EmDrive Thrust/Load Characteristics. Theory, Experimental Results and a Moon Mission.

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Abstract

EmDrive is the name given to a new propellant-less propulsion technology which has its origins in cold war missile research. The subsequent development work has been shrouded in secrecy and public controversy, and has therefore been largely overlooked by the wider propulsion community. With the technology now maturing, it is time for EmDrive to come out of the shadows.

This paper examines one aspect of EmDrive which has caused many experimental problems. The search for thrust from a variety of EmDrive type thrusters, operating at safe, low microwave power levels, has led to very sensitive thrust measurements being attempted. These experiments mainly use torsional balances. In practice this has inevitably led to no thrust being measured. The problem is that, unlike a rocket, but more like an electrical machine, EmDrive requires to work against a load before thrust can be measured. The theory behind this statement is given and a simple idealised experiment is described. The results for overload, optimum load and no load conditions are predicted.

An experiment was set up using the original SPR Flight Thruster, recovered after years of testing with two other research groups. The thruster was mounted on a counterbalanced beam with thrust and load measured on a precision electronic balance. A set of experimental results, originally revealed in a lecture given at The UK Defence Academy Shrivenham, are presented. The experiment confirmed the predictions. This is not surprising, as the original radiation pressure theory behind the EmDrive concept is firmly based on classic physics, and complies with the laws of Conservation of Momentum and Energy.

The implication of this result is that EmDrive will not necessarily accelerate a spacecraft, when in a true free-space orbital environment, unless steps are taken to introduce a load vector. It further illustrates that in-orbit tests, using a single EmDrive thruster, will give anomalous results. However when EmDrive is applied to a direct flight to the Moon, where a gravity load vector is present, preliminary mission analysis gives very encouraging predictions.

The results of a subsequent study of a manned Moon mission are presented.

List of Abbreviations and Symbols

2G	Second Generation
3G	Third Generation
a	Acceleration
AM	Amplitude Modulation
CW	Continuous Wave
F	Net Force
F_g	Radiation Force
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
M	Mass
PSV	Personal Space Vehicle
Q	Quality Factor for a resonant circuit
Q_i	Input circuit Q
Q_L	Loaded Cavity Q
Q_u	Unloaded Cavity Q
R	Reaction Force

SPR Satellite Propulsion Research Ltd

SSPA Solid state power amplifier

T Thrust

TWTA Travelling Wave Tube Amplifier

V_g Group Velocity

1.Introduction

This paper reports on a second programme of tests carried out on the SPR C-Band Flight Thruster. The first series of tests, together with the design and development of the thruster was fully documented in December 2017 [1]. The original version of [1] was issued as a test report in July 2010, as part of the deliverable documentation for the Contract with Boeing, under Purchase Contract No 9CS1145H. This contract was subject to an Export Licence issued by the UK Export Control Organisation in January 2008, and to a Technical Assistance Agreement issued by the US State Department in May 2009.

The Flight Thruster is illustrated in Fig.1.

Fig.1

Since the original test programme was completed at SPR, the Flight Thruster was loaned to two independent UK research groups, who carried out a number of investigations and tests, using different types of test equipment. Also a number of research groups in other countries have attempted to design and test EmDrive type thrusters.

After a review of the mixed results from all of these programmes, it was decided to carry out this second series of tests, specifically to illustrate the basic theory of EmDrive operation, rather than just to determine the Thruster performance.

In addition, because the basic theory implies that a continuous EmDrive thruster will not accelerate a spacecraft in a free-space environment without an additional load vector, the results of a manned moon mission analysis are presented. In this analysis, a direct flight path is assumed enabling the varying Earth and Moon gravity vectors to be utilised as load vectors on the EmDrive thrusters.

2.Theory

EmDrive is a new class of electrical machine that produces a force which is termed Thrust. Microwave energy is directly converted into Thrust without the need for a propellant. The Thrust results from the difference in radiation pressure on each end plate of a truncated conical resonant cavity. This radiation pressure difference is a result of the different group velocities of the travelling wave, at each end of the cavity. The theory was originally introduced in 2005 [2] and updated in 2015[3]. This paper now adds to that theory.

Some of the subsequent discussion of the theory has addressed EmDrive as if it were a device upon which a force acts, with the source of this force attributed to a number of different new principles of Physics. This has led to much confusion and misguided experimentation.

The theory of operation of EmDrive, upon which all design development and tests were carried out by SPR, is based on classic physics. At its most fundamental, the theory assumes that the principles of Conservation of Momentum and Conservation of Energy are not compromised. This second series of tests is aimed at demonstrating compliance with these principles.

The Thrust produced by the difference between the radiation pressure forces will give rise to an equal and opposite Reaction Force. The difference between the two forces is best illustrated by assuming the thruster is in free space, as illustrated in fig 2.

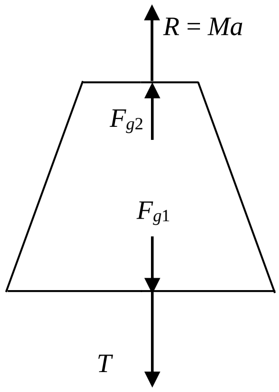

Fig 2. Thruster Force Diagram

The net force (F) created within the thruster is given by the basic equation

$$F = Q_u\left(F_{g1} - F_{g2}\right) \qquad (1)$$

where F_{g1} and F_{g2} are the radiation forces caused by group velocities V_{g1} and V_{g2} at the two ends of the thruster, and Q_u is the unloaded Q of the cavity, and is defined as stored energy divided by energy lost per cycle.

This internal force F is measured by an outside observer as the Thrust T, a force acting against the observer in the direction shown. It is important to emphasise that Thrust is a force generated by EmDrive, just as an electrical machine generates force. Thrust is not an outside force, originating from new physics, acting on the cavity. Indeed in [4], Cullen shows that the basic equation for radiation force, is derived in the same way that the basic force equation for an electrical machine is derived. This paper, [4] was the original paper from which the radiation pressure theory of EmDrive operation was derived.

It was discovered many years later, that a colleague of Cullen had gone on to expand his microwave wattmeter experiments to increase the measured force, by use of a resonant cavity [5]. This is also how EmDrive generates useful levels of thrust. Very high levels of symmetrical forces are regularly generated in the superconducting cavities of many particle accelerators, used in high energy physics experiments.

Newton's laws state that T must be opposed by an equal and opposite reaction force R, such that

$$R = Ma \qquad (2)$$

where M = mass of the thruster
a = acceleration of the thruster in the direction shown.

Clearly, where T and R exist, they will cancel out any attempt to measure them by simply placing the thruster on a balance. This was demonstrated by the results of the calibration tests carried out in [1] and during many subsequent test programmes.

Therefore to successfully measure Thrust, the thruster needs to accelerate against the restraining force of a balance, in accordance with the principle of Conservation of Momentum. However if there is no load on the thruster, i.e. no initial restraining force from the balance, all initial thrust will be instantly converted to kinetic energy, causing the stored energy in the cavity to approach zero. This will cause the Thrust to approach zero, in accordance with the basic Thrust equation, and demonstrates compliance with the Principle of the Conservation Of Energy.

Therefore a test which subjects the thruster to a zero load condition will measure zero Thrust or zero Reaction Force. Similarly if the load is increased to a value above the Reaction Force, resulting in no acceleration, no Thrust or Reaction Force will be measured.

Note that if thrust cannot be generated where there is no load applied, then an unmodified EmDrive Thruster will not work in a true free space environment. There are a number of modifications that can be applied, and one is to use Amplitude Modulation. This was addressed during the second series of tests.

3.Thruster Design

At the heart of an EmDrive thruster is an asymmetric microwave cavity with very high Q values. Successful design of this cavity requires a numerical software model which solves standard microwave engineering equations, for successive elements of the cavity along the central axis. This is the basis of the TWTA design revolution, which finally enabled reliable designs to be produced during the early years of communications satellite development.

SPR has developed design software using 0.1 mm elements which produces accurate models for all the

different modes built and tested over a number of years. The equations solved give the guide wavelength and wave impedance for each increment. The standard equations for both rectangular and circular waveguides and both TM and TE modes are given in [6]. The guide wavelengths are integrated over the full axial length and the calculations are iterated to give the resonant frequency at the required number of half wavelengths for the selected mode. Fig.3 gives a plot of the guide wavelength against axial position along the cavity, for the Flight Thruster.

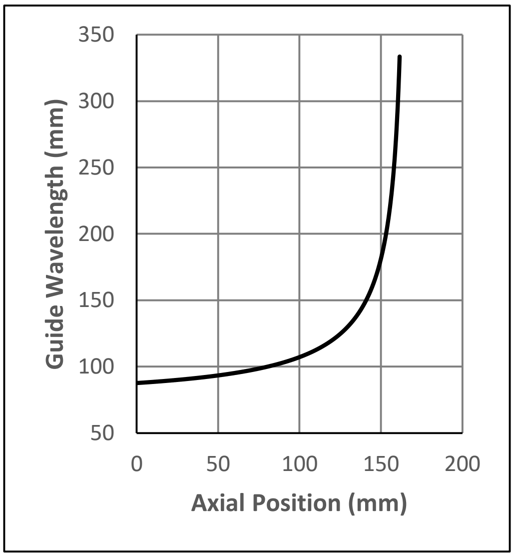

Fig.3. Flight Thruster Guide Wavelength

The plot shows the rapid increase in guide wavelength as the narrow end of the cavity is approached and the group velocity drops towards zero.

Clearly the model assumes that the geometry and machining tolerances during cavity manufacture are such that at any point across the wave-front, the path length between reflection points on each end plate are equal. A simplified view is that the Q of the cavity equals the number of times that a full power wave-front traverses the cavity axis. For a Q value of 50,000 and a path length of 160 mm this implies an accuracy of better than three microns. In practice the relationship between machining tolerances and Q is very complex, and with correct plate alignment, the Flight Thruster achieved a Q of 55,000, with a specified machining tolerance of 0.1 mm [1]

To achieve such accuracy the end plates clearly cannot be flat, as the path length difference between the side walls and the central axis would be excessive, and lead to an unacceptably low Q value.

Three different circular cavity geometries have been tested, each giving satisfactory Q levels, and are shown in Figs 4a to 4c.

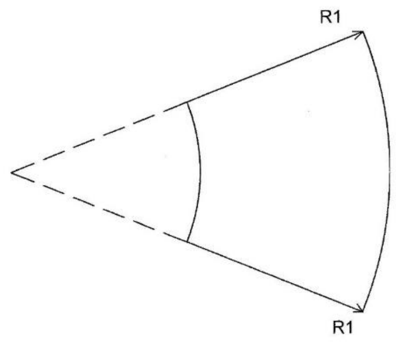

Fig.4a

Fig. 4a shows a convex small plate and a concave large plate, with all path lengths being equal fractions of the same radius R_1. This is the simplest cavity geometry.

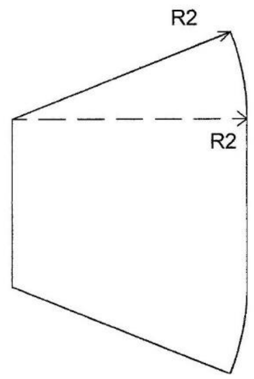

Fig. 4b

Fig. 4b shows the central part of this cavity is cylindrical, with a diameter equal to the diameter of the small end plate. The tapered annular section terminates in a curved large end plate section, with a radius R_2. This is the geometry used for the flight thruster.

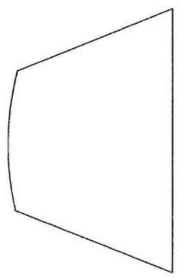

Fig.4c

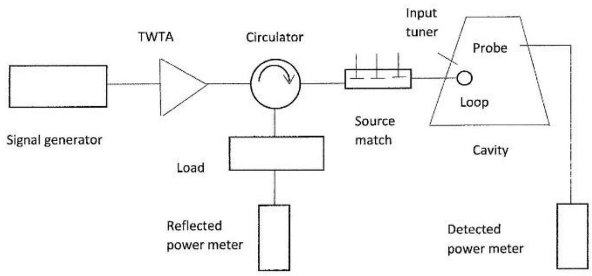

Fig.5

Fig. 4c shows a geometry employed in superconducting cavities, which enables the large end plate to be flat. The concave shape of the small end plate is complex, and calculated to maintain equal path length across the wave-front [7].

To obtain the necessary high Q values to produce viable thrust, it has been found that not only must high machining tolerances be specified, but that the end plates must incorporate the capability for accurate alignment. In the flight thruster this was achieved with careful shimming between end plates and the cavity wall section. In superconducting cavities this is achieved with piezo-electric elements.

The need for accurate end plate alignment can be seen from the consideration of the simple geometry of two parallel mirrors, and the large number of paths in a resonant system. When applied to the Flight Thruster with a Q value of 55,000, a minimum radius of 50mm, and an axial length of 160mm, the angular alignment required for no distortion is less than one thousandth of a degree.

Once a high Q cavity has been achieved, it is then necessary to introduce into the cavity the power available at the signal source. For the Flight Thruster, the source was a digital signal generator and a 500 W TWTA.

Fig. 5 shows the essential elements of a complete thruster. To ensure an optimum transfer of power, the source impedance, usually 50 ohm, must be matched to the input circuit impedance. The matching element may take a number of forms, but for laboratory testing, is generally a 3 stub tuner. The input circuit, whether a loop, a slot or a post will need a tuning element to ensure that at the resonant frequency, the input impedance is matched to the wave impedance, at the input position along the cavity axis. The wave impedance is determined by the design software. With careful design, the source matching can also be achieved by the input tuner.

Finally the actual power in the cavity, as opposed to merely to the power dissipated in the input circuit, needs to be monitored by a probe positioned at an E field maximum. The position of the probe is again determined by the design software.

This detected power probe is designed to monitor the power propagating in the cavity by use of a loosely coupled, broadband stub, monitoring the power level at least 20 dB down on actual power. In this way the cavity Q is not significantly loaded by the probe, but enables the loaded Q of the cavity to be accurately measured. Q measurement is by the industry standard method of sweeping across the cavity resonance, and measuring the bandwidth 3 dB down from the peak. Note that it is essential to sweep at a sufficiently low sweep rate, to allow the dwell of the data points sufficient time to exceed the time constant of the high Q cavity. A factor of 10 is typically used.

Microwave circuit theory states that to ensure optimum power transfer from the input circuit to the cavity, their Q values should be equal. The measured Q of the cavity, loaded by the coupling to the input circuit is given by:

$$\frac{1}{Q_L} = \frac{1}{Qu} + \frac{1}{Qi} \qquad (3)$$

Where Q_L is the loaded Q measured by test, Q_u is the unloaded Q of the cavity and Q_i is the Q of the input circuit when correctly matched at the resonant frequency.

A second power meter is used to monitor the power reflected from the cavity input via the circulator and load. It is essential to use both power measurements when tuning and aligning the cavity. If the input

circuit is not closely coupled to the cavity, simply optimising the input tuning for maximum return loss will only ensure that all the power is dissipated in the input circuit, and none is transferred to the cavity. Therefore no thrust will be measured. A guide to optimum tuning is when the return loss at resonance, is half the maximum, and the reflected power characteristic is a mirror image of the detected power characteristic.

Tuning a poorly designed cavity for the resonance of the input circuit rather than the cavity itself is a common mistake. A remarkable example of this occurred on the flagship ESA project OLYMPUS, which was the first large European geostationary communications satellite. The local oscillator unit, which provided the reference signal for the whole payload, used a cavity oscillator which was unstable for the first eight years of the project. In fact the cavity would happily resonate, within specification, at room temperature, without the end plate. Once the problem became apparent, during temperature testing of the whole payload, the cavity was redesigned and the problem went away. The satellite was eventually launched in 1989.

An independent method of verifying that power is correctly transferred to the cavity is to monitor the temperature rise of the cavity wall close to the input, and to compare it with end plate temperatures. Excessive temperature rise at the input indicates high losses in the input circuit. Comparing thermal dissipation at the two end plates can verify the ratio of forces, and thus the basic EmDrive theory of operation. This verification process was described in [1], where the predicted ratio was 0.66 and the measured ratio was found to be 0.69.

For a flight qualified thruster both the reflected power and detected power data is used for initial start-up of the thruster, and for control of the source frequency over the full power and environmental temperature ranges.

For laboratory testing, initial thruster start-up is controlled by a frequency sweep algorithm, which is programmed according to initial temperature and final power level. This is more fully described in [1], and is essential, because the thermal characteristics of the input circuit, and the cavity itself, are very different.

For an input circuit employing a tuned loop, the high Q of the circuit means that very high circulating currents exist in the loop. The cross section of the loop must be large enough to minimise the losses, and thus the temperature rise. Nevertheless, once power is flowing through the loop, the conductor temperature will rise rapidly and, if there is no initial frequency offset, the loop resonant frequency will not match that of the cavity, and no power will flow into the cavity. This is an inherently unstable condition, and the sweep algorithm must initially maintain resonance and coupling, until the cavity temperature characteristic predominates. The cavity thermal response is much slower and is in the opposite direction to that of the input loop. Design of the frequency control algorithm is therefore a complex and time consuming process, as it relies on obtaining a lot of measured data.

4. Thruster Performance

During the eight year loan period, the performance of the thruster decreased, with a lowered cavity Q value, due to a known misalignment of the end plates. Comparing the frequency characteristics of the cavity measured in 2010 and 2018, shown in Fig.6 and Fig.7, it can be seen that the misalignment caused a second resonance peak. This led to the unloaded Q value being reduced to 31,000 compared to the original value of 55,000.

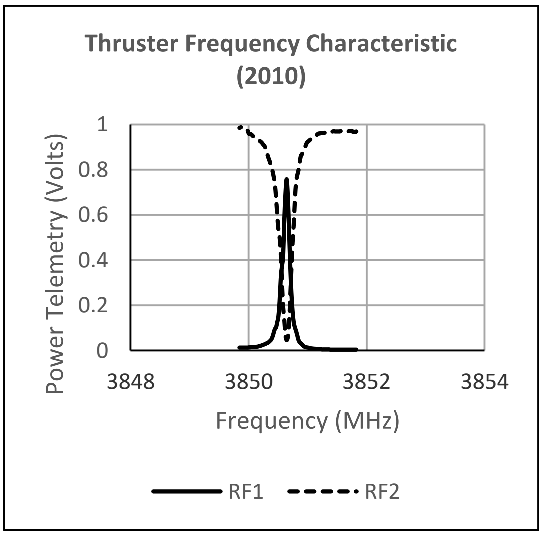

Fig. 6

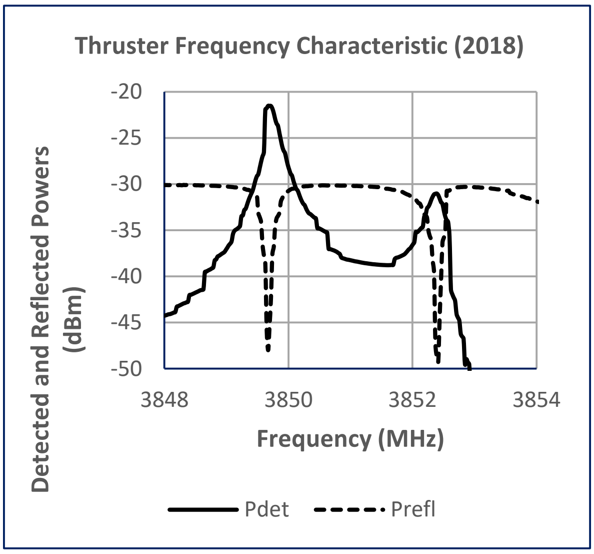

Fig.7

The plots of Thrust and detected Cavity power for a typical test run are shown in Fig.8, with a power on period of approximately 100 seconds. The Thrust and Power data sensors do not have synchronised sampling rates, leading to slight discrepancies in the time axis. The Power data has 1,038 points whilst the Thrust data has 355 points.

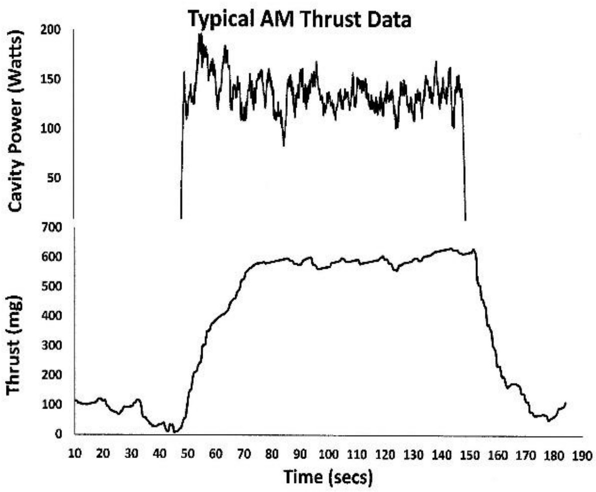

Fig.8

The Thrust plot gives a mean thrust of 506mg with a standard Deviation of 17.6mg, (29 sigma). Mean thrust is calculated by taking the average value of all the thrust data points during the power-on phase, and subtracting the average value of the data points during the before and after, power-off phases. This data processing method is retained for all Thrust and Reaction Force measurements.

The power plot shows the noise generated within the cavity due to deliberately modulating the input signal to the TWTA, and gives a mean value of 134 Watts

The mean specific thrust for this test was 37mN/kW compared to 326mN/kW for the mean of the original Flight Thruster test programme. This illustrates the significant effect of end plate misalignment, and shows the non-linear relationship between the unloaded Q value and end plate misalignment. Essentially, the Thrust equation (1) only directly applies when the end plates are correctly aligned.

The rise and fall times of the Thrust plot are due to the damped response of the balance beam, which has a total mass of 16 Kg. The longer rise time is also a result of a programmed, 10 second frequency sweep that is necessary to provide a stable acquisition of resonance, when the thermal responses of the input circuit and the cavity itself are significantly different in time and direction.

Fig.9 shows the initial thrust and power responses for a typical CW test, where the detected power steps can be more clearly seen as the loop thermal response corresponds to the frequency steps. The Thrust steps can also be seen to be following the cavity power response.

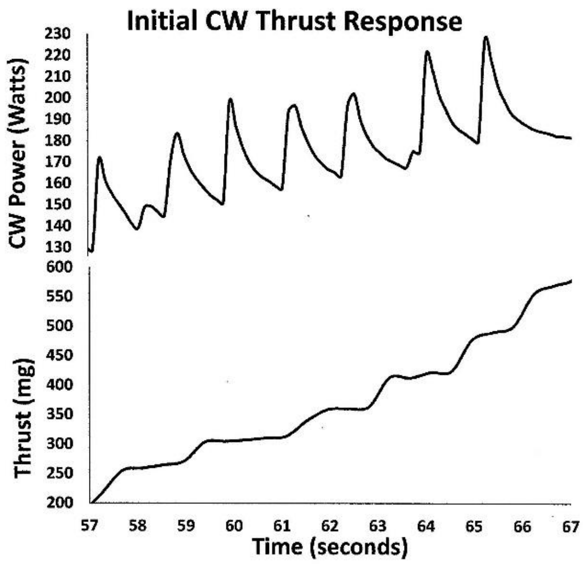

Fig.9

5. Test Balance

The beam balance is based on that used for the original experimental thruster programme and reported in [8]. The updated balance is illustrated in Fig.10.

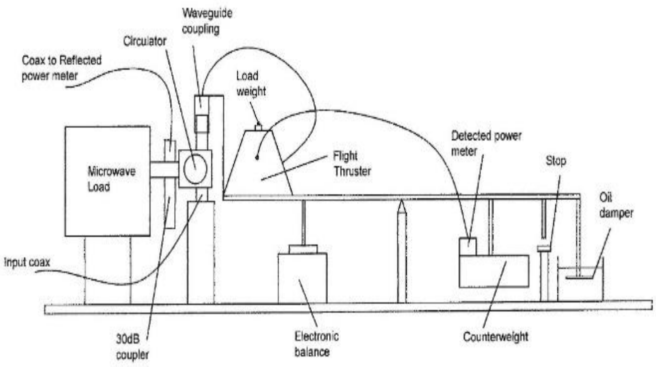

Fig.10

The balance can be used for measuring both Thrust and Reaction Force by a carefully offsetting the level of the beam, from the horizontal, by variation of the stop height. If the offset is kept very small, the calibration factor variation, which is checked before each test, is kept to an acceptable level. This is shown in Fig.11.

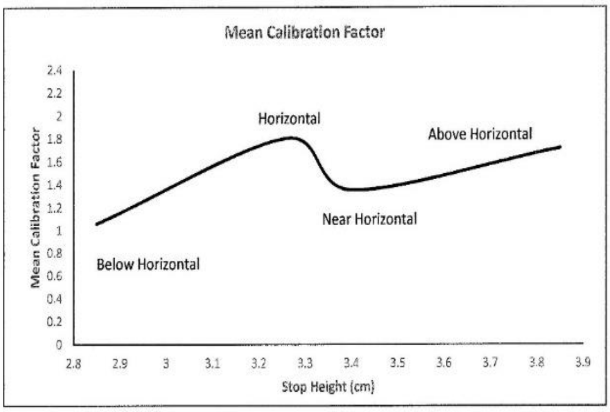

Fig. 11

With the Thruster mounted as shown in Fig.10, the Horizontal setting measures Reaction Force which is an upward force causing the balance reading to decrease. The Above and Below Horizontal settings measure Thrust, which is a downward force, causing the balance reading to increase. By setting the balance very near Horizontal, both Thrust and Reaction Force can be measured during the same test run.

To determine the balance noise due to spurious forces, caused by thermal and electromagnetic effects as well as any background vibrations, a routine test is carried out, where the thruster is tested off resonance, at typical input power levels. Thus although test conditions are as close to normal as possible, there is no contribution of either Thrust or Reaction Force. Fig. 12 gives a typical result. With the mean load force of 174mg, a noise Standard Deviation of 14mg was measured yielding a 12 sigma result.

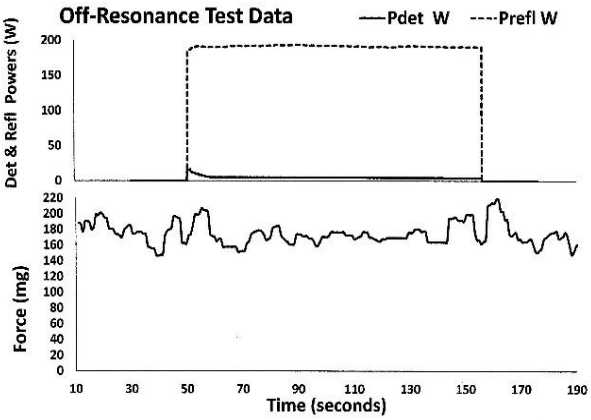

Fig 12

6.Thrust/Load and Reaction Force/Load Results

A series of 109 tests were carried out in the second Flight Thruster test programme. The tests included 26 high power, calibrated test runs, which were carried out to measure both Thrust and Reaction Force, with varying Load weights added to the top of the Thruster. The main object of these tests was to determine Thrust/load and Reaction Force/load characteristics for CW and AM inputs. To allow easy comparison of Thrust or Reaction Force data with applied loads, the values are given in mg.

After a series of modulation tests, a modulation of 300Hz square wave, was determined to be the optimum modulation for the mechanical response of the balance. It is interesting to note that the early experimental thruster, originally tested on this balance, and reported in [8], was powered by a commercial magnetron. This source had a DC high voltage input, derived from a half wave rectifier

circuit, giving an approximation to a 50Hz square wave AM on the microwave output.

The beam balance enables the load applied to the thruster to be varied by use of different balance weights on top of the Thruster. The input power to the Thruster was maintained close to a constant value for each set of test runs, to enable direct force measurements to be compared.

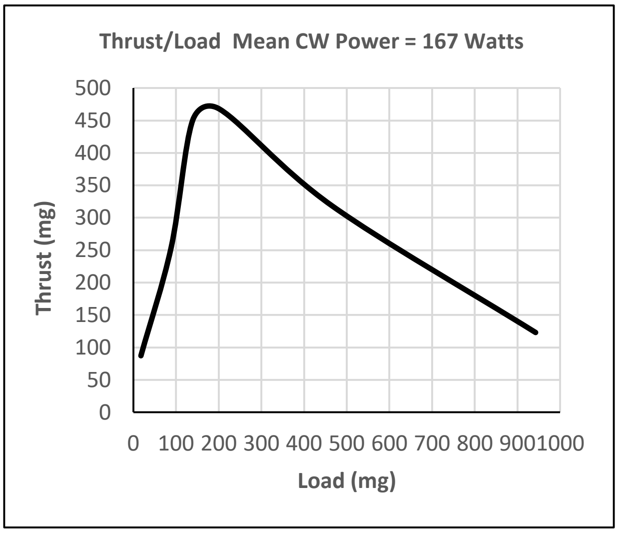

Fig. 13

Fig.13 shows the results from a set of 6 test runs with a mean CW power of 167 Watts. The balance was set to marginally Below Horizontal to enable Thrust to be measured. Thrust is in a downwards direction, therefore increasing the balance reading and being recorded as a positive value. The Plot clearly illustrates the theoretical prediction that Thrust will approach zero as the applied load approaches zero. Also as the applied load goes above the maximum Thrust measured, the thrust again approaches zero, as predicted by the theory. Maximum Thrust is 467mg at an applied load of 203mg.

Fig.14 shows the results from a set of 4 test runs with a mean CW power of 162 Watts. In this set the balance was set to exactly Horizontal, to enable Reaction Force to be measured. Clearly the Reaction force is now upwards, and therefore is measured as a reduction in balance readings and recorded as a negative value. Once again as the load approaches zero the Reaction Force goes to zero, whilst with increasing load, the Reaction Force is below the maximum value. The maximum Reaction Force is -195mg at an applied load of 157mg. In this run the beam lifted off the balance pan as it was below the lift-off limit. This means that the recorded value of the Reaction Force is necessarily

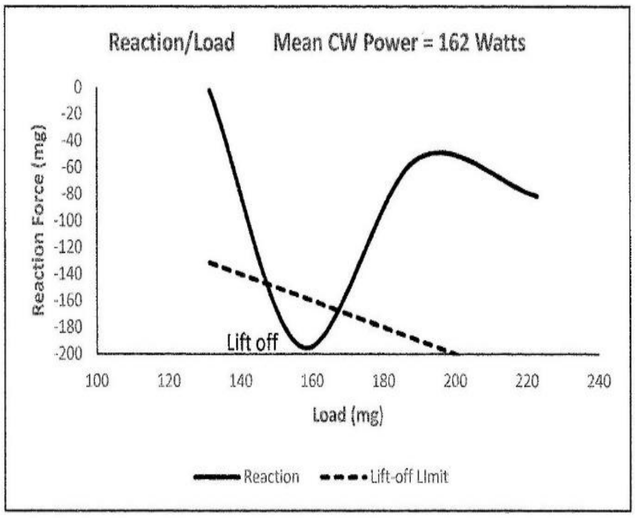

Fig.14

below the actual force. The Lift-off limit is shown in Fig.14 by plotting Reaction Force values equal to the applied load values.

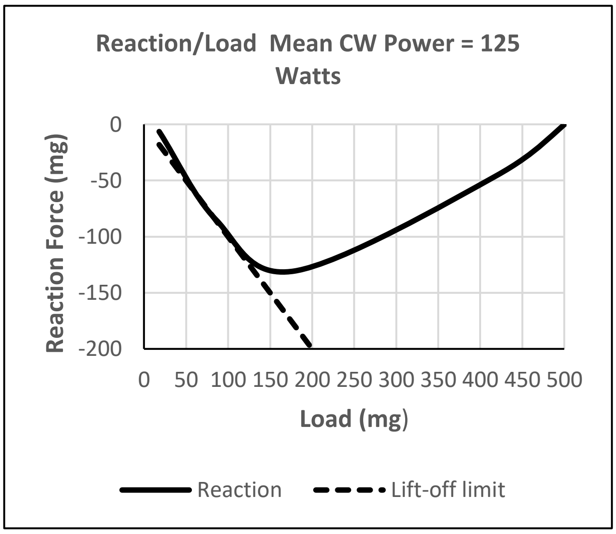

Fig.15

Fig.15 shows a second set of 5 Reaction Force measurements at a lower input power of 125 Watts. In this set, no lift off occurred, as the Reaction force values were all below the lift-off limit, and so the data set has no anomaly. Once again the plot approaches zero as the load approaches each end of the range.

Fig.16 shows the effect of AM modulation on the Thrust/Load characteristic for a mean input power of

155 Watts. The 7 test runs show an approximate level value of 300mg over the load range of 51mg to 944mg with two peak values above 500mg, at 83mg and 164mg loads. These peaks are in the same load range of maximum Thrusts and Reaction Forces shown in the CW results.

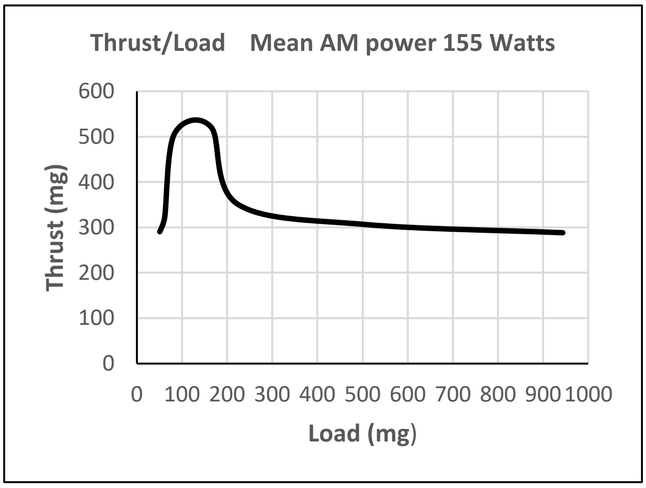

Fig.16

The Reaction Force results from the final set of 4 AM test runs, with a mean power of182 Watts, are shown in Fig.17. The higher power tests produced a lift-off at a load of 29mg with zero Reaction Force being approached at 280 mg load. All AM tests used a square wave modulation at 300Hz.

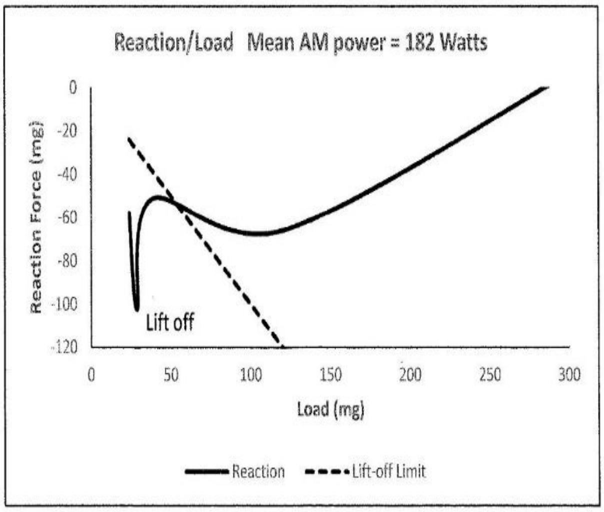

Fig.17

7. Personal Space Vehicle (PSV)

Following the revival of interest in manned Moon missions, SPR were invited to carry out a design study and mission analysis, to determine the minimum vehicle required to fly 3 men to the Moon and to safely return them back to Earth. The eventual application is envisioned to be Space Tourism, so a benign flight environment was a primary design aim. The result was the PSV described as follows.

The 10.4 Tonne, 9m diameter PSV, illustrated in fig.18,is a fully reusable vehicle, designed specifically for Moon landing and Earth return flights. It is capable of carrying a 4.5 Tonne manned capsule on top of the vehicle, or a cargo slung underneath the vehicle. The capsule would be designed for a 3 man crew, with a standard docking hatch at the nose of the capsule, and a further hatch and folding ladder in the side of the capsule, for access to the Moon surface. The docking hatch would allow for crew rescue during trans-lunar phases of the flight, with capsule separation and parachute recovery for atmospheric abort scenarios.

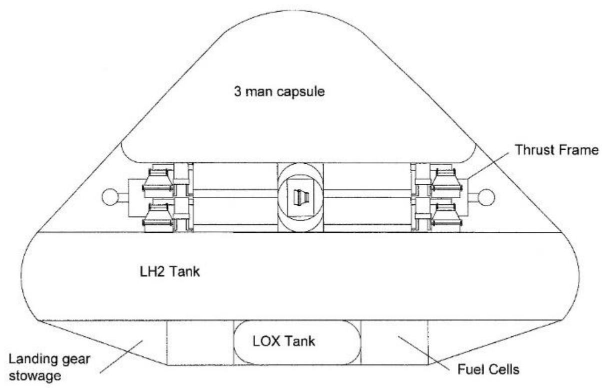

Fig.18

A critical design feature is the relatively low technology used in the airframe manufacture. This is a result of the low acceleration that the vehicle is subjected to, (max 0.01g) and the low velocity through the lower parts of the Earth's atmosphere, (max 67mph up to 30 miles altitude.) Thus mechanical and thermal stresses are low enough for sports car technology, rather than the normal spacecraft technology employed on current programmes and result in a gentle flight for tourist astronauts.

However any manned flights will still be subject to the regulatory safety and reliability requirements for manned spacecraft. This will include the requirement for full redundancy of the critical power and propulsion systems.

Four third generation (3G), high Q, EmDrive thrusters provide the primary propulsion for lift and acceleration of the PSV. This superconducting technology is described in [7]. They operate at 950 MHz in TE211 mode. Each thruster comprises two cavities, each continuously rated at 8.5kW, which operate in pulsed mode, to enable Doppler compensation to be applied sequentially by the frequency and axial length control system. They give a specific thrust of 3,857N/kW at a maximum acceleration of $0.1 m/s^2$.The thrusters operate in dual redundancy. A 3G cavity is illustrated in Fig. 19 and its operation is fully described in [7].

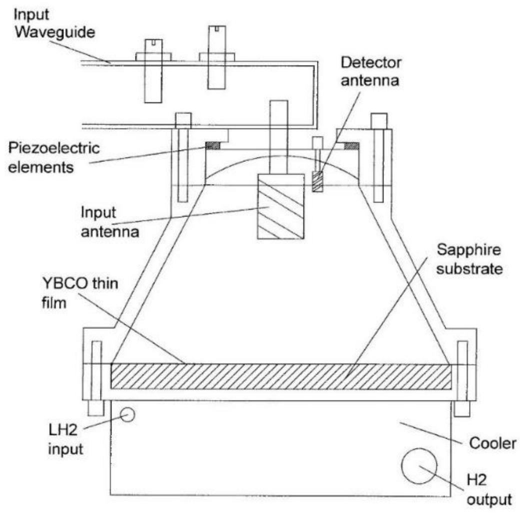

Fig.19

Pitch and Yaw control is given by variation of thrust from the four 3G thrusters, whilst Roll control, when full primary propulsion is operating, is given by four, second generation (2G) thrusters, each mounted on a single-plane, gimbal mechanism. These thrusters do not have Doppler compensation as the Q value and acceleration requirements are lower. Under the failure of two of the primary thrusters, the 2G thrusters will also give pitch or yaw control. During the cruise phase of the mission, when primary propulsion is off, the 2G thrusters provide full 3-axis attitude control.

Liquid Hydrogen (LH2) is held in dual redundant tanks with a nominal volume of 43,000 litres, covered in a thick thermal insulation to minimise boil-off whilst on the Moon's surface. Dual redundant fuel cells provide the electrical power to the SSPAs, and are fed by a fraction of the Hydrogen gas, which is boiled off from the cavity cooling. Oxygen, stored as liquid Oxygen (LOX) held in two 280 litre tanks is also required for the fuel cells.

The lower section of the PSV also provides stowage space for four retractable landing legs and an attachment rail for underslung cargo.

8.Manned Moon Mission

A simple mission analysis has been carried out to determine the major parameters of an Earth to Moon mission. The results of this analysis were used to update the PSV design. Initial inputs were the specific thrust of the primary EmDrive thrusters at a maximum acceleration of $0.1 m/s^2$. The mission was divided into 3 phases. The first is an acceleration up through the Earth's atmosphere, including a constant velocity period to limit drag, and into a trans-lunar flight path. The flight path will be designed so that any abort sequence would involve a Moon/Earth figure-of-eight orbit, enabling a rescue using a standby PSV. The rescue PSV would be fitted out for 4 man operation, and have a docking tunnel mounted in the nose of the manned module.

The initial climb is illustrated in Fig.20.

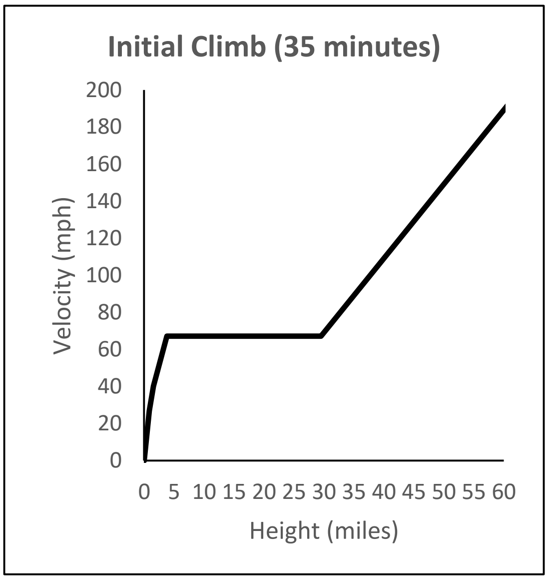

Fig.20

The 13 hour acceleration phase would be followed by a cruise phase, when the primary propulsion is only used for counteracting the much reduced gravity of the Earth. At the start of the cruise phase, Earth's gravity is .03m/s^2, compared to 9.81m/s^2 at the Earth's surface. The Crew will be have been effectively weightless for a few hours, and will be able to use the remaining flight time to adapt. The cruise phase lasts a further 11 hours and during this phase, the 2G attitude control thrusters will be used to rotate the spacecraft through 180 degrees. The velocity will be kept constant at 10,160 mph throughout the cruise phase.

The 3 phases of the outward flight are illustrated in Fig.21.

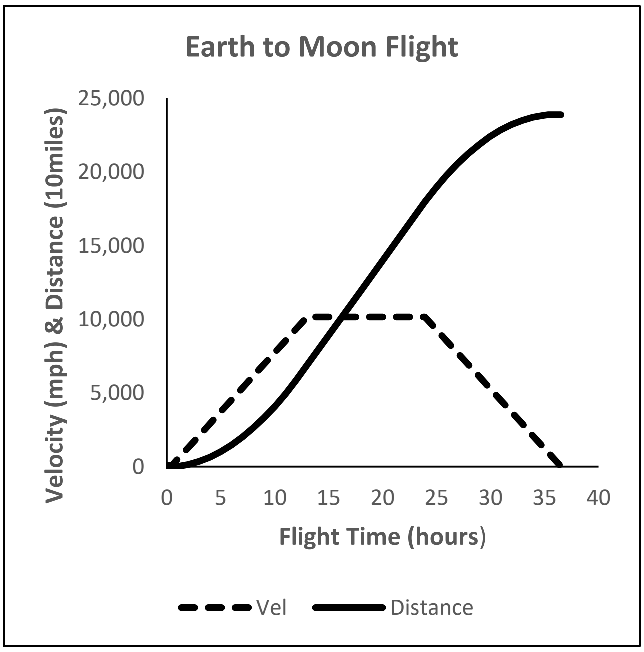

Fig.21

During the acceleration phase, the specific thrust of the primary thrusters will decrease as the gravity loading decreases. This is the effect of the Thrust/Load characteristic, described and verified in the earlier sections of this paper, and now illustrated in an actual mission analysis. The pulse modulation of the 3G thrusters will be optimised for the decreasing gravity load and the input power to the thrusters will be lowered to maintain optimum acceleration. The resulting Specific Thrust and Earth's gravity are plotted in Fig.22.

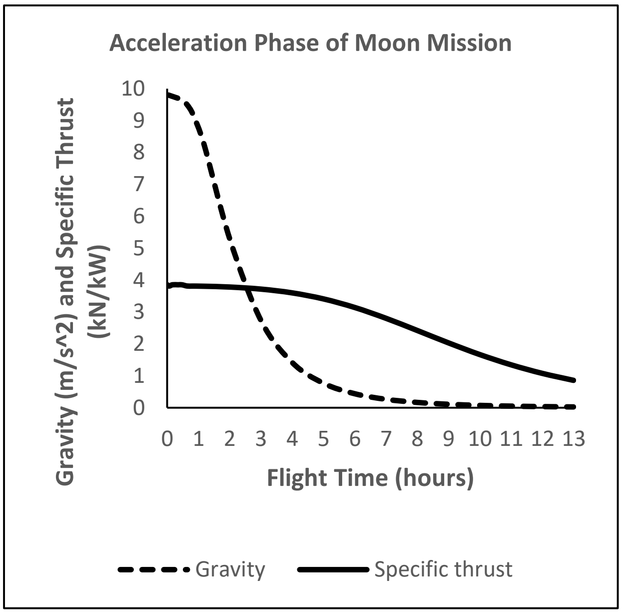

Fig.22

Rotation of the spacecraft during the cruise phase, will enable the primary thrusters to be used for deceleration, which will take a further 13 hours at a rate of - 0.1m/s^2. The final part of this phase will involve targeting of the landing site during the low speed vertical descent, followed by a hovering phase, to enable a precision landing close to the surface habitation modules. Access to the manned module will normally be via an aircraft type set of mobile steps. For the early manned flights, or in an emergency, egress would be via the folding ladder mounted on the inside of the side hatch. Following a surface stay of a few days, limited by the LH2 boil-off rate, the PSV would return with a full crew, on a flight path which is a mirror image of the outward flight. The total flight time for the outward and return flights would be 72 hours.

A cargo mission, carrying perhaps an inflatable habitation module, would require an extended hovering period, during which the primary propulsion will be used as a sky crane, to position the module for easy docking with existing modules. Once docked, the cargo rail underneath the PSV would release the module and the PSV would launch on its return flight.

9.Conclusions

Although the performance of the Flight Thruster was considerably reduced due to the known end plate misalignment, the thrust obtained was high enough to give test results well above noise. This avoided the long and tedious process of realignment using shims. The reduction in thrust clearly demonstrated the high sensitivity to end plate alignment.

Careful setting of the level of the balance beam enabled both Thrust and Reaction forces to be measured, thus supporting the basic radiation pressure theory of EmDrive operation.

The test results for the CW test runs show good agreement with the theory described in section 2 of this paper. In each set of results, the Thrust and Reaction Force values approach zero, at each end of the range of load values. This clearly supports the assertion that EmDrive obeys the Laws of Conservation of Momentum, and Conservation of Energy. This should come as no surprise, as these laws remain the basis of all accepted physics.

The application of Amplitude Modulation has been put forward as a method of enabling operation of EmDrive, when no Load is applied to the Thruster. Such circumstances can occur when the thrusters are operated in orbit. The test results support this concept, although the results are very dependent on input power and the mechanical response of the test balance. It must be emphasised that applications will need the modulation characteristics to be optimised for the input power to the thrusters, and the mass of the spacecraft being accelerated.

Another method of ensuring correct EmDrive operation in space, is to take advantage of gravity to provide a load on the thrusters. This is clearly illustrated in the flight path analysis for the manned Moon mission, where the specific thrust of the superconducting thrusters can be seen to be dependent on the gravity load.

The manned Moon mission study, which can be readily checked using the specific thrust values, gives a dramatic illustration of the efficiency that EmDrive can bring to any transportation application. If three men can be sent to the Moon, and brought back safely, in a 10 Tonne vehicle compared to a 3,000 Tonne Apollo vehicle, the future looks very different. Very low cost access to space, provided by EmDrive technology, will enable Solar Power Satellites and orbiting sunshades to solve global energy and climate change problems, as well as meeting future space exploration aspirations.

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