(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
13 October 2016 (13.10.2016)

(10) International Publication Number
WO 2016/162676 A1

(51) International Patent Classification: ***F03H 99/00*** (2009.01)

(21) International Application Number: PCT/GB2016/050974

(22) International Filing Date: 7 April 2016 (07.04.2016)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
1505870.4 7 April 2015 (07.04.2015) GB

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(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JP, KE, KG, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

Published:

— *with international search report (Art. 21(3))*

[Continued on next page]

(54) Title: SUPERCONDUCTING MICROWAVE RADIATION THRUSTER

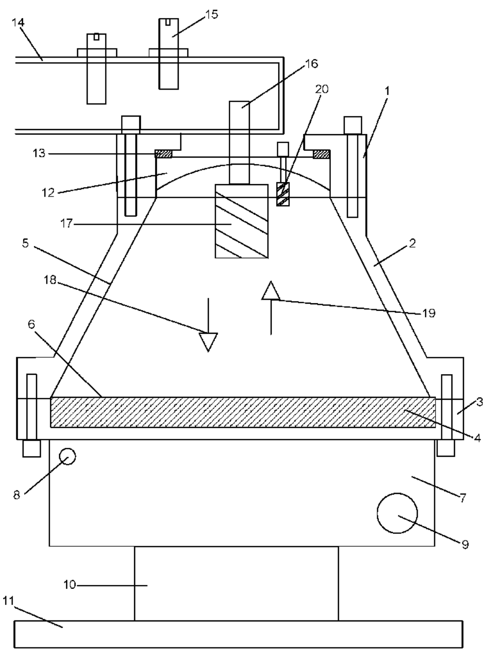

FIG. 1

(57) Abstract: A superconducting microwave radiation thruster used to accelerate a spacecraft or an airborne vehicle. The thruster includes a flat superconducting surface for the major end plate and a specially shaped, non-superconducting minor end plate and a non- superconducting taper section. This geometry considerably simplifies the manufacturing of the thruster. The thruster includes circularly polarised input and detector antennae which, when combined with a phase locked loop control circuit, enable the input frequency to be corrected for Doppler shifts, caused by acceleration of the thruster. These Doppler shifts would otherwise cause a decrease in cavity Q value, and thus an unacceptable decrease in output thrust.

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- *before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments (Rule 48.2(h))*

SUPERCONDUCTING MICROWAVE RADIATION THRUSTER

This invention is related to improving 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. In experiments, a thrust of 0.3N has been measured for an input power of 1kW at a room temperature Q of 50,000.

Very high Q values and thus very high thrust levels can be achieved by using superconducting material on the inner surfaces of the cavity. For example, a Q value of 5,000,000 has been measured using a liquid nitrogen cooled superconducting cavity, which is expected to provide a thrust of 30N for an input power of 1kW. 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.

SUMMARY OF THE INVENTION

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.

The following disclosure is given 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 schematic diagram including dimension examples

Figure 5 shows a block diagram of the control circuit

Figure 6 shows the input power, Doppler frequency shift and cavity length extension for cavity 1

Figure 7 shows the Thrust output for a two cavity engine

In figure 1 the thruster comprises a minor end plate 1, which may be fixed by screws to a taper section 2, which is fixed to a major end plate 3. The shape of minor end plate 1 is shown for example only, and the actual shape is defined as explained below. A single crystal sapphire substrate 4 is attached (for example by adhesive) to the major end plate 3. In an example the diameter of the substrate is 200mm. 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 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.

To achieve a high Q cavity the geometry should 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.

A geometry to achieve this constant path length, independent of radial position is illustrated schematically 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 should be equal to the outer and axial path lengths. A suitable geometry can be calculated by calculating the value of the machining radius CG of the curve FAH for any angle represented by GCA. This calculation may be 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.

Figure 4 shows a schematic diagram of the cavity, highlighting dimensions described in the following table which show an exemplary cavity design.

Angle B (deg)	**Rn (mm)**	**X co-ord (mm)**	**Y co-ord (mm)**	**R3 error (mm)**	**Correction (mm)**
0	266.757	266.757	0.000	0.000	0.000
0.1	266.757	266.757	0.466	0.000	0.000
0.3	266.756	266.752	1.397	0.001	0.001
0.5	266.755	266.745	2.328	0.002	0.002
1	266.749	266.708	4.655	0.008	0.008
1.5	266.739	266.648	6.982	0.018	0.018
2	266.726	266.564	9.309	0.031	0.031
2.5	266.709	266.455	11.634	0.048	0.048
3	266.691	266.326	13.958	0.067	0.066
3.5	266.67	266.173	16.280	0.088	0.087
4	266.649	265.999	18.600	0.110	0.108
4.5	266.627	265.805	20.919	0.132	0.130
5	266.607	265.592	23.236	0.154	0.150
5.5	266.588	265.361	25.551	0.173	0.169
6	266.572	265.112	27.864	0.190	0.185
6.5	266.561	264.848	30.176	0.203	0.196
7	266.555	264.568	32.485	0.210	0.202
7.5	266.555	264.275	34.792	0.211	0.202
8	266.5635	263.969	37.098	0.204	0.194
8.5	266.58	263.652	39.403	0.187	0.177
9	266.6075	263.325	41.707	0.159	0.150
9.5	266.646	262.989	44.009	0.119	0.111
10	266.696	262.644	46.311	0.065	0.061
10.476	266.757	262.310	48.503	0.000	0.000

In an example cavity, the major end plate may have a diameter of 145mm, the minor end plate may have a diameter of 97mm, and the distance between the end plates of the order of 67mm. These dimensions are given by way of example and various designs are possible as explained herein.

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 disclosure is to provide a control circuit which will carry out the frequency correction function and which is illustrated in figure 5.

Figure 5 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 6 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 inverse to the Doppler curve and is illustrated in figure 6.

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 7. 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 7) 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 7, such that the total thrust remains approximately constant with small dips each time the extension of a cavity reverts to zero.

The following table shows a set of example measurements from a prototype thruster designed in accordance with the disclosure herein, which measurements demonstrate thrust generation.

FTM test number	Thrust vector	Input power	Pfwd (Watts)	Prfl (Watts)	Pin (Watts)	Thrust (gm)	Sp thrust (mN/kW)
142	down	medium	292	23	269	10.6	386
143	down	medium	297	24	273	12.3	442
144	up	medium	348	19	329	-8.2	244
145	up	medium	360	13	347	-11.6	327
153	down	medium	366	20	346	10.1	287
154	down	medium	361	25	336	13.1	383
155	down	low	173	13	160	4.5	275
156	down	low	144	14	130	4.3	326
157	down	high	427	71	356	12.6	348
159	down	high	456	59	397	14.2	350
160	down	high	486	59	427	17.7	405
162	down	high	482	59	423	15.7	365
163	up	low	172	12	160	-3.5	215
165	up	high	485	28	457	-17.0	364
167	up	low	162	6	158	-3.2	201
168	up	medium	359	17	342	-8.4	241
169	up	medium	356	32	324	-9.2	278

174	up	high	416	69	347	-12.5	353
175	up	high	395	68	327	-13.5	403

The mean specific thrust for these tests was 326mN/kW, with a standard deviation of 67 mN/kW. The mean specific thrust for tests with the thrust vector down was 357mN/kW, and 292mN/kW with the thrust vector up.

The above disclosure has been given in relation to one or more examples with a combination of features, but as will be appreciated aspects of the disclosure can be utilised independently of one another. For example, the frequency adjustment aspects may be used independent of the cavity shape aspects.

Dimensions are given for context only and may be altered as required, for example to provide thrusters with different performance properties.

CLAIMS

1. A microwave radiation thruster for accelerating a vehicle, which has a cavity formed within a flat superconducting major end plate, a non-superconducting minor end plate, and a non-superconducting taper section between the major end plate and the minor end plate.

2. A microwave radiation thruster as claimed in Claim 1, wherein the minor end plate has a curved shape such that the path length of a wave propagating between the minor and major end plates within the cavity is equal for all radial points on the wavefront.

3. A microwave radiation thruster as claimed in Claim 1 or Claim 2, further comprising a circularly polarised input antenna and a detector antenna of the opposite polarisation to the input antenna, both antennas mounted on the minor end plate and within the cavity.

4. A microwave radiation thruster as claimed in claim 3 further comprising a control circuit configured to adjust the frequency emitted by the input antenna, such that the Doppler shift difference between the input and reflected electromagnetic waves within the cavity is minimised when the thruster accelerates.

5. A microwave radiation thruster according to claim 4, wherein the control circuit comprises a phase locked loop between the input antenna and detector antenna.

6. A microwave radiation thruster according to any preceding claim, wherein the vehicle is a spacecraft or airborne vehicle.

7. A microwave radiation thruster according to any preceding claim, wherein the major end plate is formed of a crystal sapphire substrate with a superconducting thin film coating on the face of the major plate which forms a wall of the cavity.

8. A microwave radiation thruster according to claim 7, wherein the thin film coating is formed of Yttrium Barium Copper Oxide.

9. A microwave radiation thruster according to claim 7 or claim 8, wherein the substrate has a diameter of 200mm.

10. A microwave radiation thruster according to any preceding claim further comprising a liquefied gas cooler for cooling the major end plate.

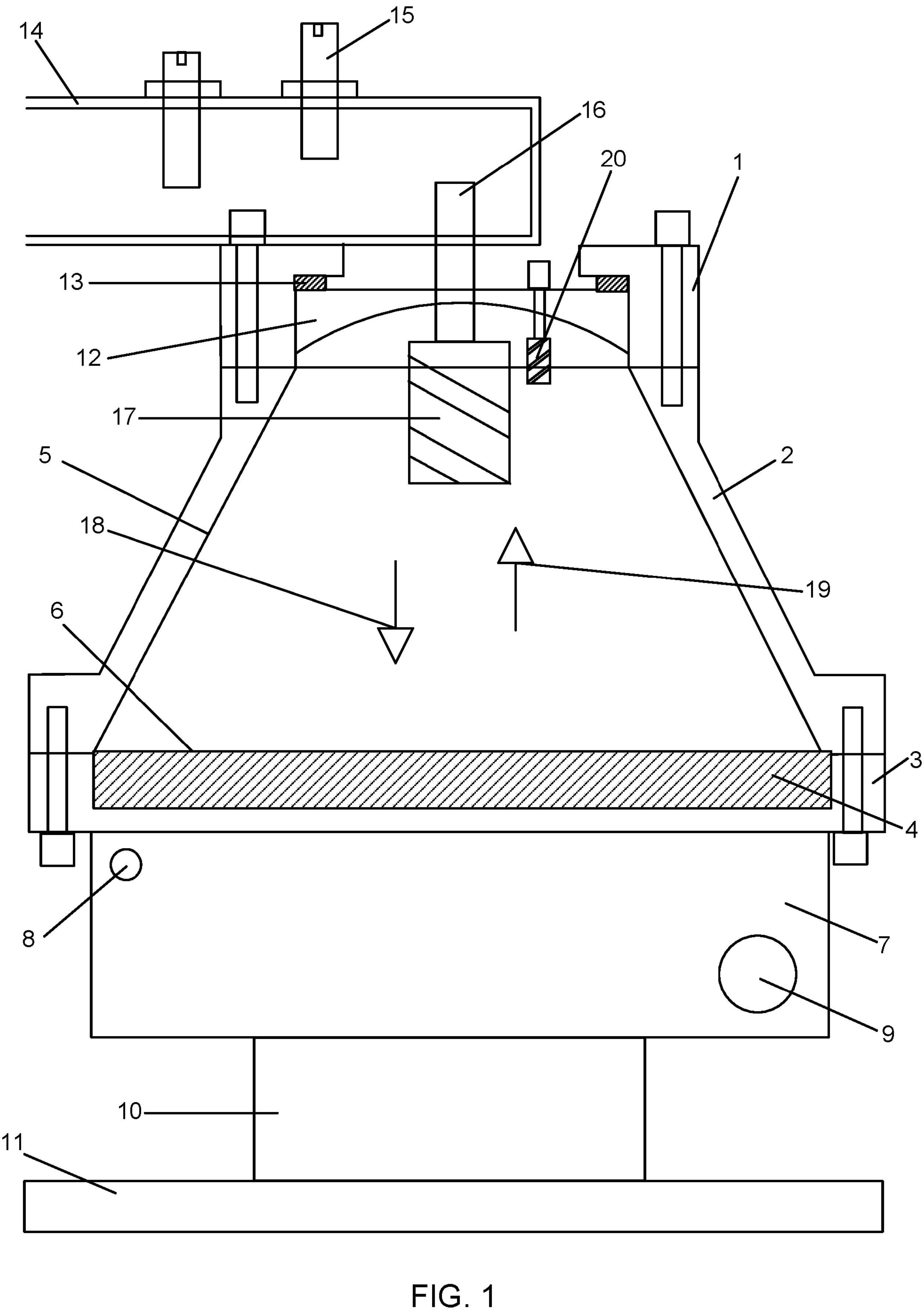

FIG. 1

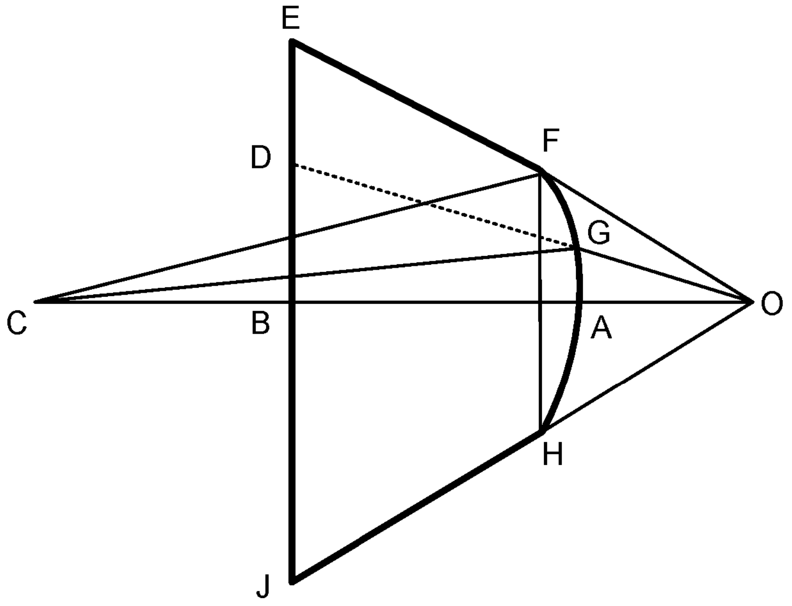

FIG. 2

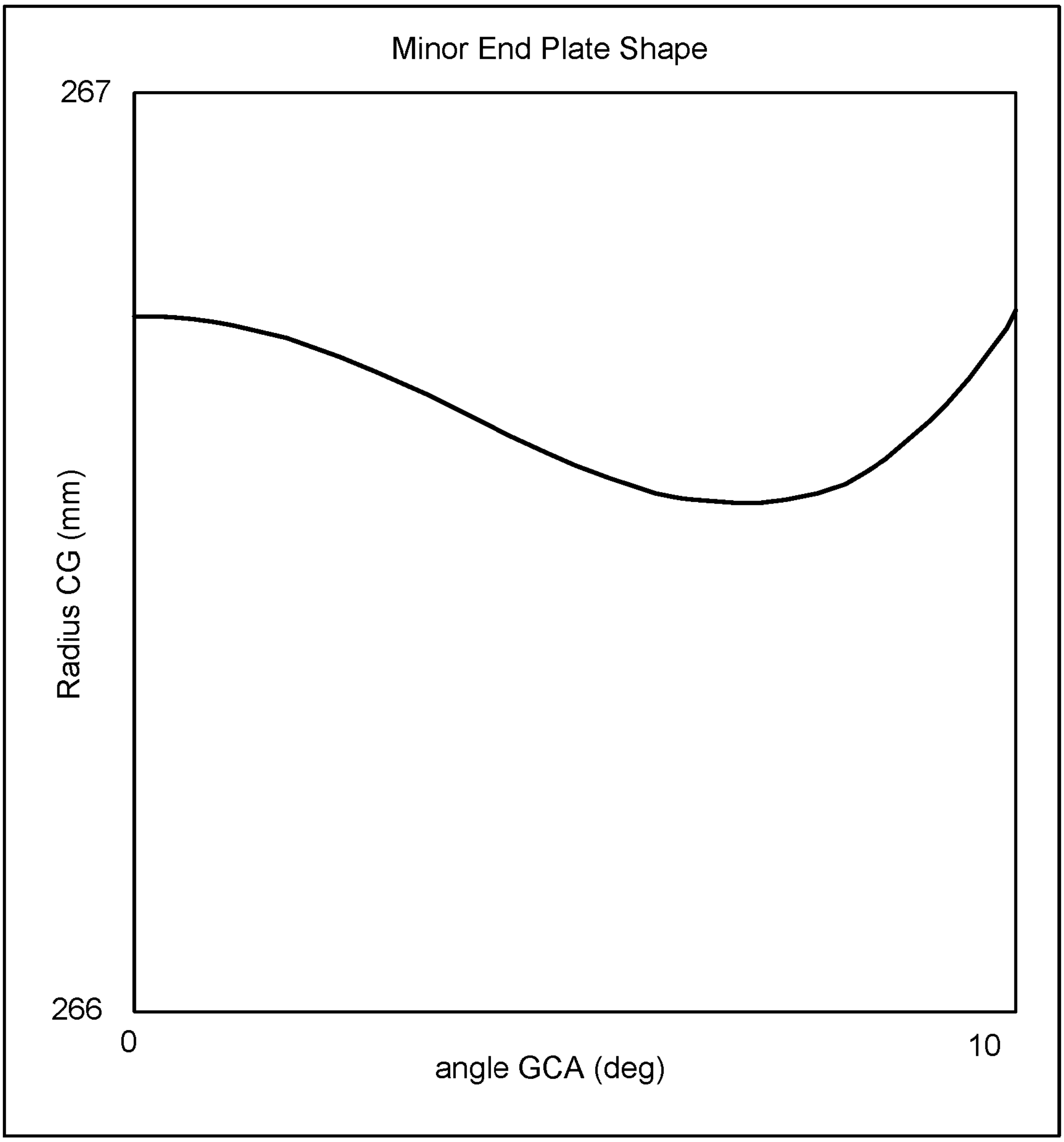

FIG. 3

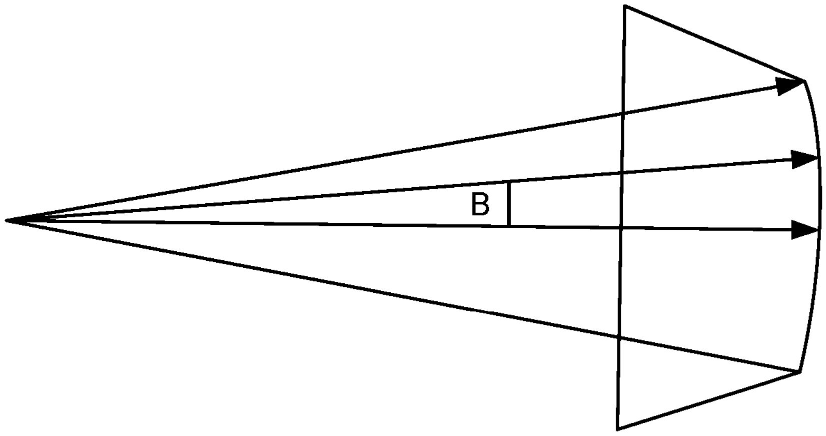

FIG. 4

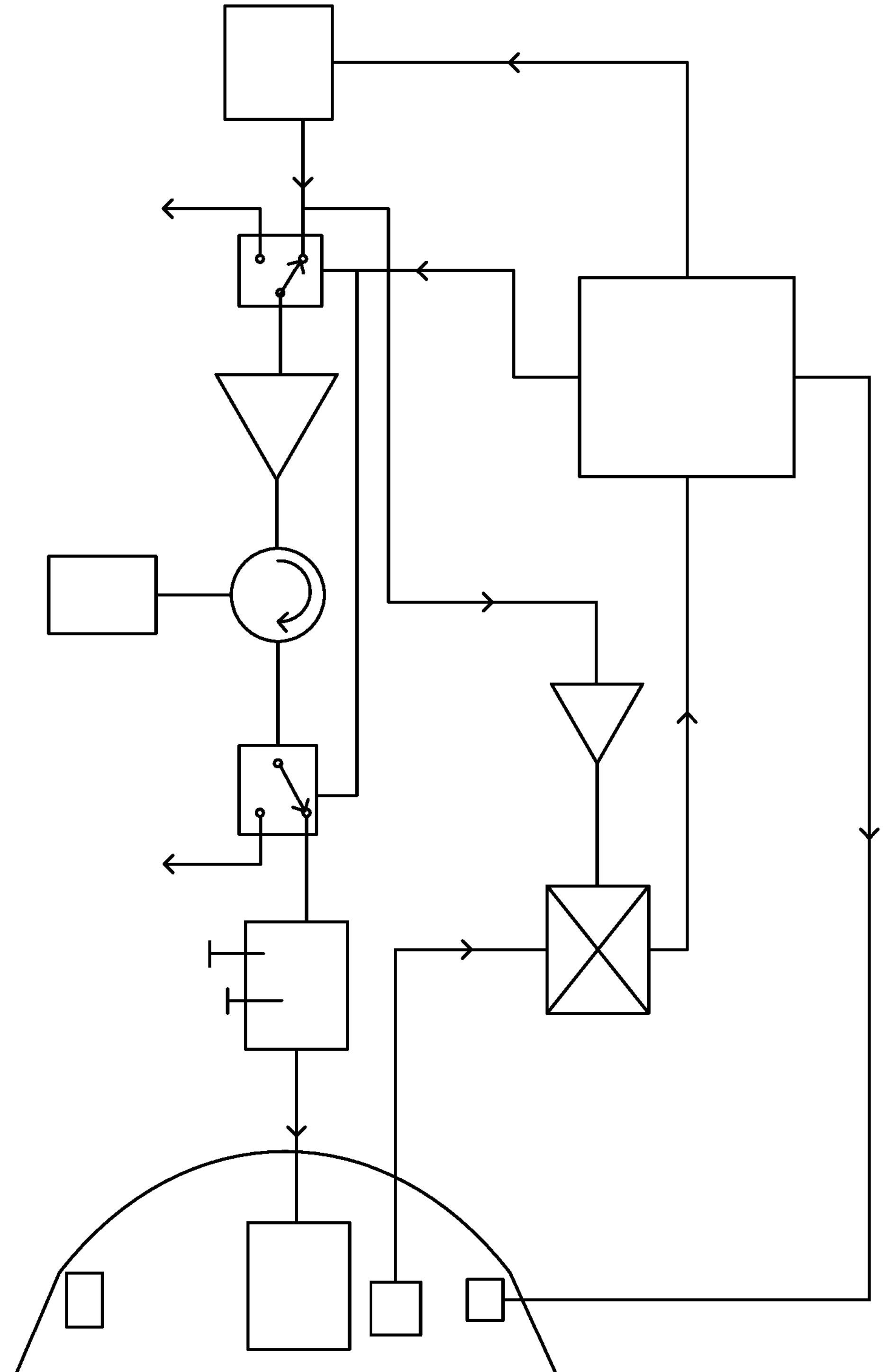

FIG. 5

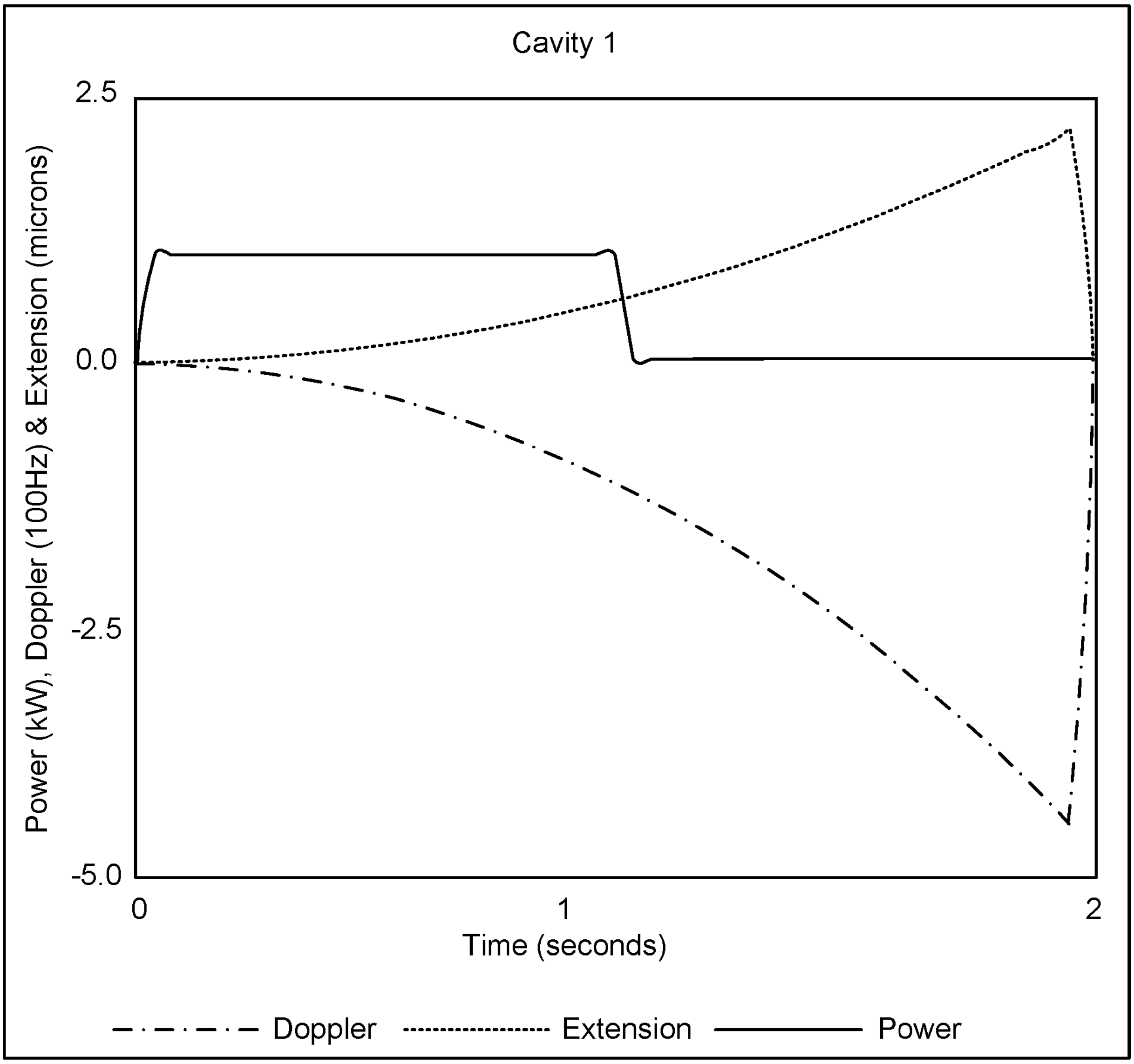
Cavity 1
Power (kW), Doppler (100Hz) & Extension (microns)
2.5
0.0
-2.5
-5.0
0
1
2
Time (seconds)
Doppler
Extension
Power

FIG. 6

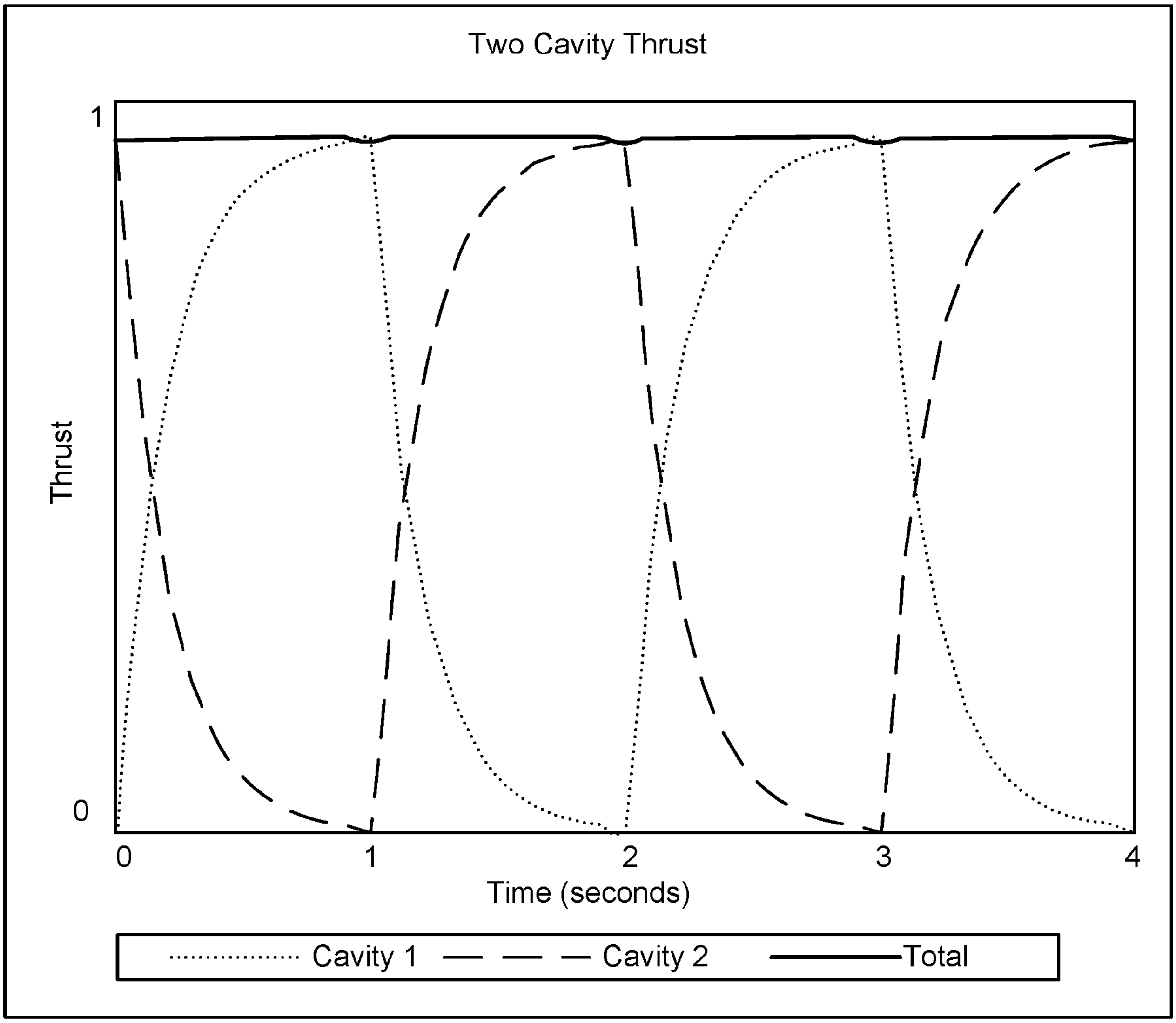
Two Cavity Thrust
Thrust
1
0
0
1
2
3
4
Time (seconds)
Cavity 1
Cavity 2
Total

FIG. 7

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2016/050974

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03H99/00
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, WPI Data, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 399 601 A (SHAWYER ROGER JOHN [GB]; SATELLITE PROPULSION RES LTD [GB]) 22 September 2004 (2004-09-22) abstract; figure 1 page 1 -----	1-10
A	GB 2 493 361 A (SHAWYER ROGER JOHN [GB]; SATELLITE PROPULSION RES LTD [GB]) 6 February 2013 (2013-02-06) the whole document ----- -/--	1-10

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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Date of the actual completion of the international search 7 September 2016	Date of mailing of the international search report 13/09/2016
Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Loiseleur, Pierre

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A,P	SHAWYER ROGER ED - CARNELLI IAN ET AL: "Second generation EmDrive propulsion applied to SSTO launcher and interstellar probe", ACTA ASTRONAUTICA, vol. 116, 10 July 2015 (2015-07-10), pages 166-174, XP029277761, ISSN: 0094-5765, DOI: 10.1016/J.ACTAASTRO.2015.07.002 the whole document -----	1-10
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T	John P. Costella: "Why Shawyer's 'electromagnetic relativity drive' is a fraud", , 5 October 2006 (2006-10-05), XP055299737, Retrieved from the Internet: URL:http://johncostella.webs.com/shawyerfraud.pdf [retrieved on 2016-09-05] the whole document -----	
T	DAVID BRADY ET AL: "Anomalous Thrust Production from an RF Test Device Measured on a Low-Thrust Torsion Pendulum", 50TH AIAA/ASME/SAE/ASEE JOINT PROPULSION CONFERENCE, 25 July 2014 (2014-07-25), XP055299725, Reston, Virginia DOI: 10.2514/6.2014-4029 ISBN: 978-1-62410-303-2 pages 11-21 ----- -/--	

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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