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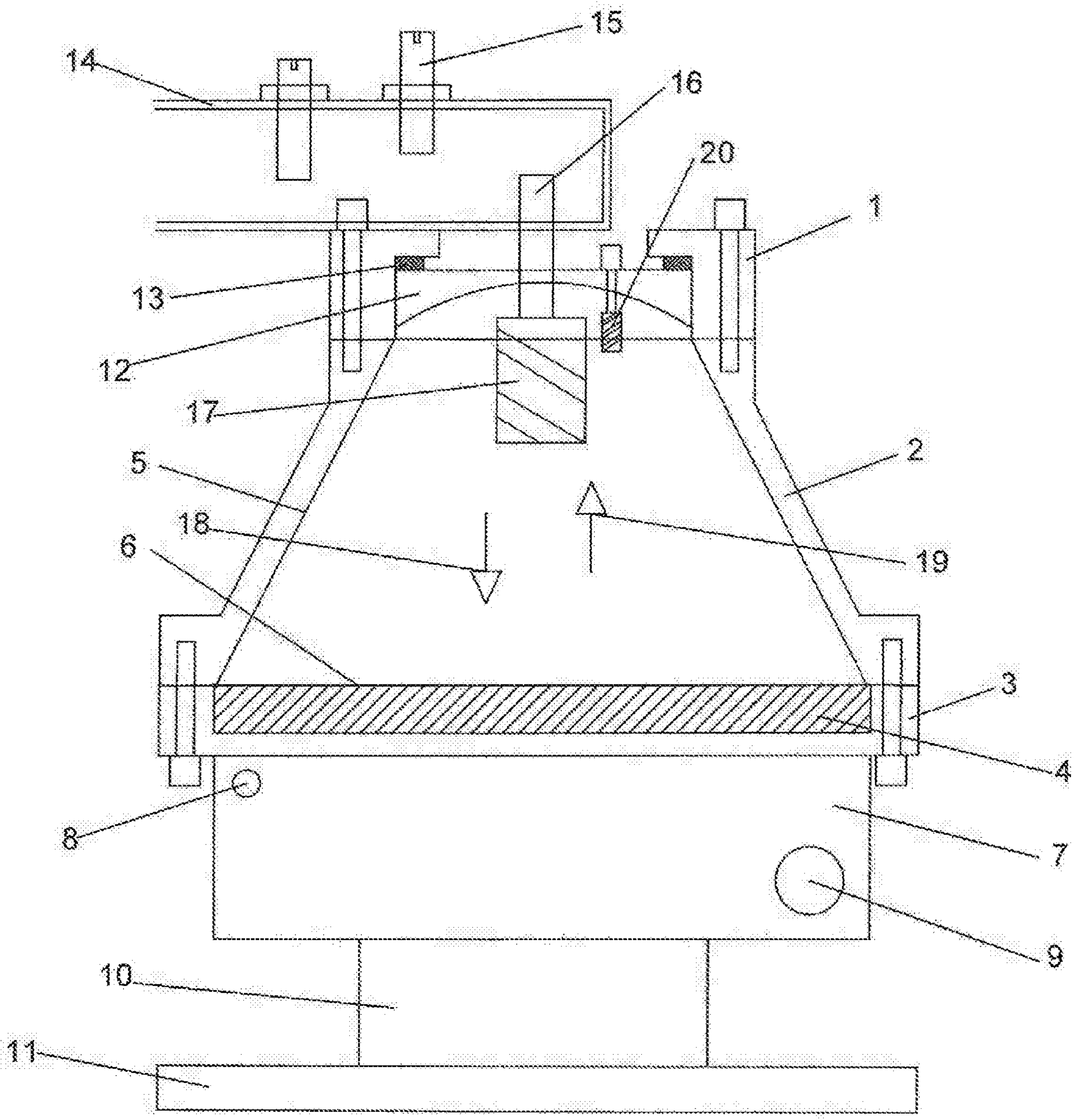

Figure 1. Schematic Diagram of the Superconducting Thruster

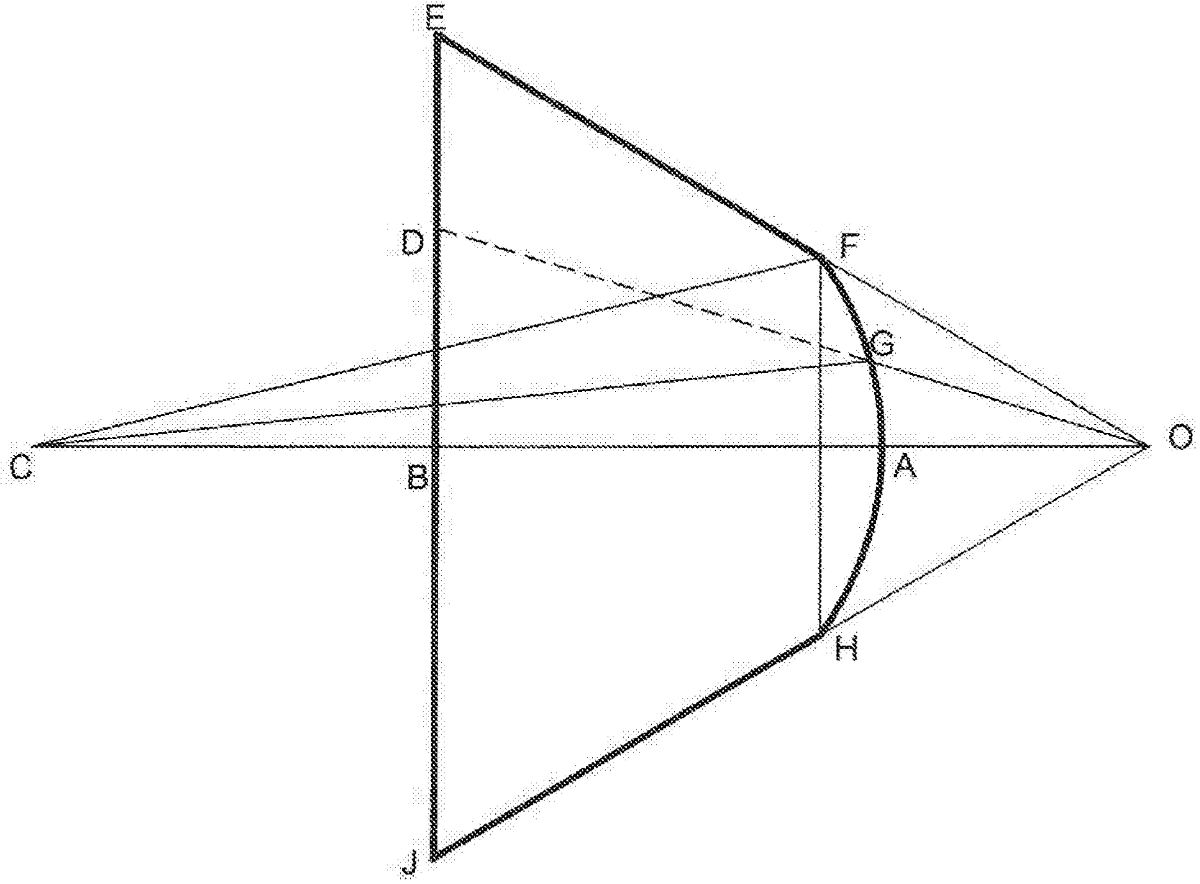

Figure 2. Cavity Geometry

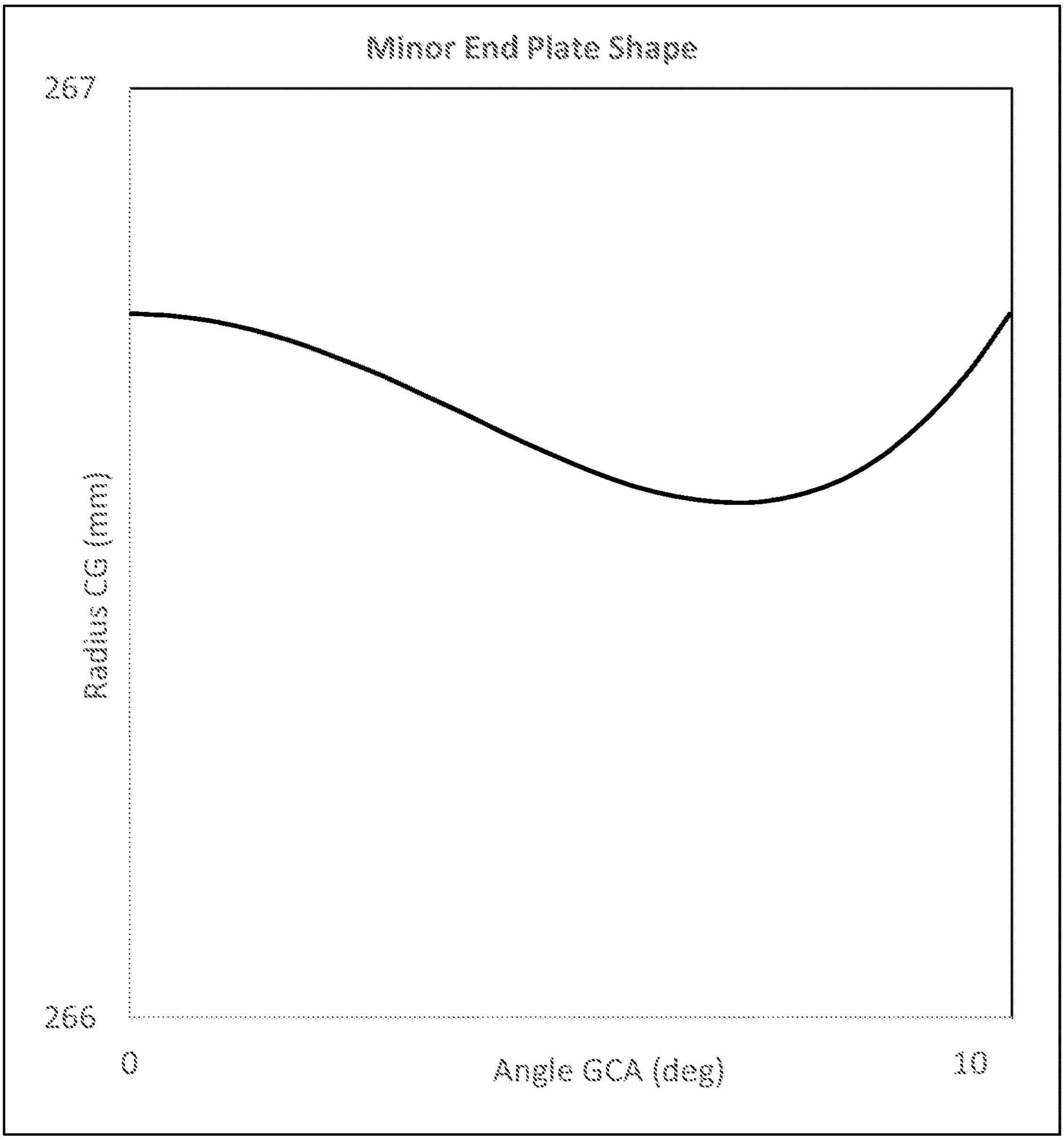

Figure 3. Shape of Inner Surface of Minor End Plate

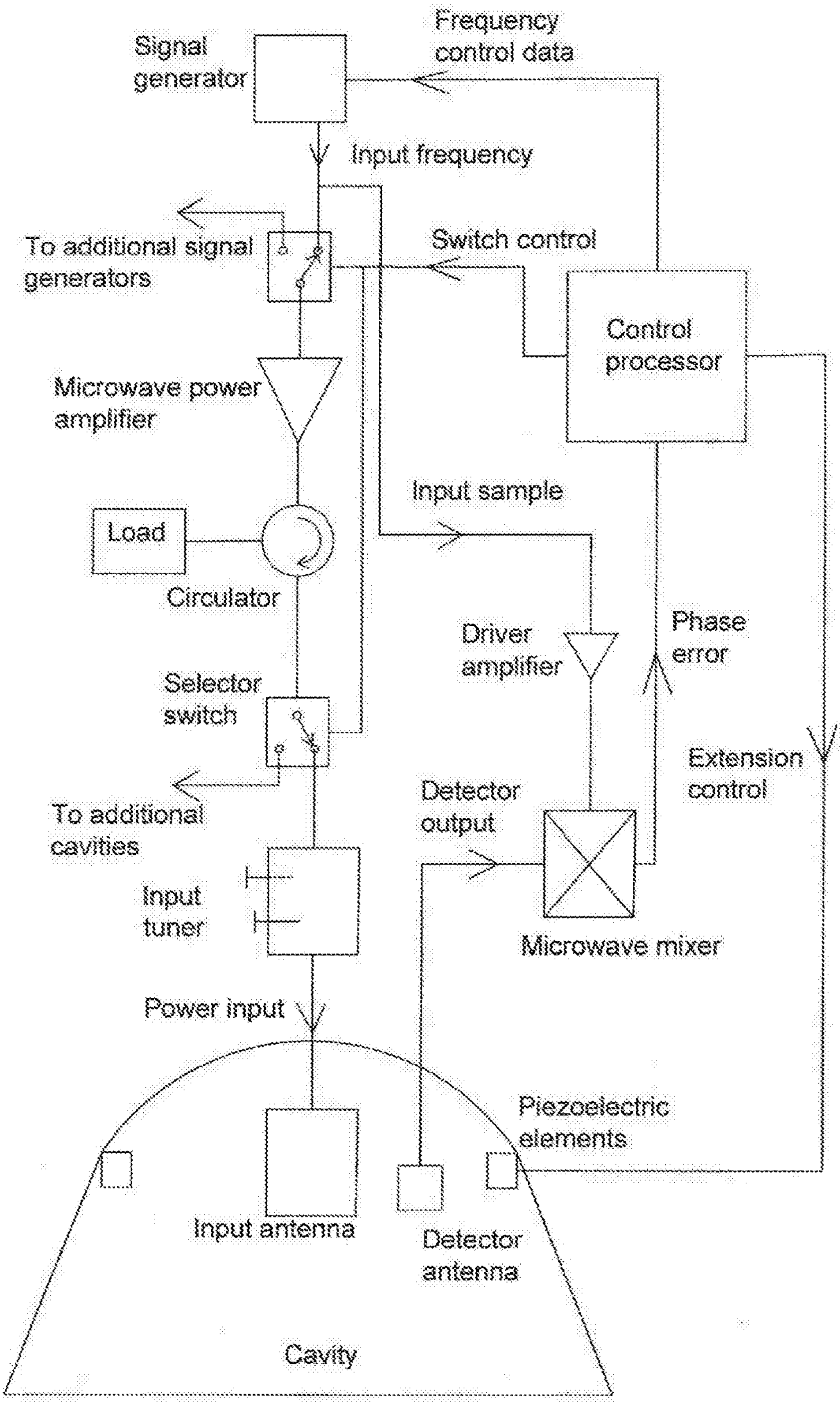

Figure 4. Block Diagram of Control Circuit

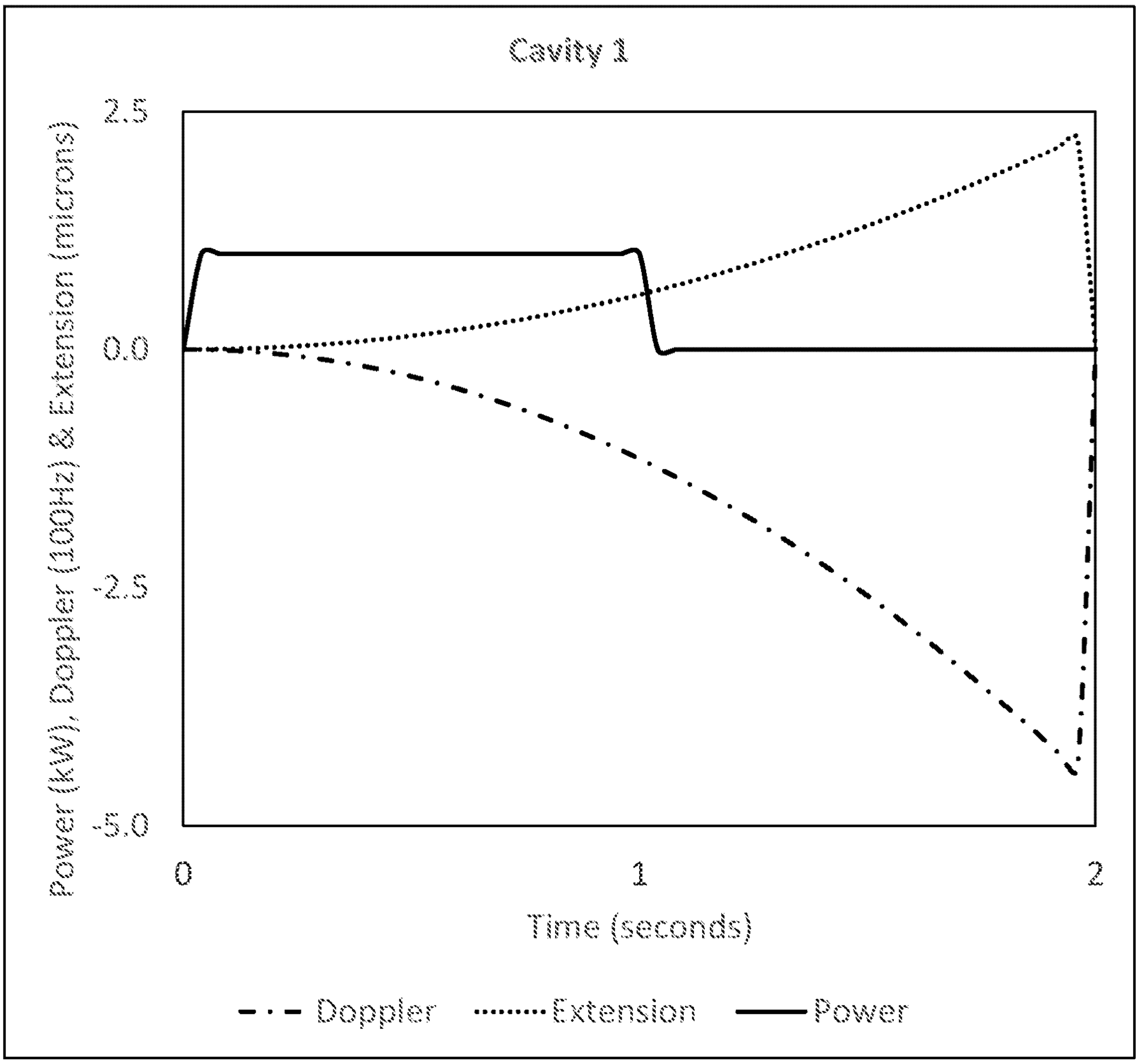

Figure 5. Input Power, Doppler Frequency Shift and Cavity Length Extension for Cavity 1.

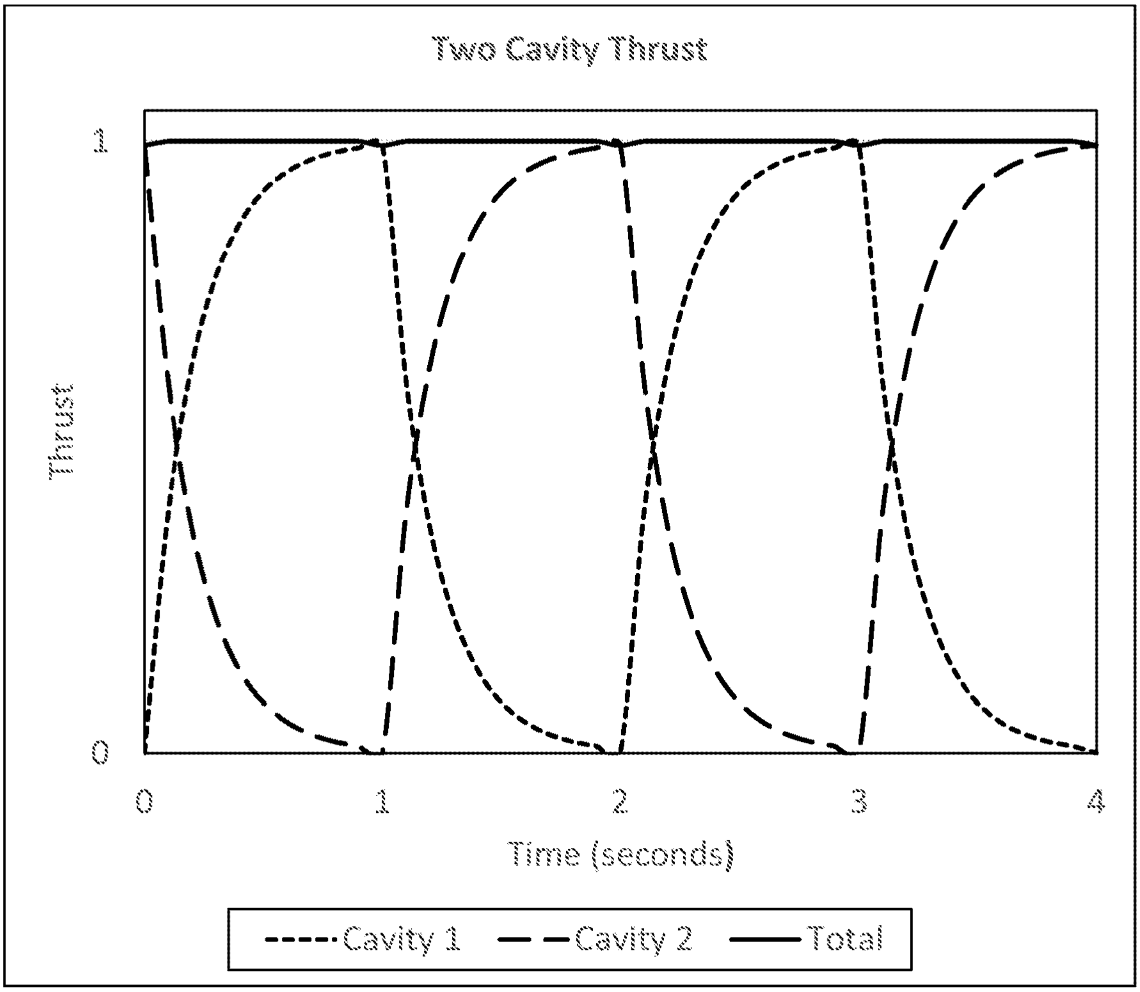

Figure 6. Thrust Output for a Two Cavity Engine

SUPERCONDUCTING MICROWAVE RADIATION THRUSTER

This invention improves on the design of a microwave thruster used to accelerate a spacecraft or airborne vehicle, as has been previously described, and sometimes referred to as an "EmDrive" thruster.

The thruster comprises a tapered resonant microwave cavity with a frustum shape where the force resulting from the electromagnetic wave reflections from the minor end plate is less than the force resulting from the reflections at the major end plate. This force reduction is due to the decrease in guide velocity of the propagated electromagnetic wave as it approaches the minor end plate. The difference in reflection forces is multiplied by the Q factor of the cavity, allowing useful levels of thrust to be achieved. Very high Q values and thus very high thrust levels can be achieved by using superconducting material on the inner surfaces of the cavity. However because the Q value is a function of the stored electromagnetic energy in the cavity, once the resultant thrust causes the cavity to accelerate, stored energy is converted to kinetic energy and the Q value falls. This demonstrates EmDrive is compliant with the law of conservation of energy. The acceleration will be in the opposite direction to the direction of thrust, thus demonstrating that EmDrive also complies with Newton's third law of motion, and thus with the law of conservation of momentum.

A number of thruster cavities can be combined to form an engine which provides a continuous thrust output.

The object of this invention is to firstly provide a cavity geometry which enables the major end plate to be flat, and thus simplifies the manufacturing process. The major end plate can then be the only component of the cavity with a superconducting inner surface. The superconducting surface can be an Yttrium Barium Copper Oxide (YBCO) thin film which is deposited on a single crystal sapphire substrate. The substrate is cooled by a liquefied gas which can be Nitrogen, Hydrogen or Helium and maintains the low temperature necessary for the YBCO film to become superconducting.

The minor end plate and taper section components of the cavity have curved inner surface which can be machined to shape from a metal such as aluminium alloy and then silver plated.

A further objective of the present invention is to provide an input circuit which includes an input antenna capable of propagating a circularly polarised waveform inside the cavity. A second, much smaller detector antenna can then be used to detector the reflected wave, which will have the opposite polarisation to the input waveform. This opposite polarisation enables any phase difference between the input waveform and the reflected waveform to be measured and the measurement used to correct the phase of the input waveform.

This arrangement can form a phase locked loop which corrects the Doppler shift caused by the acceleration of the cavity, and which if left uncorrected would cause a reduction in Q value.

According to the present invention there is provided a tapered, circular section, microwave cavity with a flat major end plate and a shaped minor end plate, whose concave shape is calculated to minimise the variation in path length across the waveform of the propagated electromagnetic wave. This shaped minor end plate and flat major end plate enable a high Q value to be achieved by minimising the phase distortion across the wavefront.

In addition the minor end plate is mounted on piezoelectric elements which control the axial lengths of the cavity as acceleration causes the frequency of the propagated wave to shift according to the Doppler Effect. The input frequency is varied to match the Doppler shifted, internally propagated wave, by means of a circularly polarised input antenna, and smaller detector antenna with opposite polarisation, which together with a microwave mixer, drive amplifier, control processor and signal generator form a phase locked control loop. Both the input antenna and the detector antenna are mounted on the minor end plate.

A specific embodiment of the invention will now be described by way of example, with reference to the accompanying drawings in which:

Figure 1 shows a schematic diagram of the superconducting thruster

Figure 2 shows the cavity geometry

Figure 3 shows the shape of the inner surface of the minor end plate

Figure 4 shows a block diagram of the control circuit

Figure 5 shows the input power, Doppler frequency shift and cavity length extension for cavity 1

Figure 6 shows the Thrust output for a two cavity engine

In figure 1 the thruster comprises a minor end plate 1, fixed by screws to a taper section 2, which is fixed to a major end plate 3. A single crystal sapphire substrate 4 is attached by adhesive to the major end plate 3. These four components form a closed cavity with silver plated inner surfaces 5 coating the walls of the minor end plate 1, and the taper section 2. The inner surface of the sapphire substrate is coated with a thin film 6 of YBCO. A liquefied gas cooler 7 is fixed to the major end plate 3 and the liquefied gas, which may be Nitrogen, Hydrogen or Helium is introduced to the cooler 7 via the input 8. After passing through the cooler 7 the liquefied gas becomes gaseous due to the input of heat dissipated at the YBCO thin film 6. The latent heat of evaporation of the liquefied gas provides the cooling effect at the YBCO surface, maintaining the film temperature below its critical temperature, thus maintaining its superconducting properties. The gas then exits from the cooler 7 via the gas output 9.

The liquid gas cooler 7 is fixed to a thrust plate 11 via a thermal insulator 10. Thrust is generated in the direction of minor end plate towards major end plate and is transmitted to the spacecraft or airborne vehicle via the thrust plate 11. In the position shown in figure 1 the thrust is therefore vertically downwards, resulting in an acceleration of the spacecraft or airborne vehicle vertically upwards. This reaction is a result of Newton's third law of motion.

The minor end plate 1 contains a shaped section 12 which slides within the minor end plate. The shaped section and minor end plate are separated by piezoelectric elements 13 which control the axial length of the cavity according to the electric signal applied to them.

Microwave power is transferred to the cavity via a waveguide input section 14. This waveguide section contains two tuning posts 15, whose length can be adjusted to give the correct impedance match to the microwave source to ensure maximum power transfer from the source to the cavity. The microwave power is transferred from the input waveguide 14 via an input probe 16 to a helical input antenna 17. This input antenna 17 propagates the microwave power as a circularly polarised electromagnetic wave 18 which is reflected from the YBCO thin film 6, to produce the reflected electromagnetic wave 19. This reflected electromagnetic wave 19 has the opposite polarisation to the input electromagnetic wave 18 and is detected by the helical detector antenna 20 which has a helix geometry that is opposite to the helix geometry of the input antenna 17.

The detector antenna geometry ensures that only a very small fraction of the reflected electromagnetic wave 19 is extracted from the cavity and the polarisation difference with the input waveform ensures that the detected signal level is above any noise signal caused by the input electromagnetic wave 18.

The axial length of the cavity is tuned by the piezoelectric elements such that it is always a whole number of half wavelengths of the input electromagnetic wave 18. In this manner the cavity is maintained at resonance and the input and reflected waves continue to be reflected backwards and forwards between the minor and major end plates. This process stores electromagnetic energy in the cavity over a time constant designated T_c dependant on the Q value achieved. The thrust produced by the cavity is also dependant on the Q value.

A critical element of achieving a high Q cavity is the geometry necessary to ensure that the backward and forward transits of the electromagnetic waves 18 and 19 traverse the same path length independent of the radial position along the wavefront. Any phase variation across the wavefront will cause phase error to build up during time constant T_c and will reduce the Q value that can be achieved.

The geometry that is necessary to achieve this constant path length, independent of radial position is illustrated in figure 2. Because the taper section is smaller at the minor end plate position, the diameter FH is smaller than the diameter EJ at the major end plate. This gives a projected apparent origin of the electromagnetic wave at position O.

The shape of the minor end plate (curve FAH) is designed to ensure that the outer and axial path lengths EF, BA and JH are equal.

In addition any path length, represented by DG in figure 2 must also be equal to the outer and axial path lengths. This geometry is ensured by calculating the value of the machining radius

CG of the curve FAH for any angle represented by GCA. This calculation is carried out by a numerical analysis in which the machining radius CG is iterated for steps in the angle GCA until the path length DG is equal to the outer and axial path lengths EF,BA and JH. The resulting curve shape FGA is shown in figure 3, where a typical result of such an analysis is given. A mirror image of this curve gives the curve AH and thus the complete concave shape of the minor end plate can be machined.

When the cavity is subject to an acceleration, due to the thrust it produces, a Doppler shift will occur in the input and reflected electromagnetic waves 18 and 19 in figure 1. Because the guide velocities are different at the major and minor end plates, these Doppler shifts will not cancel each other out. It is therefore necessary to introduce an input circuit to modify the input frequency and a mechanical circuit to modify the axial length for the cavity under acceleration conditions. A further feature of this invention is to provide a control circuit which will carry out the frequency correction function and which is illustrated in figure 4.

Figure 4 shows the input frequency is generated at a low power level by the signal generator. This device, which may be a digital microwave synthesiser, is capable of varying the cavity input frequency by means of a frequency control data input. The frequency signal from the signal generator is sent to a microwave power amplifier via a switch which can select a frequency signal from any one of a number of additional signal generators. The output of the microwave power amplifier is fed through a standard circulator and load protection circuit, to a second selector switch which enables the output power to be sent to any one of a number of additional cavities. In this manner the microwave power amplifier can be used to amplify pulses of input power to any number of cavities in sequence.

The microwave power is then fed to the input antenna inside the cavity via an input tuner comprising the input waveguide 14 and tuning posts 15 shown in figure 1. The oppositely polarised detector antenna then provides a very low level fraction of the reflected electromagnetic wave 19, illustrated in figure 1, to the input port of a microwave mixer. The local oscillator port of the mixer is fed via a drive amplifier whose input is a sample of the input frequency being generated by the signal generator.

The output of the microwave mixer will therefore be a phase error corresponding to the Doppler shift difference between the input and the reflected electromagnetic waves. This phase error is then fed to the control processor where it is processed to produce the frequency control data which is sent to the signal generator. Thus a phase locked control loop is set up to maintain the Doppler shift difference to a minimum under acceleration conditions, and to thus maintain the high Q of the cavity. The control processor also provides a voltage to the piezoelectric elements to control the extension to the cavity axial length.

However the input frequency cannot be continuously corrected during constant acceleration and the accompanying extension of the axial length of the cavity cannot be unlimited. Therefore the Doppler correction function is carried out over a specific period which starts and stops the power input to the cavity as shown in figure 5. This pulse period is greater than the cavity time constant T_c. The start and stop of the power input to any given cavity is controlled by the switches described previously and illustrated in figure 4.

Figure 5 shows the input power pulse, the Doppler frequency shift and the cavity length extension for cavity 1 of a two cavity engine. Any number of cavities can comprise an EmDrive engine but for illustration purposes two are described in this invention. In this example the input power pulse lasts for one second, and the acceleration causes the Doppler frequency to lower the input frequency according to a curve which can be calculated from a numerical analysis of the dynamic response of the cavity. The extension of the cavity axial length therefore increases the cavity length according to a curve which is an inverse shape compared to the Doppler curve, and is illustrated in figure 5.

At the end of the power pulse, the Doppler shift and extension curves are continued as the stored energy, and the electromagnetic waves forming that energy approach zero.

For the two cavity engine described, the power pulse period is one second and the thrust output for each cavity is shown in figure 6. This shows that during the power pulse to cavity 1 the thrust builds up to the rated thrust output (1 on the vertical axis of figure 6) in an exponential curve. When the power pulse is switched to cavity 2 at one sec, the thrust in cavity 1 falls exponentially to approach zero at two seconds. At the two second point, the extension is reverted to zero and the thrust drops to zero, as the cavity is no longer tuned to the Doppler shifted frequency. Meanwhile in the period one second to two seconds, the power pulse is applied to cavity 2 and the thrust from cavity 2 rises exponentially. The cycle continues as shown in figure 6, such that the total thrust remains approximately constant with small dips each time the extension of a cavity reverts to zero.

CLAIMS

1. A superconducting microwave radiation propulsion unit which has a cavity with one flat superconducting major end plate, and a specially shaped minor end plate and taper section both manufactured from non-superconducting material.

2. A superconducting microwave radiation propulsion unit as claimed in Claim 1 employing a minor end plate with a curved shape such that the path length of the propagated wave within the thruster cavity is equal for all radial points on the wavefront.

3. A superconducting microwave radiation propulsion unit as claimed in Claim 1 or Claim 2 that employs a circularly polarised input antenna and a detector antenna of the opposite polarisation to the input antenna, both mounted on the minor end plate.

4. A superconducting microwave radiation propulsion unit as claimed in any proceeding claim with a control circuit which provides a phase locked loop formed between the circularly polarised input and detector antennae in order to correct the input frequency, such that the Doppler shift difference between the input and reflected electromagnetic waves within the cavity is minimised when the thruster accelerates.