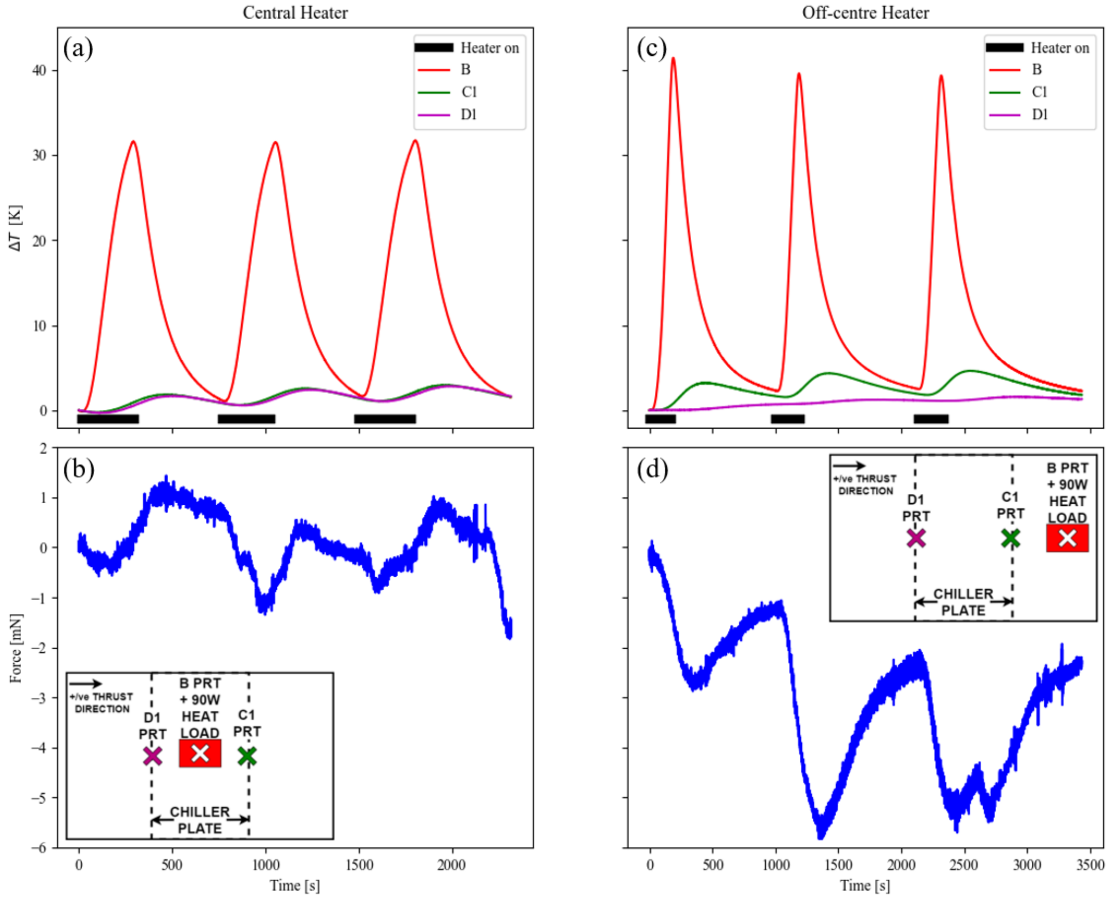

Figure 6. Temperature sensitivity studies of the thrust stand at Robinson. The first column displays results where the heat source is in the centre of thrust stand, and the second column with an off-centred heat source. Panel (a) shows the temperature change at locations noted in the schematic in panel (b); B (on the heater), C1 and D1. The heat source is duty cycled as indicated by the bars at the bottom of panels (a) and (c) showing at which times the heater is on. Panels (c) and (d) show the case when heat source is off-centre.

Furthermore the thrust stand is more sensitive to a temperature distribution that is asymmetrical about the pivot axis, as would occur from an off-center heat source. This is case shown in the right column of Figure 6, panels (c) and (d), where the heater has been moved to the end of the thrust stand. There is now a 5 K difference between the ΔT of ‘C1’ and ‘D1’, and a clear correlation between the measured force and the temperature with a peak-to-peak variation of 5 mN. Our hypothesis is a thermal expansion of one side of the stand that shifts the centre-of-mass causing the force, but this is yet to be quantitatively tested using finite-element modelling.

IV. Discussion

The experiments described above were undertaken so that direct and accurate thrust measurements of a superconducting AFMPDT can be made at both Robinson and DLR. The results thus far are very promising in light of that goal. We could show that even in the presence of $\sim 1g$ vibrations from a cryocooler and ~ 100 mT stray magnetic fields meaningful force calibration data was obtained (although noting that some modifications to the measurement hardware and methods were required to achieve this, as discussed in the results sections). Indeed, adding an oscillator to a thrust stand may be a worthwhile strategy to reduce hysteresis arising from stiction! As such, measurements of the AFMPDT accurate to within 2 mN appear achievable[a] with our facilities, compared with an expected total thrust up to 100 mN (depending on the operating conditions). Of course, this remains to be demonstrated.

The most significant outstanding consideration and risk to making good thrust measurements remains the management of heat flux onto the thrust stand. For example, thermally-induced drift in the baseline force reading could make accurate thrust measurements difficult, requiring significant post-processing of the data and assumptions in the baseline drift to be made. More severely, there is a risk that thermal-induced drift causes the force reading to go out-of-range before the AFMPDT experiment can be completed. This was already seen just after 14:30 in the experiment shown in Figure 5, albeit under conditions designed to maximize the thrust stand's thermal sensitivity. That risk is exacerbated in our case by the extended length of time (∼1 day) required to have the cryocooler operating in vacuum, and dissipating up to 180 W of heat flux, before the superconducting magnet is at its operational temperature. Furthermore, we believe it an important capability to have the thruster running for several hours whilst still being able to make thrust measurements.

As such, the experiments in this paper have also informed what further design considerations and optimizations can be made to the measurement systems and the AFMPDT so that accurate thrust data can be obtained. The most important relate to thermal management; effective cooling of the heat-sources on the thrust stand, temperature monitoring and control of the thrust stand, and using high-thermal conductivity paths for an isotropic temperature distribution about the pivot axis of the thrust stand. Less likely to severely impact thrust measurements, though still worth considering is characterizing and managing potential acoustic resonances between a fully-laden thrust stand and vibration harmonics from the cryocooler. And for completeness, we note there are many other considerations that go into making accurate, direct thrust measurements of EP systems which have been discussed in the literature, see e.g. Refs.[4,15] and citations therein.

The key next stage of this project however involves comparative measurements of a superconducting AFMPDT at Robinson and DLR, planned to run throughout 2025. By significantly reducing the size, weight and power of the magnet system, superconducting magnet technology significantly improves the attractiveness of AFMPD electric propulsion. Confidence in the accuracy of performance data from flight-like AFMPDT hardware, especially thrust data, also significantly improves the likelihood of the technology's uptake. As such, we see this project as an important part of taking AFMPDTs out of the laboratory, and into space.

V. Conclusion

Robinson and DLR are working together on a project to measure thrust from an AFMPDT with a conduction-cooled superconducting magnet used for the applied field module. In this paper we presented results of the characterization and modification of the thrust stands at DLR and Robinson to meet the additional challenges of associated with direct and accurate thrust measurement of such an AFMPDT. We found that after some relatively minor modifications to parts, the stray magnetic field expected from the superconducting magnet will have a negligible impact on the accuracy of our force measurements. The vibrations from a cryocooler on the thrust stand, although large at approximately $1g$ peak acceleration, can be effectively filtered out in post processing of the data. Moreover, the vibrations may improve the quality of the measurement by reducing hysteresis arising from bearing stiction. A variety of methods will need to be carefully employed to reduce the sensitivity to temperature, particularly to an uneven temperature distribution across the pivot axis. As such, with careful design and characterization work such as that laid

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[a] A full uncertainty analysis will be presented as a separate paper detailing the design and characterization of test facilities at Robinson.

out in this paper, we deem it feasible to make direct thrust measurement of a flight-like superconducting AFMPDT accurate to within a few mN. We are looking forward to the next phase of this project.

Acknowledgments

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References

[1] Coogan W and Choueiri E 2017 A Critical Review of Thrust Models for Applied-Field Magnetoplasmadynamic Thrusters *53rd AIAA/SAE/ASEE Joint Propulsion Conference* AIAA Propulsion and Energy Forum (American Institute of Aeronautics and Astronautics) URL `https://arc.aiaa.org/doi/10.2514/6.2017-4723`

[2] Balkenhohl J, Glowacki J, Rattenbury N and Cater J 2023 *Journal of Electric Propulsion* **2** 1 ISSN 2731-4596 URL `https://doi.org/10.1007/s44205-022-00036-5`

[3] Acheson C, Glowacki J, Nakano R, Maeshima D, Saile D, Pavri B, Takagi R, Mori R, Pollock R, Olatunji J, Goddard-Winchester M, Strickland N, Ichihara D, Wimbush S and Kinefuchi K 2023 *Journal of Electric Propulsion* **2** 26 ISSN 2731-4596 URL `https://doi.org/10.1007/s44205-023-00060-z`

[4] Polk J E, Pancotti A, Haag T, King S, Walker M, Blakely J and Ziemer J 2017 *Journal of Propulsion and Power* **33** 539–555 publisher: American Institute of Aeronautics and Astronautics URL `https://arc.aiaa.org/doi/10.2514/1.B35564`

[5] Voronov A S, Troitskiy A A, Egorov I D, Samoilenkov S V and Vavilov A P 2020 *Journal of Physics: Conference Series* **1686** 012023 ISSN 1742-6596 publisher: IOP Publishing URL `https://doi.org/10.1088/1742-6596/1686/1/012023`

[6] Zheng J, Liu H, Song Y, Zhou C, Li Y, Li M, Tang H, Wang G, Cong Y, Wang B, Wang Y, Wu P, Qu T, Zhu X, Zhu L, Liu F, Cheng Y and Zhao B 2021 *Scientific Reports* **11** 20706 ISSN 2045-2322 bandiera_abtest: a Cc_license_type: cc_by Cg_type: Nature Research Journals Number: 1 Primary_atype: Research Publisher: Nature Publishing Group Subject_term: Engineering;Physics;Space physics Subject_term_id: engineering;physics;space-physics URL `https://www.nature.com/articles/s41598-021-00308-4`

[7] Nick Long, Avinash Rao, Jamal Olatunji, Rodney Badcock, Jakob Balkenhohl, Thomas Berry, John Cater, Jakub Glowacki, Max Goddard-Winchester, Christopher E Hann, Pauline Harris, Andrew Limmer-Wood, Benjamin PP Mallett, Nicholas Rattenbury, Nick Strickland, Thomas Weaver, Emile Webster, Hubertus W Weijers, Stuart Wimbush and David Wright 2022 Toward On-Orbit Demonstration of a High Temperature Superconducting AF-MPD Thruster (Boston, MA: Electric Rocket Propulsion Society) p 480 URL `https://www.electricrocket.org/IEPC_2022_Papers.html`

[8] Pollock R, Głowacki J, Goddard-Winchester M, Hellmann S, Huang X, Mallett B, Olatunji J, Pavri B, Shellard C, Strickland N, Webster E, Rao A, Wright D and Parashar T 2024 *2024 IEEE Aerospace Conference, Big Sky, MT, USA* 1–11 URL `https://doi.org/10.1109/aero58975.2024.10521198`

[9] Jakub Glowacki, Emile Webster, Sebastian Hellmann, Steven Smart and Gennady Sidorov 2024 Discharge characteristics of a low-power applied-field magnetoplasmadynamic thruster in a tesla-level magnetic field (Toulouse, Fr: Electric Rocket Propulsion Society)

[10] Webster E, Mallett B, Jane C and Smart S 2024 *in preparation*

[11] Neumann A 2018 *Journal of large-scale research facilities JLSRF* **4** A134–A134 ISSN 2364-091X URL `https://jlsrf.org/index.php/lsf/article/view/169`

[12] Neumann A, Simon J and Schmidt J 2021 *EPJ Techniques and Instrumentation* **8** 1–19 ISSN 2195-7045 number: 1 Publisher: SpringerOpen URL `https://epjtechniquesandinstrumentation.springeropen.com/articles/10.1140/epjti/s40485-021-00074-7`

[13] Schmidt J, Simon J and Neumann A 2023 *International Journal of Energetic Materials and Chemical Propulsion* **22** ISSN 2150-766X, 2150-7678 publisher: Begel House Inc. URL `https://www.dl.begellhouse.com/journals/17bbb47e377ce023,7b1719907bb1c9ee,72deb2bf1deda939.html`

[14] Haag T W 1991 *Review of Scientific Instruments* **62** 1186–1191 ISSN 0034-6748 publisher: American Institute of Physics URL `https://aip.scitation.org/doi/abs/10.1063/1.1141998`

[15] Neumann A, Volkmar C, Geile C and Hannemann K 2017 Mitigation of detrimental electric thruster force measurement effects *35th International Electric Propulsion Conference, Georgia Institute of Technology* (Electric Rocket Propulsion Society) URL `https://elib.dlr.de/115125/`