Progress In Electromagnetics Research M, Vol. 101, 1–8, 2021

Straightforward EMDrive Setup with NASA-Like Cavities

Hugo Peyre*, Jérôme Sokoloff, Olivier Pascal, Olivier Pigaglio, and Nathalie Raveu

Abstract—For replication concerns, this paper describes the work of the LAPLACE Electromagnetism Research Group to build NASA-like cavities in order to exploit the same electromagnetic configuration: the same resonant mode. These cavities are then implemented in our straightforward EMDrive experimental setup with a 0.1 mN sensitivity. Force measurement protocol is presented and discussed while more than 150 W of RF power is injected into the cavities. Results are compared to the NASA stated thrust to power ratio of 1.2 ± 0.1 mN/kW.

1. INTRODUCTION

The EMDrive engine is a concept of electromagnetic thruster that would be able to produce thrust without exchanging mass nor energy with an external medium. This type of propellantless engine seems to violate the principle of momentum conservation [1–3]. If this tiny but continuous thrust exists, it could, over time, accelerate a spacecraft to speeds inconceivable with current thrusters. This EMDrive engine is built on the assumption that a global force appears in a frustum cavity conveniently fed with microwaves. Up to now, no theoretical approach, accepted by the scientific community, can explain this phenomenon.

For ten to fifteen years, many research teams have been trying to experimentally demonstrate the existence of this force. According to White et al. [1], from the Johnson Space Center (NASA), their cavity produces an EMDrive-like force of 1.2 ± 0.1 μN per Watt of RF power injected into it. In order to independently check that result, some other research teams [2, 3] focused on replicating the NASA experiment (experimental setup, cavity, protocols, etc). With our own setup, our paper also fits this replication approach.

For our study, at the LAPLACE Plasma and Energy Conversion Laboratory, we developed a basic setup producing almost instantaneous calibrations and results [4–6]. In this paper, we present how we replicated two NASA-like cavities in order to exploit the same electromagnetic configuration, or resonant mode. In this way, Section 2 will describe why we are confident in feeding the right mode in quasi-identical cavities.

Once replicated, the cavities have been implemented in our straightforward EMDrive setup which main elements and advantages are recalled in Section 3.1. We then detail the protocol that allows us to measure an hypothetical EMDrive force with a sensitivity of 0.1 mN (see Section 3.2). Force measurement results are presented in Section 4 and discussed in Section 5.

2. NASA CAVITY REPLICATION

After the work described in [4] and [6] with frustum aluminium cavities, significant effort has been devoted to replicating the NASA Cavity.

Received 9 December 2020, Accepted 26 January 2021, Scheduled 30 January 2021

* Corresponding author: Hugo Peyre (peyre@laplace.univ-tlse.fr).
The authors are with the LAPLACE, CNRS, Université de Toulouse, Toulouse, France.

2.1. Cavity and Mode Identification from NASA Paper [1]

From reference [1], we can pick up some information about the cavity and the electromagnetic mode operated by White et al. at the JSC. The cavity is a 22.9 cm-high copper frustum with inner diameters of 27.9 cm for the large base, and 15.9 cm for the small one. Its remarkable feature is the presence of a dielectric cylinder (polyethylene) fixed inside at the small end. The cylinder is 5.4 cm-high and has a diameter of 15.6 cm (Figure 1). Although the type of polyethylene used isn't further specified in this paper, other studies [2, 3] precise that a disc of high-density polyethylene (HDPE) is used, with a relative permittivity ϵ_r of 2.25.

Through the lateral face of the frustum, White et al. chose to insert a 13.5 mm-diameter excitation loop in order to feed an azimuthal magnetic field close to this wall. At 1.937 GHz, this loop drives the cavity in a high Q-factor mode, called "TM212" by White. The mode's fields lines are depicted in the Figure 2 [1]. After multiple tests, White optimized the RF configuration and gave a Q-factor of 7,123 at a resonant frequency of 1.937 GHz.

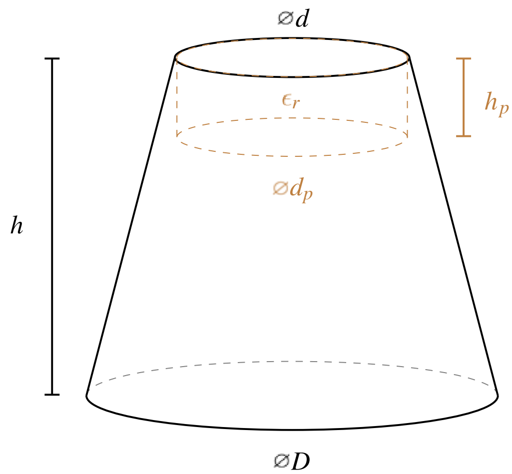

Figure 1. NASA frustum cavity design.

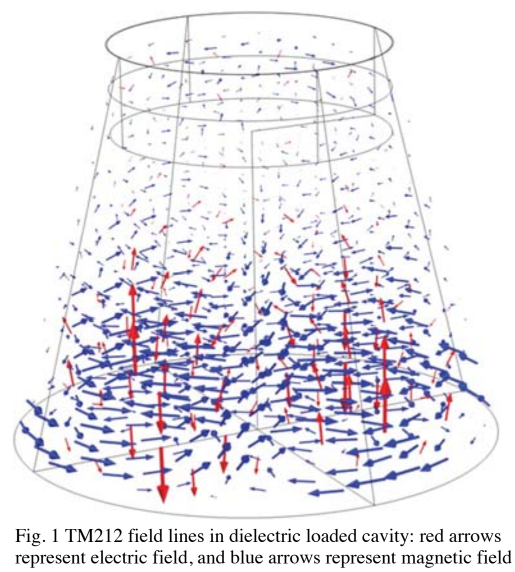

Figure 2. Electromagnetic field configuration of the "TM212" mode in the NASA cavity [1].

2.2. Replication of the Electromagnetic Configuration

All of the major EMDrive studies that followed [2, 3] were focused on replicating exactly the NASA cavity, in order to verify the results claimed by White et al. [1]. At the LAPLACE laboratory, we usually use microwave power in the 100 W range and around 2.45 GHz for plasma ignition purposes. To use our devices, we then need to switch up the resonant frequency. However, the crucial thing is to operate with the same electromagnetic configuration, i.e., the same resonant mode, the TM212 (see Figure 2). By homothetically reducing all the cavity dimensions, the resonant frequency of the mode is proportionally increasing without changing its electromagnetic field configuration. Thus, the new cavity has the same size according to the wavelength and hence keeps the same original shape but only looks smaller.

The first step of this replication approach is carried out through electromagnetic simulations, performed thanks to the ANSYS Electromagnetic Desktop software. With all the information picked up in the reference [1] (see Section 2.1), we can simulate an eigenmode inside the NASA cavity.

With the same dimensions and materials, the high Q-factor resonant mode, dubbed TM212 by White, can be achieved in the cavity with a resonant frequency of 1.974 GHz (see Figure 3(a)).

By comparing Figures 2 and 3(a), it is easy to guarantee that we have found the same resonant mode TM212. The fields are concentrated at the bottom of the cavity and are organized with four field

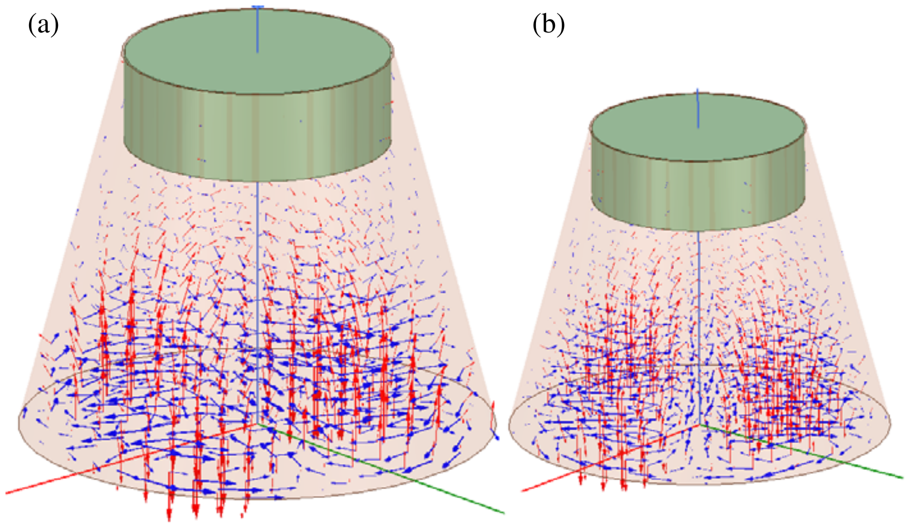

Figure 3. TM212 electromagnetic configuration simulated from the NASA cavity design (a) at 1974 MHz and (b) at 2450 MHz. Blue arrows represent magnetic field, and red arrows represent electric field.

maxima where the transverse magnetic field rotates around the longitudinal electric field. The slight difference in the resonant frequency (1.974 GHz instead of 1.937 GHz) may come from the classical deviation between reality and simulation (or even from ϵ_r variation), and, above all, from the insertion of the excitation loop (not simulated for Figure 3).

Now that we have found the TM212 mode at 1.974 GHz, we can perform a frequency translation towards 2.45 GHz to get into the frequency band of our RF source (cf. Section 3.1). Then, we have to reduce the cavity dimensions by multiplying all of them by a homothetic ratio $\kappa = 1974/2450 = 0.8057$. This transformation leads to the following cavity dimensions: $D = 22.48$ cm; $d = 12.81$ cm and $h = 18.45$ cm. The HDPE cylinder is then 4.35 cm high and 12.57 cm in diameter.

As expected, with these new dimensions, the TM212 mode is found at a resonant frequency of 2.45 GHz. Indeed, we get the right configuration with four field maxima concentrated in the bottom part of the cavity as we can see on Figure 3(b).

Driving such a high order mode with high Q-factor is not easy. In order to do it, a magnetic excitation loop is designed to be introduced on the lateral side of the cavity, as White et al. have done (Section 2.1) [1]. The goal here is to feed the azimuthal magnetic field close to this wall. A specific design of loop was simulated to correctly feed the cavity with a good Q-factor. Its insertion leads to a resonant frequency shifting as the effective cavity volume is reduced.

For calibration purposes outlined in Section 3.1, two units of this cavity have been manufactured with 0.5 mm-thick copper sheet to reduce their weight. They will later be called "Cavity A" and "Cavity B". A long experimental study has been carried out in order to empirically determine which feeding loop geometry to adopt.

Finally, it was found that a loop much larger than the simulated one was able to correctly drive the mode around 2.45 GHz. Such a larger loop causes a shifting of the resonance towards higher frequency. Figure 4 shows the reflection at the feeding access of both cavities under experimental conditions measured by the Vector Network Analyser (VNA) ANRITSU 37369C.

In Figure 4(a), we can see the spectral distance from adjacent resonant modes. Whether in simulation or in measurements, these modes appear poorly matched and far away from the targeted one, considering the 100 kHz tuning capability of the microwave source. We assume that this distance guarantees that we are feeding the same mode as White.

Figure 4(b) highlights the strong resonance of the cavities at 2.464 GHz for Cavity A, and at 2.4633 GHz for Cavity B. Despite all our efforts to make two identical loops for both cavities, the resonant frequencies are 700 kHz apart. However, both of them are well matched (reflection below −28 dB) and have good Q-factors.

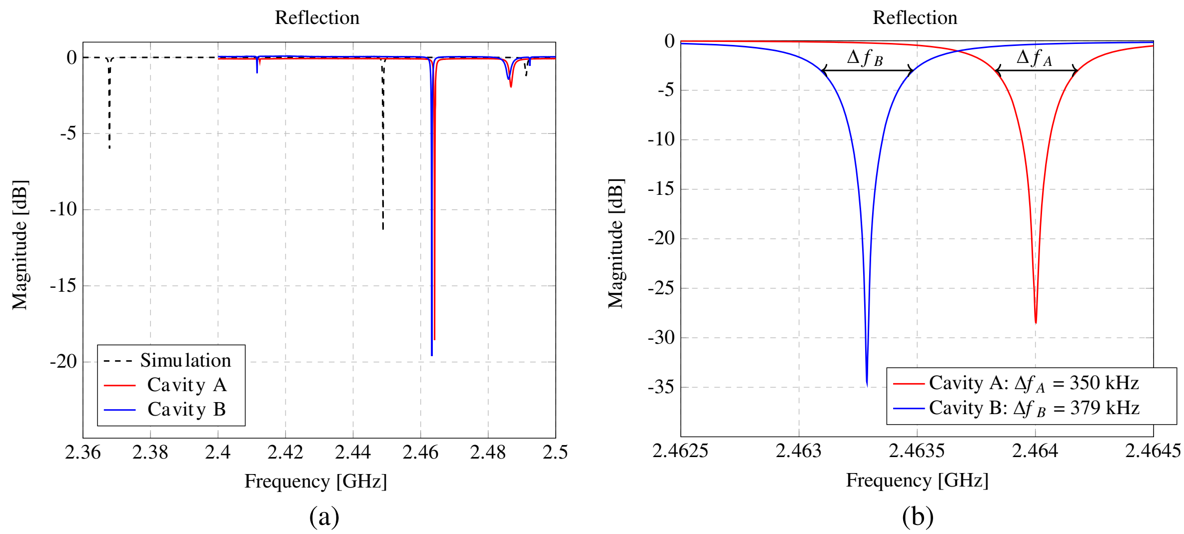

Figure 4. Simulated reflection (dashed curve) and measured one (solid curves) for both cavities (a) on a wide frequency band, (b) and on a narrower band around the measured cavities resonances.

The dimensionless Q-factor, or quality factor Q, of a resonant cavity expresses its ability to store energy compared to the energy lost on the walls (ohmic losses) and in the dielectric. When a feeding port is inserted into the cavity, access losses are added to the total losses, and the corresponding quality factor is called loaded quality factor Q_L. At the resonant frequency f_0, Q_L can be evaluated from the reflection measurement as:

$$Q_L = \frac{f_0}{\Delta f} \tag{1}$$

where Δf is the frequency bandwidth for which the reflected power is less than half of the incident power, i.e., reflection below -3 dB. Therefore, from Figure 4, the loaded Q-factors can be evaluated at 7039 for Cavity A and 6508 for Cavity B. Table 1 gathers the main characteristics of the TM212 mode excited in each cavity, and allow to compare them to those of the NASA cavity [1]. Despite the frequency translation, all these characteristics are very close.

Table 1. TM212 characteristics based on VNA measurements.

Cavities	Cavity A	Cavity B	NASA cavity [1]
Resonant frequency f_0 (MHz)	2464.0	2463.3	1937.4
Best matching (dB)	-28.5	-34.5	-31
Loaded quality factor Q_L	7039	6508	7123

3. FORCE MEASUREMENT METHOD

3.1. Experimental Setup

The main parts of the LAPLACE's EMDrive experimental setup, depicted in Figure 5, are extensively described in our previous papers [4–6]. Actually, the setup configuration is almost identical to that established in reference [6]: the cavities in Shaker configuration, positioned on the precision balance, are fed by the RF power unit through the contactless microwave transition.

The two quasi-identical copper cavities are assembled and oriented in opposite directions. Combined with an RF switch, this Shaker configuration allows to switch the direction of the hypothetical EMDrive-

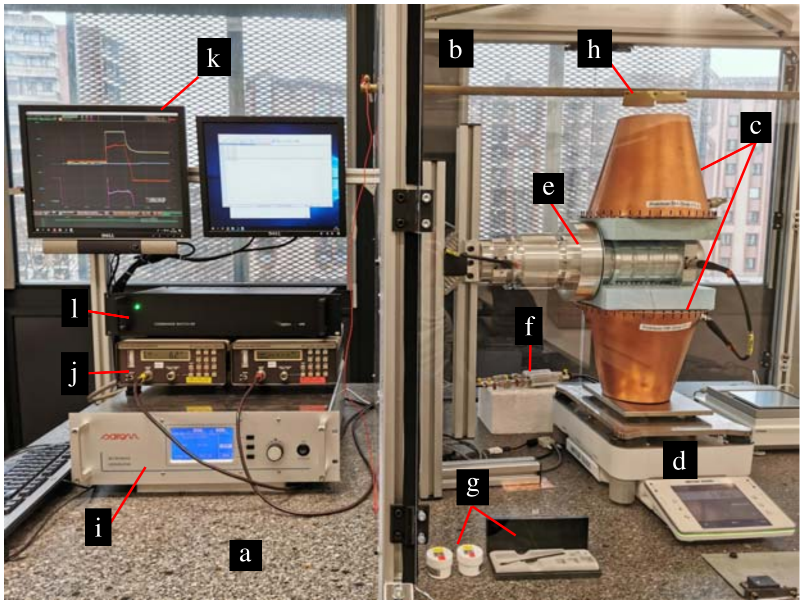

Figure 5. LAPLACE's EMDrive experimental setup mounted (a) on a marble block. (b) Under the Plexiglas enclosure, the operating part includes (c) the NASA-like cavities A and B in shaker configuration positioned (d) on the precision balance and fed thanks to (e) the contactless microwave transition [5]; (f) power probes collect the incident and reflected powers, (g) and F1 class standard weights are used for the calibration processes of the balance, achieved thanks to (h) the double calibration mechanism. On the left of the enclosure, the monitoring part is made up of (i) the microwave source, (j) the powermeters, (k) a computer for real-time monitoring and control, (l) and the RF switch driver to remotely select which cavity to feed.

like force without changing the parasitic effects [4]. Moreover, at the instant of the cavity switch, a relative force of twice the EMDrive-like force is measurable [6].

The RF power unit, feeding these cavities, is mainly composed by the microwave source which provides power up to 200 W at a frequency accurately tuned between 2.43 GHz and 2.47 GHz. A bi-directional coupler is used in the feeding circuit in order to measure the injected and reflected powers with power meters.

The Shaker configuration is fed thanks to the contactless microwave transition. This transition has been designed to transmit high RF power (≈ 150 W, taking into account the losses in RF cables and connections) without affecting the force measurement [5]. This quadrupole device allows to transfer the power through two independent channels in order to feed both cavities. To select which cavity to feed, the RF switch is then placed between the coupler and the contactless transition.

Force measurement is performed by a precision balance. Its display accuracy is 10 mg (≈ 0.1 mN). The cavities have been made with thin copper sheet (0.5 mm) so that the total weight of what is on the precision balance (cavities + part of the transition) is around 4.350 kg.

The time response of the balance has already been characterized in [6]. Loaded with the device under test, its sensitivity is 0.2 mN with a response time overestimated at 1 s. Indeed, the precision balance is able to detect a minimum standard weight of 20 mg by measuring it at 10 mg with a response time of 1 second or less.

An in-house software makes it possible to monitor in real time the progress of the experiment run. Every 20 ms, it records and displays the evolution of the power measurements from power meters and of the weighing measurement from the precision balance. Moreover, it remote controls the RF power unit: the power and frequency of the wave delivered by the source, as well as the output of the RF switch, can be programmed.

3.2. Protocol

The measurement runs used in this paper (Section 4) are very similar to those presented in the previous one [6]: calibrating, powering-up, switching between cavities (in shaker configuration) phases are adequately sequenced. Indeed, in order to surely determine if the balance is able to measure a force greater than or equal to 0.2 mN, two calibration steps are performed at the beginning and at the end of a measurement run. They consist in depositing a 20 mg standard weight on top of the Shaker configuration. As already mentioned in [6], a small mechanical system allows to make the deposits without disturbing the sensitive balance measurement, and these weights are detected as an increase of 10 mg.

During the powering-up phase, a single switch between the two matched cavities is performed acting on the microwave switch and slightly changing the source frequency. The RF switching time is in the millisecond range and is then much lower than the acquisition time of the software (20 ms) and the response time of the precision balance (1 s). Each feeding duration is chosen at 3 seconds so that it is longer than the response time of the balance but not too long to reduce the total measurement time and avoid the risk of parasitic thermal effects emerging.

In this way, the great improvement of the force measurement protocol is the capability to program a test sequence in which the injected frequency and power can be changed together with the switch output.

At the instant of the switch, the direction of the hypothetical force is changing without any intervention of an operator. The relative force that can be measured in this configuration is then twice the EMDrive-like force that one cavity could produce. The whole setup sensitivity to EMDrive-like force is therefore the half of that of the balance (0.2 mN), and is then equal to 0.1 mN.

The protocol is finally achieved with the following sequence: first calibration step, power up: 200 W is delivered by the RF source towards a first cavity at its resonant frequency during 3 seconds, then the RF switch redirect the frequency adjusted power towards the second cavity during 3 seconds before shutting down the generator and final calibration step.

Since we can only add a standard weight during the calibration steps (not remove it), they can only account for the ability of the balance to detect an increase in the measured weight (downward force). Since the orientation of the EMDrive force is unknown, two measurement runs will be presented in Section 4. In the first one, the initial cavity to be fed is Cavity A; and in the second one, it is Cavity B. If an EMDrive-like force exists, one of these two runs surely corresponds to an increase in the apparent measured weight.

4. RESULTS

This section presents the force measurements performed by the LAPLACE's straightforward EMDrive setup implementing NASA-like cavities.

The measurement protocol described above (Section 3.2) was applied and resulted in two measurement outcomes displayed in the form of chronograms. On the upper part of these, the weight reading of the precision balance is shown in blue (mg scale on the left axis). Below, the incident power curve is plotted in orange and the reflected power curve in red (W scale on the right axis).

Figure 6 illustrates the measurement run where cavity A is fed first, followed by cavity B, while Figure 7 corresponds to the reverse scenario. Each of these runs has been repeated multiple times giving the same final result.

During the power-up phase, the microwave source delivers a power of 200 W, and only about 160 W reaches the input of the cavity to be fed. In both runs, the measurement of the reflected power demonstrates that the cavities are very well matched when being powered. Moreover, the frequency change is effectively done at the same time as the cavity switch and is almost imperceptible on the reflected power curve.

As expected, during all these runs, the 20 mg weights are always measured at 10 mg. However, no weight variation is recorded when the cavities are switched, neither when the microwave power is turned on and off. Then, it can be concluded that no force greater than 0.2 mN is detected by the precision balance when microwave power is modified.

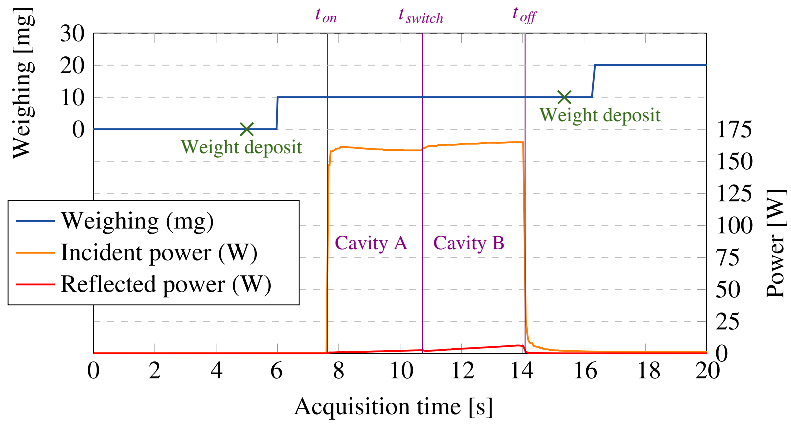

Figure 6. First experimental run chronogram gathering all the collected measurements. Cavity A then Cavity B. Two 20 mg-calibration steps: one before powering-up, the other after.

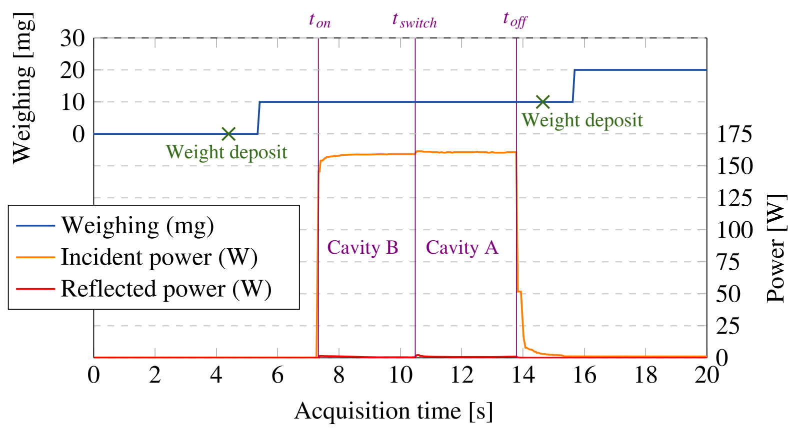

Figure 7. Second experimental run chronogram gathering all the collected measurements. Cavity B then Cavity A. Two 20 mg-calibration steps: one before powering-up, the other after.

5. DISCUSSION

Thanks to the measurement protocol and Shaker configuration, the relative force is theoretically doubled at cavity switch events. Then, the sensitivity of the whole experimental setup is reduced at 0.1 mN. In Figures 6 and 7, the 1-second window after the t_{switch} mark corresponds to the period during which we would expect a response from the balance that would be an EMDrive-like force signature. However, in both runs, no force has been measured during this phase. Therefore, no EMDrive-like force has been detected above the sensitivity of 0.1 mN.

In addition, an average RF power underestimated at 150 W has been injected into our NASA-like cavities that are built with the same materials. The same TM212 mode is powered inside, despite the homothetic ratio. We have also demonstrated that they have electromagnetic characteristics similar to those of the NASA cavity (Section 1). If we assume having also the same efficiency of 1.2 ± 0.1 mN/kW [1], then each of our cavities could produce an EMDrive-like force of at least 0.165 mN. Nevertheless, we do not detect any, whereas the sensitivity of our experimental setup is 0.1 mN at the switch moment. In other words, each of the cavities would produce a force of 0.165 mN when fed at its resonant frequency. At the moment of the switch, the relative force is doubled and would then be equal to 0.33 mN. However, the balance has not detected any, even though it is perfectly suited to measure a force greater than or equal to 0.2 mN.

6. CONCLUSION

First of all, the NASA Cavity design has been successfully replicated and manufactured in two units with 0.5 mm-thick copper sheet. Despite the homothetic ratio, the TM212 resonant mode is properly fed around 2.46 GHz. As for White et al. [1], the loaded Q-factors approx 7000 or a bit less, and the best matching is at least -28 dB.

The sensitivity of the precision balance is 0.2 mN. Nevertheless, the Shaker configuration and measurement protocol make it possible to create a relative force of twice the EMDrive-like force that one cavity could produce. The sensitivity of the experimental setup can then quite safely be considered at 0.1 mN. However, no EMDrive-like force has been detected above this sensitivity.

Despite all our efforts, we still work at the limit of the current precision balance's sensitivity. In this way, the last step of our EMDrive study will consist in performing similar force measurements with a more accurate new precision balance.

ACKNOWLEDGMENT

All the authors would like to thank both CNES (french National Centre for Space Studies) and AID (french Innovation and Defense Agency) for funding Hugo Peyre's work.

REFERENCES

1. White, H., P. March, J. Lawrence, J. Vera, A. Sylvester, D. Brady, and P. Bailey, "Measurement of impulsive thrust from a closed radio-frequency cavity in vacuum," *Journal of Propulsion and Power*, Vol. 33, 830–841, Jul. 2017.
2. McDonald, M. S., M. W. Nurnberger, and L. T. Williams, "Preparations for thrust measurement and error discussion of the impulse resonant microwave cavity," *Journal of the British Interplanetary Society*, Vol. 70, 415–424, 2017.
3. M. Kößling, M. Monette, M. Weikert, and M. Tajmar, "The SpaceDrive project — Thrust balance development and new measurements of the Mach-Effect and EMDrive Thrusters," *Acta Astronautica*, Vol. 161, 139–152, Aug. 2019.
4. Sokoloff, J., O. Pascal, O. Pigaglio, N. Raveu, and H. Peyre, "Proposal of a handy setup for discriminating parasitic effects for the measurement of impulsive thrust from a microwave cavity," *Progress In Electromagnetics Research C*, Vol. 98, 269–281, 2020.
5. Peyre, H., O. Pascal, J. Sokoloff, K. Elis, O. Pigaglio, and N. Raveu, "High power transmission using contactless microwave transition on an emdrive setup," *Progress In Electromagnetics Research Letters*, Vol. 90, 15–20, 2020.
6. Peyre, H., J. Sokoloff, O. Pascal, O. Pigaglio, and N. Raveu, "Sraightforward emdrive setup using a microwave contactless transition: First results on frustum cavities," *Progress In Electromagnetics Research M*, Vol. 95, 45–52, 2020.