Review of "Technical Report on the Experimental Microwave Thruster Roger Shawyer September 2002"

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1. INTRODUCTION

The EmDrive is a new concept in electric propulsion for spacecraft which directly converts electrical energy to thrust. The theoretical principles have been developed, an experimental model has been constructed and experimental testing, to verify the performance, undertaken. Patents have been granted for this invention. This work has been performed by Roger Shawyer of Satellite Propulsion Research Ltd under a DTI SMART award.

2. APPLICABLE DOCUMENTATION

2.1 Applicable Documents

Technical Report on the Experimental Microwave Thruster - Roger Shawyer - September 2002

2.2 Reference Documents

The EmDrive 'Microwave Propulsion for the Space Industry' - Roger Shawyer - July 2002

During the review I have constantly referred to:-

Telecommunications by A.T. Starr
Electrical Engineering Handbook compiled by Siemens

3. DOCUMENT SCOPE

This document covers a review of a report entitled "Technical Report on the Experimental Microwave Thruster" by Roger Shawyer of Satellite Propulsion Research Ltd dated September 2002. Note has been taken of a paper Entitled "The EmDrive" by Roger Shawyer dated July 2002 where appropriate. The work was authorised by Satellite Propulsion Research Ltd on 8-Oct-02. Much of the data is proprietary and is covered by an NDA signed on the 5-Oct-02. Thus the information contained in this report must not be disclosed to a third party without the approval of both Satellite Propulsion Research Ltd and J.W. Spiller.

4. THE REVIEW

4.1 Review Approach

The report is divided into three main sections - Theory, Design, Test Programme plus conclusions. I have followed this layout in the review but have divided the test section into a review of the test programme and a review of the results. I have reviewed the report's conclusions before adding a final section on my conclusions from the review.

I have read the theoretical section with interest and hesitate to comment other than to observe that matters which involve relativity are much more difficult to verify unambiguously than for classical physical concepts. I understand that this section has been confirmed by a independent review. However I have done my best to look for flaws in the theory, but I am of the opinion it is the testing which provides the most convincing proof.

The design section which describes the actual experimental hardware is clear and describes what was built. The build is inevitably from parts which are readily available and is in some cases not optimum. An appreciation is offered of what improvements might be possible for the next prototype. Foreseen difficulties in the conversion of the design for use in space are also discussed.

The test programme section was the most difficult to review. Because I consider it to be the most important concept proof aspect of the review, I have given it particular attention. Inevitably, with a new concept, development of testing techniques go hand in hand with the design. As a result of these changes to the test programme it was not always easy to see the details of the test set up and often, because of interfering effects, the actual performance of the Thruster was difficult to deduce.

The sections and figures quoted in this section of the review refer to those of the report reviewed.

Numerous questions and points of clarification arose during the review process and have in general been clarified by telephone or email. These clarifications have then been discussed in the relevant sections of the review.

4.2 Theoretical Review and Comment

The theoretical analysis of section 2 has been checked and follows established theory. So provided the physical principles are correct then the Thruster can be realised.

The physical principles are not well explained particularly the differences between a Newtonian, or closed system, and an Einstein, or open system. It is this difference which is crucial to the realisation of a working thruster. A further discussion with the author has helped to clarify the difference between the two types of system. His explanation hinges on the interaction at the interface between the working fluid and the Thruster end walls as the thruster approaches the speed of light. Where in the closed system the velocity difference between the working fluid and the end wall does not change but in the open system it reduces to zero. So there must be difference in the physical principles of the two systems. It is this difference which the author asserts leads to the proposed thruster design.

For my own understanding I took the approach of comparing the microwave system with an equivalent sound system. If we look at a tapered sound resonator, a typical closed system, then the force on the end walls is given by 2P/v where P is the total power in a plane sound wave and v is the particle velocity. For a tapered microwave resonator, an open system, the force on the end walls is given by 2P/c; here v is replaced by c the speed of light. Now v is dependent on the area of the interaction but c is not. So in a closed system the force on the end walls cancels out while in an open system it does not.

The theoretical reasoning was checked by comparison to known sources, by numerical substitution at the authors suggestion and by careful examination of the consistency of units.

It is interesting to observe that, from equation 9, to obtain the maximum thrust for a given power the ratio of the large end diameter over the small end diameter needs to be maximised and the Q of the resonator needs to be maximised. There is a lower limit to the size of the end wall because of wave guide cut off. As is often the case this leads to a practical compromise in that in order to minimise the small end diameter whilst keeping above the wave guide cut off dielectric loading is used which reduces the Q. It is possible that so little improvement can be realised with the dielectric section it may be better to do away with it. The relativity correction term S_0 is quite small and again affected by the dielectric.

The mean thrust is predicted as 1.72 grms for a mean power of 850 watts. Power is supplied as half wave rectified; thus the peak power is 2400 watts and the peak thrust is 4.86 grms.

4.3 Design Review and Comment

The design is well considered and carefully constructed around easily available parts. This inevitably leads to some compromises which are in general obvious and do not effect the demonstration of viability. The main limitation as far as testing is concerned is the limited cooling which severely limits test times and the pulsed operation. The thermally imposed limitation of 50 sec operation leaves little time for a steady state condition to be achieved. So much of the test time is not under steady state conditions, leading to variable results. The pulsed operation, due to the half wave power rectification, makes interpretation of the test results difficult because of the EMC noise introduced into the measurement system.

The theoretical model of the air section of the cavity is evidence of a careful approach. However this was not carried through to the design of the dielectric section. It turns out, though not explained, that the dielectric was a given and the air section matched to it. This results in some confusion, which has no effect on the operation, between the schematic of figure 1 and the as built dimensions of figure 3 (Author's Comment - Figure 1 will be clarified). In fact a tapered dielectric section would probably give the best results. The RF performance and the tuning of the cavity has been carefully carried out and is well documented. Some attention has been given to the EMC design so that the effects of the high currents on the sensitive measurement amplifiers are minimised.

Some consideration needs to be given as to how the design could be made suitable for space operation. The RF cavity design can easily be adapted; the only note of caution would be multipaction in the area of the dielectric. There is no space qualified magnetron. Qualifying a magnetron for space would require a special development in its own right. There is ample experience of qualifying TWTs for space radar applications which are similar to this application. This would give a good start for the technology for the heater/cathode assembly and the anode/RF output assembly. Most space qualified tubes of this power are direct radiation cooled. If higher powers were to be used a Stirling cycle or liquid magnetically pumped cooler would probably be needed. The thermal design is likely to be the most difficult task. It is assumed that the magnetron would be run from a DC supply which, may be pulsed to keep within the thermal design constraints. Design of high power, high voltage DC power supplies for TWTs and ion engines are well understood but require much attention to the detail.

It is suggested that the next model of the Thruster moves some way to incorporating some of the features of the final space version. A suggestion might be continuous long pulsed operation, DC supply and a specifically designed dielectric section or none at all. Cooling could be via a conductive plate radiating to a liquid cooled cold plate. In air this arrangement would have to be arranged so that convection currents did not affect the results but would be clear of such effects in vacuum.

4.4 Test Programme Review and Comment

The test programme breaks down into five parts - the design verification of the Thruster, performance testing using a balance and load cell, a balance and precision scales, direct measurement with a precision scales and pulse measurements using a load cell and storage oscilloscope. During the performance tests considerable effort has been put into the investigation of spurious effects.

The design verification of the Thruster shows good agreement with the design predictions and the cavity could be easily optimised for RF performance. Variations in measured Q are more worrying as they contribute directly to the thrust performance and should be better and more reliably quantified. The other effect which could mask the true Thruster performance is striking delay and the thermal detuning of the magnetron due to temperature effects. These last for a significant proportion of the operating cycle. A magnetron arrangement which could operate for considerably longer would eliminate these uncertainties. These effects do not affect the demonstrating of principle but rather the confirmation of performance predictions.

A load cell measures pressure which is then converted to mass by a calibration factor. It does not allow for any linear displacement of the measured object. In order to achieve the sensitivity required the weight of the Thruster is offset by a counter balance. Testing is always going to be difficult as measurements of 1 part in 10^4 are required. The optimisation of the Thruster spurious effects due to mechanical thermal expansion, cooling fan operation, buoyancy, outgassing, magnetic effects and electromagnetic effects due to the high currents involved on the measurement electronics were all considered. The technique developed of making three runs - normal, inverted and zero thrust - considerably reduces many of the spurious effects. One effect which did not seem to be covered by these tests is magnetic effects with metal objects in the test rig and in its vicinity. Further explanation by the author demonstrated that the testing was performed in different locations and the various test configurations had very different magnetic characteristics. Thus it is unlikely that local magnetic effects are significant although these were not specifically tested for.

Replacing the load cell with a precision balance opens a different aspect of measuring thrust. The precision balance measures the displacement of a spring due to the thrust applied. In doing so it allows the Thruster to move. This opens up the possibility of measuring the momentum change due to the Thruster directly as a rate of change of force and differentiating this from normal forces produced by other effects such as magnetic forces. Measurements made with the Thruster acting directly on the scales allows measurements to be made with a different spring constant. Whilst this arrangement is less sensitive, a different differential between momentum and directly acting forces is obtained. Using this approach many of the potential spurious effects with the load cell arrangement can be eliminated. The theory of this measurement technique is well covered.

The conversion of the load cell balance to integrate over time was used to compare the original measurements with the later ones. The considerable EMC noise introduced into the measurement system makes it difficult to be certain that the thrust measured is not a spurious effect. The suggestion of using a DC supply to the magnetron would probably make it much easier to remove spurious effects.

Because of the novel nature of the physical principles involved after another model has been built which is easier to test it will be necessary to have this measured by an independent test house in an independently constructed test rig.

4.5 Test Results Review and Comment

The basic Thruster performance measurements made using the various test techniques give a nominal peak value of between 1.5 and 1.9 grms. This agrees quite well with the theoretical value of 1.72 grms. This is further confirmed by the graphs shown in figure 21.

The time constants of the load cell measurements will interact with the thrust measurements. From figure 8 it appears that the time of the Thruster operation is unfortunately of the same order as the measurement time constant, presumably due to integration in the electronics. Thus the maximum thrust can not be read off from the graph. This must question the accuracy of the thrust measured. This could be overcome by lengthening the Thruster on time.

The later technique of attempting to measure the thrust pulses could also overcome this problem but the noise in the measurement, see figure 27, due to EMC effects makes it very difficult to evaluate the results. The AC coupling of the measurement electronics again introduces the question of time constants.

The thrust variation with RF tuning shows that the profile, as the Thruster is tuned through resonance, is very much as expected and in line with the power delivered.

A considerable amount of effort has been given to the identification and elimination of possible spurious effects. Effects due to the buoyancy of the air in the enclosure have been satisfactorily eliminated. Temperature effects in the mechanical arrangement are also considered to have been eliminated.

The electromagnetic effects due to the high currents and their interaction with magnetic materials in the test equipment are difficult to eliminate, as are their effect on the sensitive electronics of the measurement system. It is suggested that some measurements of the magnet field and its position due to the current pulses could be made, allowing its interaction with the test equipment to be estimated. This information can then be used to improve the measuring equipment by reducing the EMC generated noise.

4.6 Conclusions Review and Comment

The comments on the conclusions of section 5, below, assume that these are numbered 1 to 23.

1. The theory is fine but depends on the correct interpretation of the physics pertaining. This is always difficult when relativity is involved.
2. The expression follows from the theory.
3. This was thoroughly done.
4. This confirmed the design.
5. This confirmed the design.
6. This confirmed the design.
7. Repeatability of design was established.
8. Measured results indicated a difference but could have been due to spurious effects which were then investigated.
9. Reasonable agreement was achieved in some of the tests but measurement difficulties with the pulsed operation of the Thruster detracted from the credibility of some of the results.
10. These tests were as expected.
11. Test results not included. (Author's Comment - This conclusion will be removed)
12. As expected.
13. As expected.
14. As expected.
15. Interaction with magnetic material in the neighbourhood of the Thruster has now been considered and is unlikely to have an effect.
16. As expected.
17. Not fully explained in the report but correct.
18. Useful for the elimination of spurious effects.
19. A better demonstration of performance than the first set of tests.
20. Useful demonstration of the effects of spurious forces with perhaps the exception of magnetic effects.
21. Difficult to confirm because of the EMC induced noise in the test system.
22. Ditto.
23. "Totally" (Author's Comment - Totally will be deleted) is a bit strong without independent verification of the test results.

5. CONCLUSIONS AND RECOMMENDATIONS

I have found this a most interesting piece of work to review and am most impressed by the novelty of the invention.

I do not feel qualified to pronounce upon the physical principles exploited by the invention but I understand others have done so. I would recommend that an explanation of these principles should be included in the report (Author's Comment - An explanation will be included). Accepting these as valid I have been able to check the theory and design of the Thruster which is well described and appears valid.

The Thruster design is quite practical and can be adapted to operate in a space environment using established design practices. I have suggested that the next model incorporates some improvements to make measurements easier and go some way towards a space qualified design. A decision would also have to be made on the incorporation, or not, of an improved dielectric section. This next model would, I think, be somewhere between an elegant breadboard and an engineering model.

Some improvement to the test arrangement needs to be made to reduce the EMC effects and to choose suitable time constants which are compatible with the Thruster operation. Some of this work could be done with the present Thruster.

Much work has already been done on removing spurious effects from the measurements. With improvements in the Thruster design and measurement technique it should be possible to demonstrate good agreement between the theoretical and measured performance without the distraction of many of the spurious effects. It is suggested that some further work be done with the present configuration to eliminate magnet effects.

The applications of a practical thruster which does not use propellant will be many and varied. The mass savings achieved can be considerable and the consequential commercial advantages of great value. Some of these are touched on in the reference material and lead me to the conclusion that further work on the Thruster must be undertaken. This should take the form of an improved model and a further test programme, part of which should include an independent test of performance.