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Membrane actuation by Casimir force manipulation

Fabrizio Pinto

InterStellar Technologies Corporation, 115 North Fifth Avenue, Monrovia, CA 91016, USA

E-mail: fabrizio.pinto@interstellartechcorp.com

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Abstract

In our laboratory, we have been developing a practical demonstration of actuation by means of the Casimir force inspired by the capacitive detection approach originally described by Arnold, Hunklinger and Dransfeld (1972 *Rev. Sci. Instrum.* **43** 584–7). In this paper, we first describe the mathematical challenges pertaining to the electrostatic calibration of our measuring device, which has been enhanced by our recently published results regarding the computation of electrostatic fields in axial systems, such as the long-standing classical circular capacitor problem. We also discuss our computational approach to the calculation of the Casimir force in our system, including our adoption of analytical descriptions of the dielectric functions of semiconductors extended to the case of axial geometries. We will illustrate how the original AHD apparatus has been drastically improved upon, for instance by means of modern nanopositioner technology, and we shall discuss our published experimental results on the dynamics of a vibrating membrane with a central disc, which have provided the first direct verification of the mechanical resonances of such a system. The emphasis of our effort is not exclusively directed to fundamental physics research but is focused on, and ultimately motivated by, our goal of identifying viable industrial applications leading to commercially marketable products based on Casimir force actuation. Therefore we conclude this paper by briefly discussing the contribution we believe these results will offer to some current technological problems, in particular in nanotechnology, including some thoughts on the possibility that dispersion forces may enable a new and rapidly expanding industry to develop in the near future.

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1. Introduction

The dependence on illumination of van der Waals forces in semiconductors was first reported by Arnold, Hunklinger and Dransfeld (AHD hereinafter) [2], who made use of a dynamic detection technique novel to that application [1, 3]. Although those early efforts were only partially conclusive, they presented for the first time the intriguing possibility to alter dispersion forces between boundaries, for instance by means of radiation. Such a development was very significant since van der Waals forces have been traditionally treated as a fabrication and performance limitation and not as an engineering resource [4–13].

In this paper, we report about the recent progress of a project to demonstrate the actuation of a macroscopic membrane by means of time-dependent dispersion forces carried out in our laboratory by significantly expanding on the AHD experiment. The original approach of those authors consisted of a strategy generally familiar from the dynamical measurement of contact potentials [14–18]. In the AHD case, a small dielectric disc cemented to the center of the membrane of a condenser microphone interacted with a convex 'lens' placed at a submicrometer distance from the disc itself. The lens was attached to the diaphragm of an ordinary speaker that was driven into vibration by an external, time-dependent voltage source. The resulting time-dependent gap width between the lens and the small disc caused the van der Waals force between the two boundaries to become periodic thus forcing the membrane into vibration. By modulating the dispersion force between the two elements at the fundamental resonant frequency of the membrane-disc system under a moderate vacuum, the resulting displacement caused a measurable electric signal. Finally, this electromechanical response could yield the magnitude of the van der Waals force provided the system had been previously calibrated by means of electrostatic forces of known intensity [1, 3].

In a very important development, those authors later investigated the effect of illumination on the van der Waals force between semiconductors. This was achieved by depositing a thin layer of amorphous silicon on a small, central region of the lens facing the disc assembled on the membrane. By back-illuminating the silicon deposition with white light of constant intensity, the technique described above demonstrated for the first time that the magnitude of the van der Waals force in semiconductors depends on the charge carrier number density. However, agreement with the predictions of the Casimir–Lifshitz theory of dispersion forces [19–23] was not entirely satisfactory [2]. Importantly, a new perspective on the results of the AHD experiment has been provided by the recent investigations of the van der Waals force involving semiconductors conducted with sophisticated atomic force microscope (AFM) techniques, which also resulted in an unsatisfactory agreement with the Lifshitz theory [24–26].

2. Motivations for the present study

The intriguing discrepancies just described provide a first motivation to attempt to gain a much-improved characterization of the electromechanical response of the type of sensor employed in the AHD experiment. A second research subtopic has been the search for a realistic experiment centered on dispersion forces to differentiate between the apparently equivalent predictions of stochastic- (SED) and quantum-electro-dynamics (QED) [27–31]. Finally, and most importantly to our effort, is the compelling need to explore the technological connection between dispersion force manipulation and nanoactuation. This stems from the fact that all demonstrations of micro-electro-mechanical-system (MEMS) actuation by means of the Casimir force have so far transferred mechanical energy to the microdevice by physically altering the interboundary Casimir gap width by means of an external mechanical actuator—similarly to the original AHD experiment described above. Although this is an interesting achievement, it does not represent the stand-alone actuation of a microstructure, which is the critical goal needed to design useful products based on dispersion forces. However, the transfer of energy to a MEMS can be achieved by designing ordinary thermodynamical engine cycles based on dispersion force manipulation, as first shown by the present author [30].

The above research directions demand that a drastic improvement on the accuracy of previous numerical computations of the Lifshitz integral in semiconductors be achieved [32, 33] while at the same time enhancing their flexibility. For this purpose, we employed, also for the first time, a highly accurate Kramers–Kronig consistent, five-oscillator critical point (CP) model of the band spectrum of silicon [30, 34, 35]. As clearly stated by Etchegoin *et al* in their work on the optical properties of gold [36]: 'One could argue that an analytical model for $\epsilon(\omega)$ is not really necessary, and that it is always possible to resort to interpolations of the experimental data. However, the advantages of having a realistic analytic representation of $\epsilon(\omega)$ with a small number of physically meaningful parameters are self-evident, not only for simulations but also to understand situations where the intrinsic parameters of the metal might be modified by external perturbations.'

These comments are especially relevant in light of the well-known 'frustrating uncertainties' [37] in the numerical details of $\epsilon(\mathrm{i}\xi)$ generation from optical data available in various data banks and software repositories [38] as well as non-standardized sample preparation and experimental methodology [36, 39, 40]. In particular, parametric approaches to dispersion force calculation promise to be quite effective to investigate our early result that the Casimir–Lifshitz theory may need refining on thermodynamical considerations [30], the above puzzling discrepancies revealed by the AFM measurements [26], as well as to address various industrial applications under development in our laboratory.

3. Logical importance of the electrostatic calibration procedure

At the foundation of any conclusion regarding the behavior of dispersion forces in real materials there necessarily lies an accurate characterization of the response of the sensing device to other forces which must be *independently* known. Quite typically, one employs electrostatic test forces whose behavior is obtained from 'textbook results.' It is therefore important to reflect on the fact that the quality of our present understanding of dispersion forces, including the existence of the above possible disagreements between theory and experiments, comes to logically rest upon the assumption that a few 'elementary electrostatics' results can indeed accurately model the systems to which they are applied. For instance, since earlier experiments, the relative determination of the distance between two conducting objects has relied upon analytical equations for the capacitance [41]. However, attempts to electrostatically calibrate a MEMS device employed to detect the effects of variable optical properties on the Casimir force were reported to have been 'not successful' as the results were 'not reproducible' [42].

In the case of the AHD experiment, calibration was summarily described as having being carried out by replacing the lens assembled on the loudspeaker by a 'small metal plate' and by establishing a periodic potential between it and the microphone membrane [1, 3]. By assuming that the force between the two conductors can be found, presumably from the elementary equations for a circular capacitor partially filled with a dielectric, the electrostatic force acting on the membrane was obtained (the interboundary distance was measured interferometrically and not electrostatically). However, this procedure, familiar in acoustics, is well known to only yield reliable results as a secondary calibration, mainly because of difficulties to accurately measure the distance between the electrostatic actuator and the microphone membrane. In addition, the entire process typically neglects fringing effects and it assumes that the electrostatic pressure is a constant everywhere on the membrane [43–52].

At the present time, we are investigating whether such uncritical reliance on elementary electrostatics results to calibrate Casimir force experimental devices is appropriate by exploring, both numerically and experimentally, some geometries relevant to dispersion force research. Some advancements made in formulating the problem of electrostatic field computation in axisymmetric geometries in the presence of both conductors and dielectrics have recently been reported and an error in the literature has been recently identified [53].

In principle, once the test force acting on the sensing element is computed, it is possible to model the electromechanical response of the system. However, this step as well assumes that the dynamical response to either the test force or the dispersion force be well understood. For instance, the non-trivial frequency response of a membrane-disc system of the type used in the AHD experiment, even if driven by an axisymmetric electrostatic excitation, has only recently been explored for the first time by the present author [54].

4. Potential in realistic actuator-microphone systems

In order to explore the applicability to laboratory situations of the elementary equations typically used in the calibration of dispersion force experiments, we started from an investigation of the classical circular capacitor problem, which has a very long history [53, 55–59]. Initially, we carried out successive overrelaxation (SOR) computations of the capacitance of two identical plates symmetrically placed within a grounded conducting enclosure by means of finite-difference schemes in axisymmetric geometries [53] and we compared our results to the predictions of both the elementary equation for capacitance and those from the so-called Kirchhoff approximation [60, 61].

This geometry was then further complicated by adding a small dielectric disc in the center of one of the two conducting plates. This case is extremely rarely treated in the literature even numerically because, in order to reduce fringing, any dielectric material in the gap is usually allowed to extend well beyond the outer circumference of the capacitor [53]. In the case of a dielectric disc partially filling the gap, any elementary analytical approximations were found to be unsatisfactory when compared with the SOR results both for relatively small and large gaps.

Finally, the above predictions were experimentally verified by measuring the mutual capacitance of pairs of aluminum mirrors assembled on computer-controlled actuators and placed within a grounded cavity. These measurements were then repeated after epoxing a small disc of fused silica (High Purity Fused Silica Corning 7980 of UV grade) to one of the two optical flats within the grounded enclosure. The results, to be reported in detail elsewhere, have conclusively shown that, even in the absence of dielectrics, the Kirchhoff approximation can at most serve as a useful guide to obtain an initial best-fit of the behavior of the capacitance by means of numerical models.

In the following step of this project, these relatively idealized geometries were relaxed and the potential field of a realistic microphone modified with a dielectric disc and in proximity of an electrostatic actuator was computed. These results allow us to obtain the electrostatic pressure acting on the disc-membrane system, which is a critical dynamical variable needed to compute the calibrated electromechanical response of the microphone [63, 62]. As is clearly visible in a typical result (figure 1), the pressure across the annular area surrounding the disc is not constant and, although this problem can be reduced, it cannot be eliminated since of course the gap cannot be made smaller than the thickness of the dielectric disc.

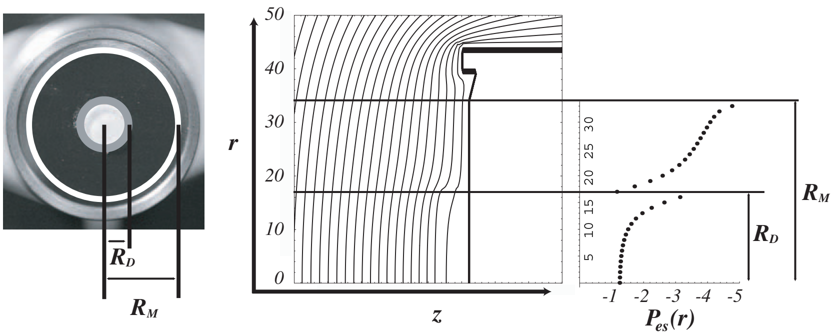
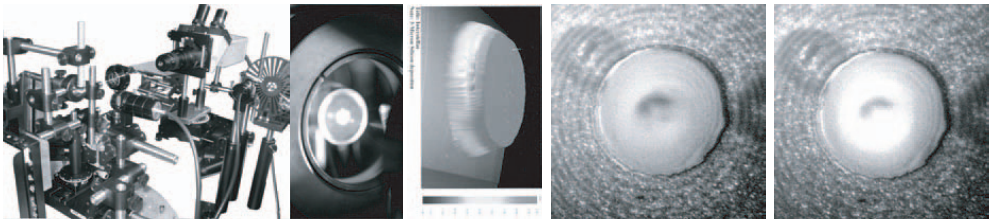


Figure 1. A condenser microphone (ACO Pacific model 7013) with membrane radius $R_M = 0.495$ cm modified by cementing a disc of fused silica ($\epsilon_r = 3.78$) with radius $R_D = 0.125$ cm in its center (left); a sample SOR computation ($R_D = 0.25$ cm for clarity) of the equipotential curves for a microphone-actuator gap $s = 0.5$ cm showing the fringing effects of the disc and of the sharp tapering of the membrane at the outer locking ring (center); the electrostatic pressure on the membrane-disc system is not uniform both on the disc and on the free annular membrane area surrounding it (right).



(*a*) (*b*) (*c*) (*d*) (*e*)

Figure 2. (*a*) The membrane actuation proof-of-concept inspired by the original AHD experiment (see the text); (*b*) the backside of the lens and silicon deposition illuminated by laser radiation; (*c*) scan of a 3 μm amorphous silicon deposition; (*d*) the silicon deposition backside imaged by a microscope and Hamamatsu 1394 ORCA high speed CCD camera located outside the vacuum chamber (not shown) while laser pulses illuminate the center of the silicon deposition (bright dot in (*e*)). Newton's rings for positioning are visible around the deposition. The grainy appearance of the image is due in part to the texture of the silica disc and microphone steel membrane on the opposite side of the lens.

5. Membrane actuation proof-of-concept

The central goal of our present effort, as the expected effects of radiation on the Casimir force are accurately modeled and a logically consistent calibration procedure is completed, is to move beyond basic measurement and to demonstrate the application of Casimir force manipulation to nanoactuation in devices with practical technological usefulness. For this purpose, we have implemented a proof-of-concept demonstration which leverages the many significant instrumentation advances made since the original AHD experiment (figure 2). The distance of the amorphous silicon deposition from the facing disc-membrane capacitive sensor is monitored by a high speed CCD camera which can image Newton's rings while a piezoelectric nanoactuator provides extremely stable and reproducible positioning. Further adjustment of the absolute position of all critical elements under vacuum is provided by multi-axis, digitally controlled servo-motors.

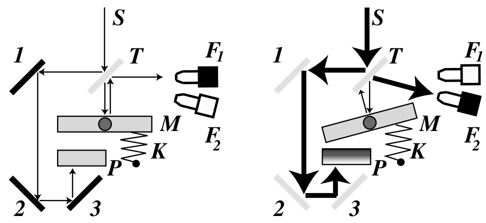


Figure 3. Schematic view of a possible implementation of a thermodynamical engine enabled by Casimir force manipulation. A rotating mirror *M* is held in equilibrium by the torque due to an elastic force of constant *K* and that due to the Casimir force between the mirror itself and a semiconducting plate, *P* (left). The intensity of the Casimir force is controlled by a radiation beam *S* of suitable frequency, which is first split at *T* and then directed in part to the backside of the semiconducting boundary by the fixed mirrors $1 \to 2 \to 3$. The remainder of the beam is received by optical fiber F_1. If the intensity of the beam is increased (right), the Casimir force also increases and the beam is directed to fiber F_2 (angular values are chosen for illustration only). This device can act, for instance, as an optical switch, an adaptive optics element, an energy storage system, or a Casimir force-driven oscillator.

Special care is being paid to characterizing and drastically reducing the radiation pressure and thermal effects of photons possibly directly impinging upon the microphone membrane [25]. In addition, we are exploring various alternative configurations of the disc-membrane sensor, including approaches in which the Casimir force is not axially symmetric and it excites modes of oscillation in which the dielectric disc is periodically tilted away from the plane of the membrane. Finally, we are experimenting with sensors in which the dielectric disc is completely absent and the Casimir force acts directly on the microphone membrane itself. Since some of our novel geometries could only very tentatively be treated analytically, our experiment is supported by an ongoing parallel mathematical effort to provide accurate estimates of the Casimir force in our specific system based on numerical Green function computation [65].

6. Nano-electro-mechanical-system applications

Since the beginning of our industrial effort, it has become increasingly clear that dispersion force manipulation represents a viable solution to several problems of great strategic importance in the future development of micro- and nano-technology [66]. A timely example is that of energy conversion and storage on the nanoscale, which has recently attracted attention because of its potential applications in bio-nanorobotics [67, 68]. Whereas those authors suggested that the energy needed for their piezoelectric nanogenerators could be provided by various 'body movements' or some other 'mechanical vibration,' we have proposed that nano-devices based on engineering the quantum vacuum could very effectively convert energy from their surrounding environment by implementing engine cycles based on the interplay between mechanical (or electrical) energy and dispersion forces (figure 3).

In addition, since dispersion force manipulation strategies are usually focused on the use of semiconducting boundaries, the obvious potential exists for 'on-chip' integration of computing power and nano-electro-mechanical capabilities. We believe that this could lead to the development of solar panels capable of 'intelligent' energy conversion, storage and management.

More in general, dispersion force manipulation could decisively benefit several other areas of technology under constant market pressures to downscale their products, yet still based on traditional approaches. For instance, electrostatic actuation is a commonly used strategy in MEMS-based adaptive optics systems [69, 70]. In contrast, our experimental membrane actuation demonstration could be viewed as a first practical proof-of-concept for an adaptive optics system in which wavefront correction is achieved by light itself (figure 3). Similarly, RF-NEMS oscillators based on the actuation of vibrating nanostructures by means of dispersion forces might yield device densities far higher than presently possible and be ready to meet the exponentially increasing capability demands of the mobile telecommunications market.

7. Conclusions

It is appropriate to stress that our industrial effort is constantly inspired by the life-long leadership activities of Hendrik Casimir (1909–2000) at the Philips Naturkundig Laboratorium in Eindhoven [71, 72], which he deliberately chose over the opportunity to succeed Kramers at the Leiden Institute [73]. Although today Casimir is almost exclusively cited in the fundamental research literature because of his seminal theoretical papers [19, 20], one cannot fail to also be impressed by Casimir's own forceful advocacy to protect research funding as well as by his writings on the mutually supporting roles of academia and industry [74, 75]. There is reason to believe that the present phase of dispersion force manipulation experimentation will spur vigorous technology transfers according to Casimir's 'spiral model' of industrial development [75] and eventually lead to significant applications in energy, medicine, optics and telecommunications [64, 76].

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