IAC-13,C4,P,44.p1,x17254

THE DYNAMIC OPERATON OF A HIGH Q EMDRIVE MICROWAVE THRUSTER

Roger Shawyer C.Eng. MIET. FRAeS

SPR Ltd UK sprltd@emdrive.com

ABSTRACT

The static operation of an EmDrive microwave thruster has once again been demonstrated by the Chinese experimental work reported in REF 1. The work repeats and enhances results obtained in earlier UK experiments, REF 2, and confirms the direct relation between specific thrust and Q factor of the cavity.

This paper considers the dynamic operation of a thruster with the very high Q factors obtained when a cavity employs superconducting technology. The very high specific thrusts resulting from such second generation (2G) devices must be subject to the law of conservation of energy. It follows therefore, that there must be a mechanism which limits the acceleration of any vehicle propelled by a 2G EmDrive thruster.

A mathematical model of a 2G thruster is described which illustrates such a mechanism. The results from the model illustrate the Doppler changes, which occur when a thruster is subject to acceleration. For Q factors around 1 x 10^9, the total Doppler shift moves the frequency outside the narrow resonant bandwidth of the cavity. This causes the loaded Q of the cavity, and thus the specific thrust, to decrease and therefore limits the acceleration.

A technique, employing pulse operation and dynamic control of the cavity length, is described which enables partial compensation for the effect. The resulting thruster design, employing YBCO superconducting walls and liquid hydrogen cooling, achieves a specific thrust of 1 Tonne per kW, provided the acceleration is limited 0.5m/s/s.

This low acceleration rate is compatible with primary in-orbit propulsion applications, and will be particularly suitable for deep space missions. For launch vehicles, the acceleration limitation is no obstacle; as a flight profile is proposed where high velocity is only achieved once clear of the atmosphere. Indeed the reusable, EmDrive propelled carrier vehicle itself, is only used to lift the payload to geostationary altitude, where an expendable propulsion module is used to provide orbital velocity. The resulting costs to geostationary orbit are predicted to be 130 times lower, when compared to current launch vehicles.

1.INTRODUCTION

The EmDrive microwave thruster is the world’s first propellantless thruster capable of providing specific thrust levels comparable to present ion engines. The theory and experimental results have been presented in a number of published papers by the author and the work has been repeated and extended by a group at NWPU in Xi’an, working under the direction of Professor Yang Juan. REF I and REF 2. An important result of the experimental work has been the confirmation that the specific thrust (mN/kW) is directly proportional to the Q factor of the resonant cavity. Thus a proportionate increase in the presently reported thrust levels, achieved using typical Q factors of 5x10^4, will be expected, when superconducting cavities with Q factors approaching 5x10^9 are used. Thus a typical room temperature specific thrust of 300mN/kW would be expected to increase to 30kN/kW.

These very high specific thrusts resulting from such second generation (2G) devices must be subject to the law of conservation of energy. It follows therefore, that there must be some mechanism, which limits the acceleration of any vehicle propelled by a 2G EmDrive thruster. Early theoretical work, REF 3, treated the problem as a transfer of stored energy to kinetic energy. This showed that acceleration would indeed be limited as the Q of the cavity increased to such high values.

The Q factor of the cavity is defined as the stored energy divided by the energy lost per cycle. Thus as stored energy is transferred to kinetic energy, the decrease in stored energy results in a decrease in Q factor. Thus as acceleration increases, Q decreases and thus thrust decreases. The performance of superconducting thrusters was predicted using this simple energy theory, but without identifying the actual mechanism. This paper corrects this situation by describing the Doppler shifts which cause a decrease in stored energy, but which, more importantly, cause the frequency of the propagating wave to move outside the narrow resonant bandwidth of the cavity.

2. MATHEMATICAL MODEL

The model calculates the Total Doppler Shift, which takes place within an EmDrive cavity, when the cavity experiences acceleration. The cavity is shown in Fig 1.

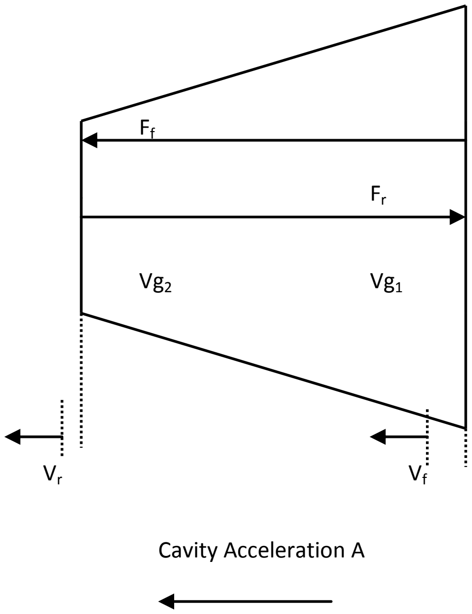


Fig.1

The cavity is supplied with a microwave frequency F_{res}, the resonant frequency of the cavity. Assume the EM wavefront propagates initially from the large end plate towards the small end plate. At the end of this forward transit, the wavefront is reflected at the small end plate. At this time, due to cavity acceleration, the cavity velocity has increased to V_r whereas the wavefront has a constant guide velocity of Vg_2. The relative addition of these velocities, gives the reflected wavefront a Doppler Shift, resulting in a reduced frequency F_r for the reverse transit.

On reaching the large end plate, the wavefront is again reflected and subjected to a second Doppler shift, resulting in the forward frequency F_f. The increase in frequency is calculated from the relative addition of the guide velocity Vg_1 and the new cavity velocity V_f.

The sequence of Doppler shifts at each reflection of the wavefront, will continue as the stored energy in the cavity builds up.

If the cavity acceleration A is zero, then the relative velocity between the large and small plates, at the time of wavefront reflection, is also zero. This will result in an overall zero Doppler shift.

However with a positive acceleration, the overall Doppler shift will be negative. This will lead to a reduction in stored energy in the cavity, and thus a reduction in Q, and a reduction in thrust. The kinetic energy gained by the cavity will be balanced by the stored energy lost by the cavity. This is EmDrive in “motor” mode.

With a negative acceleration, the overall Doppler shift will be positive. This will lead to an increase in stored energy, which is balanced by the loss of kinetic energy from the cavity. This is EmDrive in “generator” mode.

This dual mode of operation illustrates that EmDrive is a classic electrical machine. The “generator” mode offers a method of decelerating a vehicle.

3. MODEL EQUATIONS

The Transit time t_s (secs) for a wavefront to travel from one end of the cavity to the other is given by:

$$t_s = \frac{p}{2F_{res}} \qquad (1)$$

where p= number of halfwavelengths

F_{res}= Resonant frequency (Hz)

The cavity acceleration A (m/s/s) used in the model is given by:

$$A = \frac{Q_u A_{sim}}{50} \qquad (2)$$

Where A_{sim}= acceleration to be simulated.

and Q_u= unloaded Q

Clearly a full simulation would require Q_u forward and reverse transits, but as this would be impractical to model, a reduced number of transits is used, with the necessary increase in model acceleration A.

The 3dB bandwidth B (Hz) of the resonant cavity is given by:

$$B = \frac{F_{res}}{Q_u} \qquad (3)$$

For a Forward Transit, the velocity at reflection V_f (m/s) is given by

$$V_f = V_r + At \qquad (4)$$

The Reflected Frequency F_f (Hz) is given by:

$$F_f = F_r \left[\frac{1 + \frac{V_f}{V_{g1}}}{1 - \frac{V_f}{V_{g1}}} \right] \qquad (5)$$

For a Reverse Transit, the velocity at reflection V_r (m/s) is given by:

$$V_r = V_f + At_s \qquad (6)$$

The Reflected Frequency F_r (Hz) is given by:

$$F_r = F_f \left[\frac{1 - \frac{V_r}{V_{g2}}}{1 + \frac{V_r}{V_{g2}}} \right] \qquad (7)$$

The model solves the reflected frequency equations for 50 simulated forward and reverse transients, to give the Total Doppler Shift F_D (Hz)

Where $F_D = F_{f(n=50)} - F_{res}$ (8)

At the point where the total Doppler shift reaches $B/2$, the stored energy and hence thrust falls to half the static thrust. The model uses measured cavity data to predict the specific thrust as the total Doppler shift increases.

4. MODEL RESULTS FOR A FIRST GENERATION THRUSTER

The Dynamic performance of the non superconducting Flight Test model, manufactured and tested by SPR Ltd, and described in REF 3 was modelled with a cavity Qu = 50,000 and F_{res}=3.85 GHz.

Fig 2. Flight Thruster Dynamic Response for 1kW Input Power

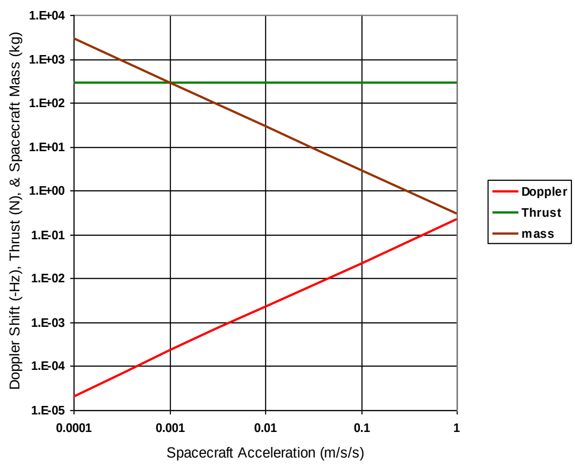


Fig 2 shows that for such a low Q factor, spacecraft acceleration levels up to 1m/s/s causes negligable Doppler shifts (<1Hz) such that no loss of Q is experienced, and therefore the thrust remains constant. To illustrate typical applications, the spacecraft mass is also plotted against acceleration, assuming 1kW of microwave input power to the thruster. It can therefore be concluded that for first generation, in-orbit propulsion applications, thrust will be constant throughout the total thrust period, and equal to the measured static thrust. This corrects the findings of earlier theoretical work, given in REF 2.

5. MODEL RESULTS FOR SECOND GENERATION THRUSTERS

Superconducting second generation thrusters were then modelled, cooled first with liquid nitrogen and then with liquid hydrogen. The thruster designs were based on the results obtained from the experimental YBCO thin film thruster described in REF 3. With the thruster cooled to 77deg K using liquid nitrogen, a Q of $6.8x10^6$ was measured.

Fig 3 shows the model results with the modified 2G thruster cooled with liquid nitrogen, giving a static specific thrust of 16.5 N/kW for an unloaded Q factor of $3.7x10^6$. With this modest value of Q it requires high acceleration to cause significant reduction of specific thrust. In this case an acceleration of 1000m/s/s (100g) gives a specific thrust reduced to 4 N/kW.

Fig 3. 2G Thruster (LN2 Cooling)

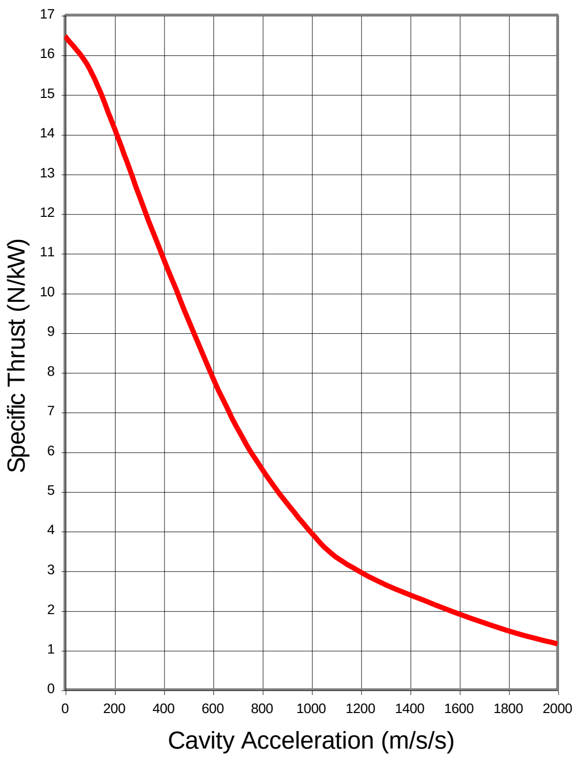


Fig 4 gives the results for a lower frequency cavity, cooled by liquid Hydrogen, thus operating at a temperature of 20deg K, and achieving a static specific thrust of 173 N/kW, with an unloaded Q factor of $3.9x10^7$. For an uncompensated thruster, the loss of Q, and hence reduction of specific thrust with acceleration is more pronounced. The model results show a specific thrust of 11 N/kW for an acceleration of 20m/s/s (2g).

Fig 4. 2G Thruster (LH2 cooling)

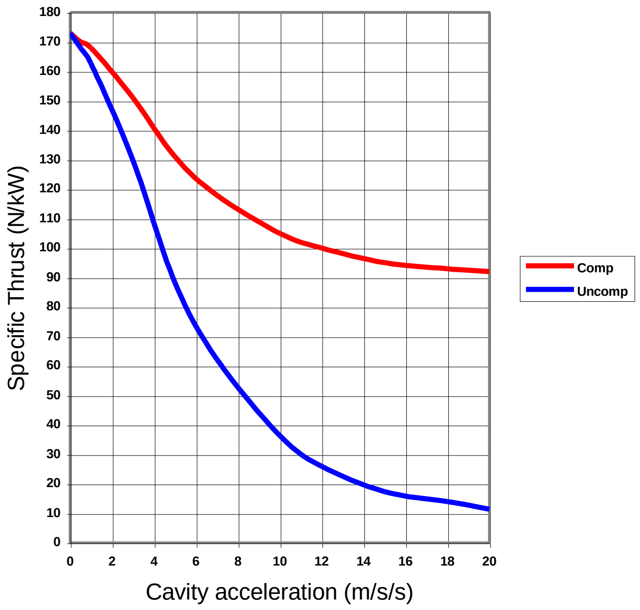
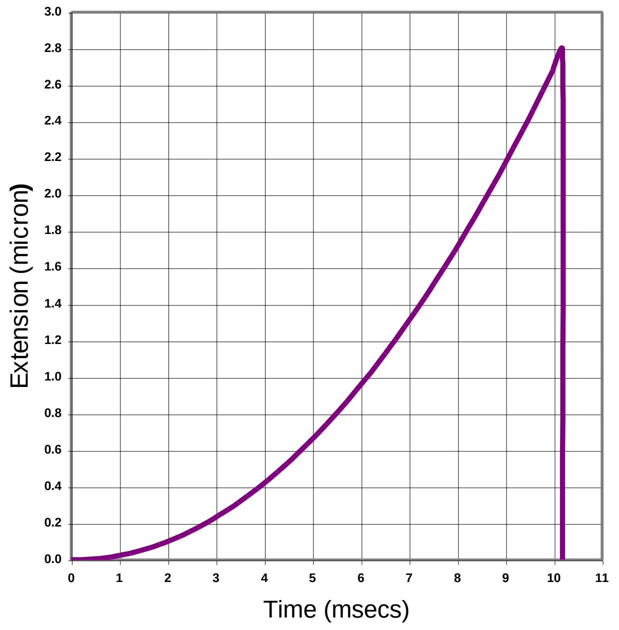


Fig 5 Cavity Extension



A compensated cavity was designed and modelled, where the axial length of the cavity is modified according to the acceleration experienced by the thruster. The cavity extension for a positive acceleration of 20 m/s/s is illustrated in Fig 5. The extension results from a pulsed voltage being applied to piezoelectric elements in the sidewall of the cavity. The pulse length is determined by the time constant of the resonant cavity. A description of such a thruster design is given in REF 4.

Clearly this simple form of compensation cannot completely compensate for the Doppler shift throughout a full pulse cycle, but fig 4 shows that the specific thrust at 20m/s/s can be improved to 92 N/kW.

6. HIGH POWER L-BAND THRUSTER

A large high power thruster was designed, operating at 900 MHz. This thruster again used a YBCO superconducting coating, and was cooled with liquid Hydrogen. The compensation technique included both cavity length extension and frequency offset, with a lower duty cycle than the 3.85 GHz thruster. A specific thrust of 9.92 kN/kW was predicted with an acceleration limit of 0.5m/s/s.

This L-Band thruster was part of a design study for a radically new approach to launch vehicles. A Hybrid Spaceplane was proposed, using 2G L-Band EmDrive thrusters as lift engines, with conventional low thrust jet engines and rocket engines for auxilary propulsion. These secondary propulsion units are fuelled by the gaseous Hydrogen, boiled off during the cooling of the EmDrive thrusters. The fuel cells used to provide DC power to the microwave power sources would also be fuelled in the same way. The initial spaceplane design was described in REF 5.

7. EMDRIVE LAUNCH VEHICLE

The initial spaceplane design described in REF 5 was updated following the dynamic modelling of the L-Band thruster, and a preliminary costing analysis was applied to the resulting design. The analysis assumed the main application would be the launch to geostationary orbit of the components of a global solar power satellite (SPS) system. It has been suggested (REF 6) that to make such a system economically viable, the launch cost of a 2GW SPS with a total mass of 6,700 Tonnes needs to be reduced to $20Billion. With conventional expendable launchers such as the Atlas V, this mass would require a total of 1,700 vehicles, at a total cost of £194 Billion. Clearly a major step forward in reusable launch vehicle design is necessary, if SPS is ever to be taken seriously as a solution to the global energy and global warming problems.

The use of 2G EmDrive thrusters as lift engines to provide vertical propulsion for a carrier vehicle offers a novel solution to this requirement. The low acceleration rates that are imposed on such high Q thrusters, as demonstrated in this paper, are not a problem in this application. Indeed the resulting low mechanical and thermal stresses on the airframe, allow commercial aircraft construction techniques to be applied with the resulting cost savings and increased service life, compared to current spaceplane proposals.

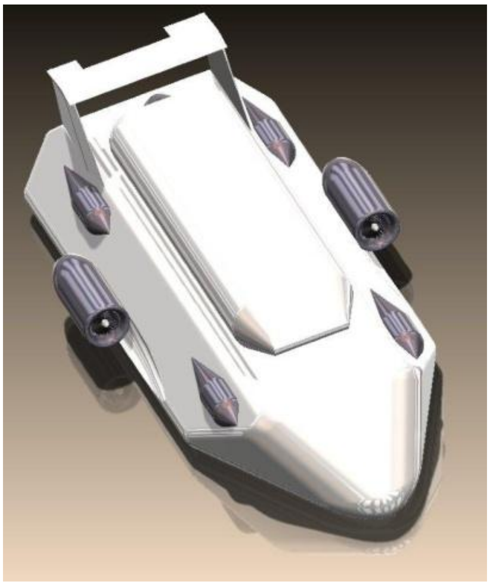


Fig 6. Hybrid Spaceplane in GEO launch configuration.

The spaceplane design is illustrated in fig. 6. A total launch mass of 315 tonnes includes a 164 tonne carrier vehicle, a 101 tonne expendable payload propulsion module and a payload mass of 50 tonnes delivered to GEO. 103 tonnes of liquid hydrogen and liquid oxygen are used in the carrier vehicle to provide cooling for the lift engines, fuel for the rocket and jet engines, and input to the fuel cells. The carrier vehicle is unmanned and is specified for a minimum of 500 flights.

The flight profile starts with a vertical take off with the carrier vehicle in a horizontal attitude. Vertical acceleration is limited to 0.5m/s/s with any horizontal component provided by the auxilary hydrogen fuelled, jet engines. A maximum velocity in the atmosphere of 256 mph is reached, ensuring low aerodynamic and thermal stresses. The ascent continues under EmDrive lift with small auxilary rockets to provide the horizontal propulsion component, once clear of the atmosphere.

After a 12 hour ascent, max altitude is reached, 21km above GEO altitude. At this point the payload module is released and its internal rocket motor provides orbital velocity. Meanwhile the carrier vehicle descends with the EmDrive lift engines providing a controlled deceleration. Return to launch site is provided by jet engines once the vehicle is within the atmosphere, followed by a vertical landing, after a total flight time of 18 hours.

The cost analysis showed that the 134 flights required to launch a 2GW SPS would be reduced to $1.5 Billion, including amortisation of the development and build costs of the carrier vehicle. This represents a cost reduction factor of 130 compared to a conventional launch system.

8. CONCLUSIONS

A mechanism which limits the acceleration of a very high Q EmDrive thruster has been described, which illustrates how the thruster complies with the law of the conservation of energy. This mechanism has been modelled using simple equations of Doppler shift. The results of this modelling exercise show that for first generation applications, there will be no reduction of specific thrust, with the typical acceleration rates and electrical power ratings of current satellites.

However for YBCO superconducting thrusters, cooled with liquid Nitrogen, high accelerations will lead to a measurable reduction in specific thrust. With a cavity design cooled with liquid Hydrogen, a compensation technique allows useful acceleration to be obtained without significant loss of specific thrust.

A high power L-Band 2G thruster is modelled and the specific thrust is given for a fully compensated cavity. This thruster design is then used in a design study for a revolutionary launch vehicle, capable of reducing the cost of launch to geostationary orbit by a factor of 130. This will ensure that Solar Power Satellite systems become an economically viable solution to future energy requirements and global warming problems.

REFERENCES

REF 1.

YANG JUAN et al

“Net thrust measurement of propellantless microwave thrusters”

NWPU, College of Aeronautics, Xi’an.

Acta Phys. Sin. Vol.61, No. 11 (2012)

REF 2.

SHAWYER, R.J.

“Microwave propulsion – progress in the EmDrive programme”

SPR Ltd UK.

IAC-08-C4.4.7 Glasgow 2008

REF 3.

SHAWYER, R.J.

“The EmDrive – a new satellite propulsion technology”

SPR Ltd UK.

2nd Conference on disruptive technology in space activities. Toulouse 2010

REF 4.

“High Q Microwave Radiation Thruster”

UK Patent No GB2493361

Published Feb 2013

REF 5.

SHAWYER, R.J.

“The EmDrive Programme – Implications for the Future of the Aerospace Industry.”

SPR Ltd UK.

CEAS 2009. Manchester 2009.

REF 6.

MANKINS J C, editor.

“Space Solar Power”

IAA Study Report. Nov 2011.