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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
1 May 2014 (01.05.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/064688 A1

(51) International Patent Classification:
H01M 10/04 (2006.01)

(21) International Application Number:
PCT/IL2013/050852

(22) International Filing Date:
22 October 2013 (22.10.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/795,640 22 October 2012 (22.10.2012) US

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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, LT, 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, 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).

Published:

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

(54) Title: ELECTROMECHANICAL BATTERY

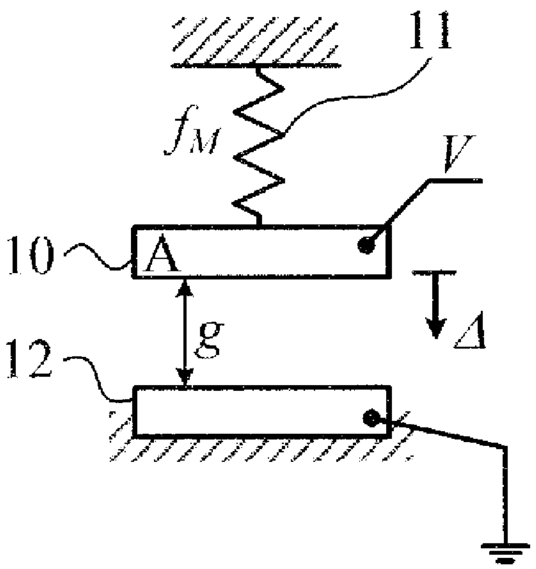

FIG. 1a

(57) Abstract: An electromechanical battery based on a parallel plate capacitor, in which mutual motion of the oppositely charged plates with change in the charge held by the capacitor is controlled by a mechanical spring having a nonlinear force-displacement relationship, predetermined such that the voltage across the capacitor remains constant with changes in the charge held by the capacitor. The charge held by the capacitor generates an attractive electrostatic force between the plates which is in equilibrium with the mechanical force exerted on the plates by the mechanical spring. The mechanical spring may be a beam with one end wrapped on a cam, such that the free length of the beam changes with flexing of the beam, or it may be the elastic flexing of the plates themselves. Protrusions having predetermined heights and positions may be used to tailor the force-displacement relationship of the flexing plates.

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ELECTROMECHANICAL BATTERY

FIELD OF THE INVENTION

The present invention relates to the field of energy storage batteries, especially those using mechanical energy as the energy storage medium

BACKGROUND OF THE INVENTION

Autonomous electronic systems which are not connected to the power grid require an electric power source. Most often a chemical battery serves as the power source in such systems. An ideal battery is a device that may store or supply electric charge while maintaining a constant voltage. A constant level of voltage is frequently crucial for proper operation of electronic systems. Chemical batteries perform as ideal devices as long as the current they absorb or supply is not excessive. If too much current is extracted from the battery its voltage may drop considerably. Likewise, if too much current is supplied to a battery during charging, it may cause irreversible damage due to overheating and unwanted chemical reactions. If excessive amounts of charge are to be stored or extracted in a relative short time, the battery may be replaced by a large capacitor, or may be supplied with a support capacitor to supply the higher current discharges when called for. A capacitor may be charged and discharged rather rapidly, but the voltage on a capacitor is not constant but rather it is proportional to the amount of charge which it carries. If a large capacitor is used, and only a small part of its stored charge is drawn during the desired current discharge, then a close to constant voltage can be obtained, but at the cost of the volume and expense of the larger than needed capacitor.

There therefore exists a need for a battery which provides a constant output voltage as current is drawn from it, which does not have the charge and discharge limitations of am electrochemical battery and which does not take up the space of a large capacitative "battery".

The disclosures of each of the publications mentioned in this section and in other sections of the specification, are hereby incorporated by reference, each in its entirety.

SUMMARY

The present disclosure describes a new exemplary electromechanical battery that stores and supplies electric charge at a constant voltage. Instead of transforming electric energy into chemical energy as in a chemical battery, in the electromechanical battery the electric energy is stored in elastic deformation such as an elastic spring. The electromechanical battery may take the form of a variable capacitor. Seemingly, the simplest ideal variable capacitor is the parallel-plate electromechanical transducer. The parallel-plate transducer is constructed from a movable plate electrode that is suspended on an elastic spring close to a fixed electrode. The movable electrode has a single degree-of-freedom, namely in the direction to and from the fixed electrode. The movable electrode may conveniently be subjected to a voltage and the fixed electrode electrically grounded, or vice versa. In equilibrium, the attractive electrostatic force between the electrode plates, which is inherently non-linear, is balanced by the mechanical restoring force in the elastic spring. If the spring is linearly elastic, then the restoring force is proportional to the displacement of the moveable electrode, and the relationship between the driving voltage between the electrodes and the displacement of the moveable plate is a non-linear function, which becomes unstable, showing a negative stiffness after the point of maximum controlled motion, beyond which the plates pull-in. The pull-in voltage associated with that point is the maximal voltage that can be applied to the linear spring system before it loses stability.

On the other hand, if, for a given capacitor plate geometry, the spring is designed to have a predetermined non-linear force-displacement relation such that the mechanical spring force is proportional to the reciprocal of the square of the residual gap between the plates, i.e.

$$f_M \propto \frac{1}{(g-\Delta)^2}$$

where f_M is the mechanical restoring force of the elastic spring, g is the initial gap between the electrodes with no voltage applied, and Δ is the displacement of the moveable electrode, then it can be shown that the voltage on the parallel-plate transducer remains constant independent of plate gap.

This result means that by using a specifically designed non-linear spring, it is possible to achieve a constant output voltage from an electromechanical storage device, and the transducer thus essentially operates as a constant output voltage electromechanical battery.

The mechanical parameters of the spring itself, such as the Young's modulus of the spring material, cannot be readily changed in static environmental conditions. Likewise, the cross sectional dimensions of the spring cannot be readily changed during operation of the battery. This disclosure describes a number of feasible methods of providing the desired non-linear characteristics. According to one method, such non-linear characteristics can be provided by means of a spring whose length is a function of the flexure applied to it. Such a spring can be provided by use of a beam wrapped over a cam with a predetermined profile, the beam being attached at one end to a point on the cam, and flexed by means of a load applied at the other free end of the beam, remote from the cam. By this means, as the load on the free end of the beam is changed and the beam flexes, different lengths of the beam become wrapped over the cam and the effective length of the beam changes, thereby changing its force-displacement relation.

A specific design of a cam-wrapped non-linear spring with a force-displacement law such that it fulfils the conditions given above for constant voltage operation, is shown hereinbelow in the Detailed Description section of this disclosure.

Another exemplary implementation of the electromechanical batteries of the present disclosure using nonlinear spring configurations, can be obtained by use of two juxtaposed capacitor plates, constructed of a flexible conductive material having known elastic properties, with a plurality of insulating protrusions distributed in the capacitor gap, to constrain the movement of the capacitor plates towards each other. A variation of this embodiment uses a three dimensional multiple-plate capacitor, comprised of two interleaved stacks of plates of opposite polarity, with the insulating protrusions disposed in the gaps between the sets of plates in each stack. By this means, a significantly higher storage energy density can be achieved.

Yet another exemplary implementation of the electromechanical batteries of the present disclosure differs from those mentioned previously in that it is based on a variable area capacitor, in which the maintenance of constant output or input voltage is achieved by means of varying the area of the capacitor as a function of the charge stored therein. As the charge input to the capacitor increases, the area of the capacitor increases accordingly, resulting in a capacitor whose voltage is not affected by the amount of stored charge, this again defining an electro-mechanical battery. Achievement of a variable area of the capacitor can be obtained by use of a rolled-up sheet electrode which acts as a constant force constraining spring, so that the extent to which the curled up sheet deploys is dependent on the charge held in the capacitor. The curled up part of the electrode provides a constant force opposing the deployment of the sheet electrode, such that the extent of the deployment is linearly proportional to the charge on the capacitor, thus maintaining a constant voltage on the capacitor.

One advantage of such capacitor-based electromechanical batteries is that they can be charged at a high rate since there is virtually no heating generated as the current flows in to charge the capacitor and store the elastic energy in the non-linear spring. This feature may make them particularly advantageous for use in electrical vehicle applications, since using a high charging current, the charging time can be made very short. Likewise they can be discharged at a high rate.

Throughout this disclosure, when capacitor devices are described as having one electrode charged and the other earthed (for convenience, generally with the moving electrode charged at the operating voltage and the static electrode grounded), it is to be understood that the invention is not meant to be limited to this arrangement, and that it could equally well be implemented with the charged and earthed electrode functions reversed.

There is thus provided in accordance with an exemplary implementation of the devices described in this disclosure, an electromechanical battery, comprising a parallel plate capacitor, comprising,

(i) at least a first plate, and

(ii) at least a second plate, disposed with its surface in proximity to the first plate,

wherein mutual motion of the plates towards or away from each other with change in the charge held by the capacitor is controlled by a mechanical spring having a non-linear force-displacement relationship, the relationship being predetermined such that the voltage across the capacitor remains constant with changes in the charge held by the capacitor.

In such an electromechanical battery, the charge held by the parallel plate capacitor generates an attractive electrostatic force between the plates, which is in equilibrium with the mechanical force exerted on the plates by the mechanical spring.

The mechanical spring having a non-linear force-displacement relationship may be a beam with one end section of its length wrapped on a cam, such that when that end of the beam remote from the cam is displaced in a direction perpendicular to the length of the beam, the free length of the beam changes. The end of the beam remote from the cam may be attached to one of the plates to control its motion. In any of these electromechanical batteries, the profile of the cam may be a parabola.

Yet other implementations may involve an electromechanical battery as described above, wherein the mechanical spring having a non-linear force-displacement relationship is the elastic flexing of at least one of the plates. Such an implementation may further comprise a plurality of electrically insulating protrusions disposed between the plates, such that the mutual motion of the plates towards each other is constrained at different positions across the area of the plates by contact with at least some of the protrusions. At least one of the heights or positions of the protrusions may be such that the elastic flexing of at least one of the plates has the non-linear force-displacement relationship necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the capacitor.

Additionally, in such electromechanical batteries incorporating elastic flexing of at least one of their plates, the parallel plate capacitor may be a multi-plate capacitor comprising:
(i) a first stack of conducting plates having elastic flexing properties,
(ii) a second stack of conducting plates having elastic flexing properties, the plates of the second stack being interleaved with the plates of the first stack,
(iii) a first electrical connection connecting the plates of the first stack together, and a second electrical connection connecting the plates of the second stack together, and

(iv) a plurality of electrically insulating protrusions disposed between the plates, such that mutual motion of the plates of the first stack relative to the plates of the second stack, as engendered by the application of a voltage between the first and second electrical connections, is constrained at different positions across the area of the plates by contact with at least some of the protrusions. In such an electromechanical battery, the heights and positions of the protrusions should be such that the elastic flexing of the plates of the first stack and that of the plates of the second stack have the non-linear force-displacement relationships necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the multi-plate capacitor.

In any of the above described flexing plate implementations, the protrusions may be attached to at least one of the plates, or to insulating sheets disposed between pairs of oppositely charged plates.

Additional implementations can include a three dimensional electromechanical battery, comprising a multi-plate capacitor, which comprises:
(i) a first stack of conducting plates having elastic flexing properties,
(ii) a second stack of conducting plates having elastic flexing properties, the plates of the second stack being interleaved with the plates of the first stack,
(iii) a first electrical connection connecting the plates of the first stack together, and a second electrical connection connecting the plates of the second stack together, and
(iv) a plurality of electrically insulating protrusions disposed between the plates, such that mutual motion of the plates of the first stack relative to the plates of the second stack, as engendered by the application of a voltage between the first and second electrical connections, is constrained at different positions across the area of the plates by contact with at least some of the protrusions.

In such a three dimensional electromechanical battery, the heights and positions of the protrusions should be such that the elastic flexing of the plates of the first stack and that of the plates of the second stack have the non-linear force-displacement relationship necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the multi-plate capacitor. The protrusions may be attached to the plates of at least one of the stacks of plates, or to insulating sheets disposed between pairs of oppositely charged plates of the stacks.

Yet other implementations involve an electromechanical battery, comprising a parallel plate capacitor, comprising,

(i) a first foil, having a fixed position, and

(ii) a second foil, disposed with its surface in proximity to the first foil, the second foil being in a rolled up state when no voltage is applied across the capacitor, the unrolling of the second foil being constrained by a mechanical spring having a constant force-displacement characteristic,

wherein unrolling of the second foil as a result of increased electrostatic attraction to the first foil because of an increase in the charge held by the capacitor, results in an increase in the capacity of the parallel plate capacitor, such that the voltage across the capacitor remains constant in spite of the change in the charge held by the capacitor.

In such an electromechanical battery, the constant force spring may be generated by the flexing tension within the rolled up foil, or it may be an external spring having a constant force as a function of displacement, and is attached to an axis around which the rolled up foil is curled. As an alternative, the constant force spring may be generated by alignment of the parallel plate capacitor out of the horizontal plane such that the rolled up section of the second foil must operate against gravity as it unrolls.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will be understood and appreciated more fully from the following detailed description, taken in conjunction with the drawings in which:

Fig.1a shows schematically a parallel-plate transducer, and Fig. 1b shows the equilibrium states of such a transducer;

Figs. 2a and 2b illustrate schematically, the response of the transducer of Fig. 1 with a linear spring. Fig. 2a illustrates the relation between voltage and charge, and Fig. 2b, the relation between charge and displacement;

Figs. 3a and 3b show schematically a spring constructed from two parallel cantilevered beams connected at their free edge; Fig. 3a shows the unloaded state, while Fig. 3b shows the deformed state under a transverse edge load f;

Fig. 4a shows schematically two edge connected cantilever beams of the type shown in Fig. 3a, wrapped over two cams, with Fig. 4b showing the local coordinate system (x,y) of one of the cams;

Figs. 5a, 5b and 5c show the response of the electromechanical battery using cam-wrapped beams; Fig 5a shows voltage/displacement curves, Fig. 5b, the voltage charge relation, and Fig. 5c, the resulting charge/displacement relation;

Figs. 6a and 6b illustrate schematically another parallel plate transducer electromechanical battery implementation with a plurality of insulating protrusions distributed in the capacitor gap, to tailor the extent of free movement of the capacitor plates towards each other; Figs. 6c and 6d show schematically how the devices of Figs. 6a and 6b can be stacked to produce a three-dimensional electromechanical battery having higher energy density than the planar embodiments of Figs. 6a and 6b;

Figs. 7a and 7b illustrate schematically a parallel plate capacitor in which one of the electrodes is rolled up as a scrolled mechanical spring; in Fig. 7a the capacitor is charged at one level, and in Fig. 7b at a higher level, such that the rolled up electrode deploys more; and

Fig. 8 shows schematically the use of gravity to apply the constant mechanical restoring force to the rolled up electrode.

DETAILED DESCRIPTION

Reference is now made to Fig. 1a, which illustrates schematically a parallel-plate transducer, constructed from a movable plate electrode 10 that is suspended on an elastic spring 11 close to a fixed electrode 12. The movable electrode has a single degree-of-freedom, Δ, in a direction generally perpendicular to the plates. The area of each of the electrodes is A, and the initial equilibrium gap between them is g . In the example shown in Fig. 1, the movable electrode is subjected to voltage V and the fixed electrode is electrically grounded, though this arrangement could be reversed. Ignoring fringing fields, the attractive electrostatic force f_E between the electrode plates is given by

$$f_E = \frac{1}{2}\frac{\varepsilon_0 A}{(g-\Delta)^2}V^2 \qquad (1)$$

where ε_0 is the permittivity of free space. If the capacitor is immersed in a dielectric fluid to increase the available capacitance, equation (1) may be amended accordingly. In equilibrium, the attractive electrostatic force f_E between the plates is balanced by the mechanical restoring force f_M in the elastic spring 11.

$$f_M = f_E = \frac{1}{2}\frac{\varepsilon_0 A}{(g-\Delta)^2}V^2 \qquad (2)$$

If the spring is linearly elastic, then the restoring force is

$$f_M = k\Delta \qquad (3)$$

where k is the stiffness constant of the spring. In this case equilibrium takes the form

$$2k\Delta(g-\Delta)^2 = \varepsilon_0 A V^2 \qquad (4)$$

The equilibrium states of the system are illustrated in Fig. 1b, as a Voltage-displacement plot. In this case, when the parallel-plate transducer is driven by voltage V, the resulting motion of the movable plate is clearly a non-linear function of the driving voltage. It is stable up to $\Delta = g/3$ and is unstable beyond that displacement, that being the point at which pull-in of the plate system occurs. The pull-in voltage V_{PI} associated with that point is the maximal voltage that can be applied to the linear spring system before it loses stability.

The capacitance of the parallel-plate transducer is given by

$$C = \frac{\varepsilon_0 A}{g-\Delta} \qquad (5)$$

Figs. 2(a) and 2(b) illustrate the response of this parallel-plate transducer with a linear spring. Fig. 2(a) illustrates the relation between voltage and charge Q, and Fig. 2(b), the relation between charge and displacement, where in both graphs, C_0, the value of the capacitance with no voltage applied, is given by : $C_0 = \varepsilon_0 A/g$.

Now, if the spring is designed to have the non-linear force-displacement relation

$$f_M = \frac{1}{2}\frac{V_{Batt}^{\ 2}\varepsilon_0 A}{(g-\Delta)^2} \tag{6}$$

where V_{Bat} is a constant, then it follows from equilibrium that

$$V^2 = V_{Batt}^{\ 2} \tag{7}$$

i.e. the voltage on the parallel-plate transducer remains constant independent of plate gap.

This result is important because it means that, by using a specifically designed non-linear spring, as defined by equation (6), it is possible to achieve a constant output voltage from a storage device, and the transducer can thus essentially operate as a constant output voltage electromechanical battery.

The stiffness of the required non-linear spring is given by the first derivative of the force:

$$k_M = \frac{d(f_M)}{d\Delta} = \frac{V_{Batt}^{\ 2}\varepsilon_0 A}{(g-\Delta)^3} \tag{8}$$

from which it is clear that the stiffness needs to be a monotonically increasing function of the displacement Δ.

In order to design the non-linear spring with the correct characteristics, it is clear that the elastic properties of the spring itself, such as the spring material Young's modulus, cannot be readily changed in static environmental conditions. Likewise, the cross sectional dimensions of the spring cannot be readily changed during operation of the battery. According to one method described below, such non-linear characteristics can be provided by means of a spring whose length is a function of the flexure applied to it. Such a spring can be provided by use of a beam wrapped over a cam with a predetermined profile, the beam being attached at one end to a point on the cam, and flexed by means of a load applied at the other free end of the beam, remote from the cam. By this means, as the load on the free end of the beam is changed and the beam flexes, different lengths of the beam become wrapped over the cam and the effective free length of the beam changes, thereby changing its force-displacement relation. In the use of such a non-linear spring in the parallel plate transducer devices of the present disclosure, the flexing force at the end of the cam-wrapped beam is the electrostatic force generated between the plates of the transducer.

Using this method, one specific design of a cam-wrapped non-linear spring with a force-displacement law such that it fulfils the force-displacement conditions given by equation (6) is now shown.

Reference is now made to Figs. 3a and 3b, which show a spring constructed from two parallel identical cantilevered beams 30, 31 which are connected at their free edge 32. The free edge may be attached to the movable plate 10 of the parallel plate transducer of the type shown in Fig. 1(a). Fig. 3(a) shows the unloaded state, while Fig. 3(b) shows the deformed state under a transverse edge load f. This type of suspension is particularly advantageous because its edge 32 does not rotate under flexure, and is therefore well suited for the parallel motion of the parallel-plate transducer.

When the connected edge is subjected to the transverse load f, the force-displacement relation of the suspension is given by

$$f = \frac{24EI}{L^3}\Delta \tag{9}$$

Here L is the length of the beams, E is the Young modulus of the beam material, and $I = \frac{1}{12}bw^3$ is the second moment of the beam cross-section, where b is the beam thickness and w is the beam width.

Now, if this concept is to be used to design a non-linear spring, at least one of the parameters in Eq. (9) must be modified. However, it is impractical to continuously modify the beam dimensions, as expressed in I, or the material parameters, as expressed in E.

Reference is therefore now made to Figs. 4a and 4b, which provide a practical schematic illustration of the above mentioned novel method, of how the beam lengths L of the two edge-connected cantilevered beams 30, 31 may be shortened as a function of the force applied to their free ends, by wrapping the beams over cams 40, 41. In Fig. 4a, the beams are shown fixed at the initial contact point at the root 42 of the cams, and the force applied to the remote free ends of the coupled beams. In the parallel plate transducer, this force is the electrostatic force resulting from the moveable electrode attached to that end. The cams are shown as being identical, to enable parallel operation. Fig. 4b shows the local coordinate system (x, y) for one of the beams with the origin at the initial contact point at the root of the cam.

When the beams are wrapped over the cam, the last point of contact is given by x_c, and up to that point the beam is assumed to conform to the cam profile $\hat{y}(x)$. The length of the unwrapped section of the beams is therefore given by $(L - x_c)$. At their free ends the beams are subjected to the transverse force F.

It can be shown that when a single cantilever beam with a non-rotating edge is wrapped over a cam by application of the transverse force F, the force-displacement relation is given by

$$F(x_c) = 2\frac{E^*I}{(L - x_c)^2}\left\{\left.\frac{d\hat{y}}{dx}\right|_{x_c} + \left.\frac{d^2\hat{y}}{dx^2}\right|_{x_c}(L - x_c)\right\} \tag{10}$$

$$\Delta(x_c) = \hat{y}(x_c) + \frac{2}{3}\left.\frac{d\hat{y}}{dx}\right|_{x_c}(L - x_c) + \frac{1}{6}\left.\frac{d^2\hat{y}}{dx^2}\right|_{x_c}(L - x_c)^2 \tag{11}$$

Here $\hat{y}(x)$ is the function describing the cam shape, where coordinate system (x, y) is shown in Fig. 4b, and x_c is the location of the last point of contact between the cam and beam.

As an example of the use of these design equations, a cam with the simple parabolic shape is used in equations (10) and (11):

$$\hat{y} = \frac{g}{L^2}x^2 \tag{12}$$

Substituting this cam shape into (11), extracting x_c and substituting it into (10) yields the edge force F . Since the suspension includes two parallel beams, the force is given by:

$$f = 2F = \frac{32g^3}{9L^3}\frac{E^*I}{(g - \Delta)^2} \tag{13}$$

Comparing this to equation (6), which is the relationship required to produce a constant voltage characteristic, it follows that

$$V_{Batt}{}^2 = \frac{64g^3}{9L^3}\frac{E^*I}{\varepsilon_0 A} \tag{14}$$

The curvature of the cam at its origin is given by

$$\left.\frac{d^2\hat{y}}{dx^2}\right|_{x=0} = \frac{2g}{L^2} \tag{15}$$

The two beams in the suspension are initially straight and they have a single point of contact with the curved cams at their clamped edge. However, the two beams begin to wrap over the cams only after the suspension deflection Δ is sufficiently large such that the curvature at their clamped edge reaches the value given by equation (15). This occurs when the deflection of the suspension edge reaches the value $\Delta = g/3$, and up to this deflection (i.e. before the beams begin to wrap over the cams) the suspension responds as a linear spring with constant stiffness $k = f/\Delta = 24EI/L^3$ (see Eq. (9).

It follows that up to the deflection $\Delta = g/3$ the suspension is linear and the parallel-plate actuator response is given by equation (5). In this region the voltage increases non-linearly from $V = 0$ to the value given by equation (14). Beyond this edge deflection, the voltage remains constant, even though the charge may continue to increase. From the capacitance equation (5), it follows that beyond this deflection, the charge Q is given by

$$Q = CV = \frac{8}{3}\frac{1}{1-\Delta/g}\sqrt{\frac{g}{L}\varepsilon_0 A\frac{E^*I}{L^2}} \tag{16}$$

The resulting voltage-displacement, voltage-charge, and charge-displacement relations are plotted in Figs. 5(a), 5(b) and 5(c) respectively. In these graphs, the responses of the electromechanical battery are shown as solid lines. The dashed lines are the response of the linear parallel-plate transducer itself, the dot being the point at which wrapping of the beams begins, and is also the pull-in point of the linear parallel-plate transducer. Fig. 5(a) shows the Voltage-displacement relation. As is observed, once wrapping begins at displacement g/3, the voltage remains constant as the displacement increases, and the voltage remains at this value so long as the displacement is greater than g/3. Fig. 5(b) shows the Voltage-charge relation, in which it is seen that even as the charge on the parallel plate capacitor increases, the voltage remains constant above g/3. Fig. 5(c) shows the Charge-displacement relation.

Reference is now made to Figs. 6a and 6b, which illustrate another exemplary implementation of the electromechanical batteries of the present disclosure using nonlinear spring configurations, involving a particularly simple method of construction. This implementation comprises two juxtaposed capacitor plates (electrodes), 60, 61, at least one of which being a flexible conductive material 60 having known elastic properties, and a plurality of insulating protrusions 62, 63, 64, ….. distributed in the capacitor gap, to constrain the free movement of the capacitor plates towards each other. This can be practically achieved by fixing the protrusions to one plate, which is generally, for ease of construction, the fixed plate, and allowing the opposing plate to move towards that fixed plate. Alternatively, both capacitor plates can be movable and flexible, and the protrusions can be attached to a third insulating sheet disposed between the two movable conducting plates (this embodiment not shown). The protrusions should have predetermined different heights, and are distributed in a predetermined pattern over the surface of the capacitor plates. In the example shown in Figs. 6a, 6b, the protrusions 62 have the greatest height, those designated 63 have a lower height, and those 64 the lowest height.

As the capacitor is charged to a charge level Q by the application of an external voltage between the plates, the plates are electrostatically attracted towards each other, the displacement being determined by the elastic properties of the moving capacitor plate 60 (or plates in the case of the double sided implementation). So long as the charge Q is sufficiently small that the movable plate 60 (or plates) is moving in free space and does not come into contact with any of the protrusions, as is shown in Fig. 6a, the plate has a known elastic characteristic for these small displacements. However, as is shown in Fig. 6b the moment that the charge on the movable plate 60 has increased to a level $Q + \Delta Q$, such that the plate 60 touches the second highest protrusion or protrusions 63, the plate's movement at that point is brought to a stop, and its displacement between protrusions 62 and 63 remains nominally fixed. The continued motion of the plate (or plates) with increasing charge is then achieved by the remainder of the still uncontstrained plate area 66. The plate area between protrusions 62 and 63 was described as being nominally fixed, since although no gross movement continues to take place, the angular orientation and curvature of the plate between the highest protrusion or protrusions 62 and the second highest protrusion or protrusions 63 can change and amend the stored elastic energy, even for this nominally fixed section of the plate. This "semi-static" section thus also contributes to the stored elastic energy and affects the elastic characteristic of the whole plate. For the purposes of defining the elastic characteristics of the entire plate, the remaining sections 66 of the flexing plate now have smaller lateral dimensions, and hence stiffer spring properties, and consequently a different force-displacement characteristic. This process continues as the remaining free sections 66 of the flexible plate contact lower and lower protrusions, and acquire stiffer and stiffer spring properties. Thus, the overall stiffness characteristic of the flexible plate 60 is synthesized from the stiffnesses of a number of secondary plates, having different stiffness characteristics, starting with that of the whole plate freely suspended only at its outer edges when no voltage is applied, and finishing, when the rated voltage is applied, with a plate that is held under electrostatic force against all of the various protrusions, and with the different sections having different force-displacement laws operating on them . By correct selection of the heights and distribution of the protrusions, it is possible to design and construct a parallel plate capacitor, in which the stiffness of the plates can be tailored to have the desired force-displacement characteristic to fulfill the conditions of equation (6), and hence to provide a constant voltage characteristic, this defining the electromechanical battery of this application. It is also feasible that a unique solution of the force-displacement characteristic may be obtained from by spraying the protrusions in the form of particles having a suitable selection of particle size distribution onto the surface.

One of the disadvantages of the implementations of the electromechanical battery shown in Figs. 6a and 6b is that the energy storage density is limited because of the planar nature of the device. Reference is now made to Figs. 6c and 6d, which show a further development of the "protrusioned plate" embodiments of Figs. 6a and 6b, in which the planar plate geometry is multiplied by means of stacking of the capacitor plates one on top of the other. By this means, it becomes possible to construct a three dimensional parallel plate capacitor, operative as a mechanical battery, and having a much higher energy storage density than the configurations of Figs. 6a and 6b. Fig. 6c shows the construction of the 3-D multiple plate capacitor in its uncharged condition. The plates are stacked with alternate plates being connected electrically, all of the shaded plates 68 being electrically connected, and all of the unshaded plates 69 being electrically connected. In this way, a multi-layer plate capacitor is formed. The insulating protrusions are shown as the black blocks, and their heights and positions are calculated to give the desired elastic characteristic for the plates such that the constant voltage property is achieved for the capacitor stack. Fig. 6d shows the effect of applying a charging voltage to the capacitor stack. The capacitor plates are attracted to each other by the electrostatic forces, storing elastic energy because of the elastic deformation the plates undergo as they move into contact with the protrusions, until they are all completely compacted against all of the protrusions. As is observed in Fig. 6d, the motion of the plates towards each other has also caused a compacting down of the stack as the protrusion spaces are filled by the plate distortion motion. In this situation, the distorted plates have the maximum rated stored elastic energy, though if the charge is increased, the plates may continue to bend more while constrained against the protrusions, but the force-displacement relation at that stage may become considerably more complex.

Such a multi-plate capacitor can have its energy storage density increased if a high dielectric constant material is positioned between the plates, such as by immersing the capacitor in a high dielectric constant oil bath. This also enables higher voltages to be used before breakdown, again leading to higher energy density. A particularly advantageous aspect of these 3-D multi-plate capacitors is that they can be constructed by planar fabrication techniques, using thin films having deformable properties, and can thus be readily used as mechanical batteries in MEMS or microelectronic circuits. Furthermore, in order to achieve even larger energy densities, it is possible to fabricate a number of such multi-plate capacitors over a larger area of the substrate on which they are fabricated, in accordance with the battery capacity required.

Reference is now made to Figs. 7a and 7b, which illustrate yet another exemplary implementation of the electromechanical batteries of the present disclosure, in the form of a variable capacitor. This implementation differs however from those described previously in that a constant force mechanical spring element may be used. The maintenance of a constant output voltage as charge is withdrawn from the capacitor is achieved by means of varying the area of the capacitor as a function of the charge stored therein. As the charge input to the capacitor increases, the area of the capacitor increases accordingly, resulting in a capacitor whose voltage is not affected by the amount of stored charge, this again defining an electro-mechanical battery. Such a capacitor configuration can be achieved by use of a charged electrode 70 positioned close to a fixed ground electrode 71, with a thin dielectric sheet 72 between the two electrodes. The charged upper electrode (where the positional relationship "upper" is being used only in order to relate to the drawings of Figs. 7) may be constructed of a thin metallic sheet, or of another semi-stiff conductive material, scrolled up in the form of a rolled mechanical spring 70, having an at least partly rolled equilibrium position with no stored charge, as shown in Fig. 7a. As the voltage applied to the capacitor is increased and the stored charge consequently also increases, the electrostatic forces between the charge electrode and the ground plate 71 cause unrolling of the scrolled up electrode 70, as shown in Fig. 7b, thus increasing the area of the capacitor and its capacitance, and hence reducing the voltage relating to the stored charge. Conversely withdrawal of charge from the capacitor causes a reduction in the electrostatic forces between the electrodes, therefore allowing the upper electrode to curl up more towards its elastic equilibrium position, reducing the area of the capacitor, yet nevertheless maintaining the same voltage between the electrodes. Correct selection of the elastic properties and dimensions of the rolled electrode mechanical “spring” is necessary in order to maintain a constant restoring force, and hence to produce a fixed voltage characteristic of the capacitor. The equilibrium between the electrostatic forces generated between the charged plates and the mechanical forces operating on the rolled-up section of the electrode, and arising from the elastic characteristics of the material of the rolled up electrode, is thus responsible for maintaining a constant voltage across the capacitor.

In the above described operating scenario, the mechanical forces have been supplied by the elasticity of the rolled up foil, acting as a constant force mechanical spring. This would appear to be the simplest way of implementing this particular configuration. However alternative methods of providing the constant mechanical force can also be used, in which case, the foil need not have any spring properties at all, but could be a completely tension-free foil having essentially zero elastic properties and no preloaded stress whatsoever.

In one such example, shown in Fig. 8, use is made of gravity in order to provide the constant mechanical force to counter the electrostatic force. This is achieved in Fig. 8 by forcing the unraveling foil to roll uphill against gravity as the charge in the capacitor is increased, and vice versa as it is decreased. Since the gravitational force on the thin foil may be very small, it may be necessary to add a weight 90 to the foil to generate sufficient reactive force to the electrostatic force. Obviously, this implementation is only usable where the orientation of the electromechanical battery is well defined and reasonably constant, such as in a static application or an automotive or locomotive application.

It is appreciated by persons skilled in the art that the present invention is not limited by what has been particularly shown and described hereinabove. Rather the scope of the present invention includes both combinations and subcombinations of various features described hereinabove as well as variations and modifications thereto which would occur to a person of skill in the art upon reading the above description and which are not in the prior art.

CLAIMS

1. An electromechanical battery, comprising:

a parallel plate capacitor, comprising;

at least a first plate; and

at least a second plate, disposed with its surface in proximity to said first plate, wherein mutual motion of said plates towards or away from each other with change in the charge held by said capacitor is controlled by a mechanical spring having a non-linear force-displacement relationship, said relationship being predetermined such that the voltage across said capacitor remains constant with changes in the charge held by said capacitor.

2. An electromechanical battery according to claim 1, wherein the charge held by the parallel plate capacitor generates an attractive electrostatic force between the plates which is in equilibrium with the mechanical force exerted on the plates by the mechanical spring.

3. An electromechanical battery according to either of the previous claims, wherein the mechanical spring having a non-linear force-displacement relationship is a beam with one end section of its length wrapped on a cam, such that when that end of the beam remote from the cam is displaced in a direction perpendicular to the length of the beam, the free length of the beam changes.

4. An electromechanical battery according to claim 3, wherein the end of the beam remote from the cam is attached to one of the plates to control its motion.

5. An electromechanical battery according to either of claims 3 and 4, wherein the profile of the cam is a parabola.

6. An electromechanical battery according to either of claims 1 and 2, wherein the mechanical spring having a non-linear force-displacement relationship is the elastic flexing of at least one of the plates.

7. An electromechanical battery according to claim 6, further comprising a plurality of electrically insulating protrusions disposed between the plates, such that the mutual motion of the plates towards each other is constrained at different positions across the area of the plates by contact with at least some of the protrusions.

8. An electromechanical battery according to claim 7, wherein at least one of the heights or positions of the protrusions is such that the elastic flexing of the at least one of the plates has the non-linear force-displacement relationship necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the capacitor.

9. An electromechanical battery according to either of claims 6 and 7, wherein the parallel plate capacitor is a multi-plate capacitor comprising:

a first stack of conducting plates having elastic flexing properties,

a second stack of conducting plates having elastic flexing properties, the plates of the second stack being interleaved with the plates of the first stack,

a first electrical connection connecting the plates of the first stack together, and a second electrical connection connecting the plates of the second stack together, and

a plurality of electrically insulating protrusions disposed between the plates, such that mutual motion of the plates of the first stack relative to the plates of the second stack, as engendered by the application of a voltage between the first and second electrical connections, is constrained at different positions across the area of the plates by contact with at least some of the protrusions.

10. An electromechanical battery according to claim 9, wherein the heights and positions of the protrusions is such that the elastic flexing of the plates of the first stack and that of the plates of the second stack have the non-linear force-displacement relationships necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the multi-plate capacitor.

11. An electromechanical battery according to any of claims 7 to 10, wherein the protrusions are attached to at least one of the plates.

12. An electromechanical battery according to any of claims 7 to 10, wherein the protrusions are attached to insulating sheets disposed between pairs of oppositely charged plates.

13. A three dimensional electromechanical battery, comprising:

a multi-plate capacitor comprising:

a first stack of conducting plates having elastic flexing properties,

a second stack of conducting plates having elastic flexing properties, the plates of the second stack being interleaved with the plates of the first stack,

a first electrical connection connecting the plates of the first stack together, and a second electrical connection connecting the plates of the second stack together, and

a plurality of electrically insulating protrusions disposed between the plates, such that mutual motion of the plates of the first stack relative to the plates of the second stack, as engendered by the application of a voltage between the first and second electrical connections, is constrained at different positions across the area of the plates by contact with at least some of the protrusions.

14. A three dimensional electromechanical battery according to claim 13, wherein the heights and positions of the protrusions is such that the elastic flexing of the plates of the first stack and that of the plates of the second stack have the non-linear force-displacement relationship necessary to the ensure that the voltage across the capacitor remains constant with changes in the charge held by the multi-plate capacitor.

15. An electromechanical battery according to either of claims 13 and 14, wherein the protrusions are attached to the plates of at least one of the stacks of plates.

16. An electromechanical battery according to either of claims 13 and 14, wherein the protrusions are attached to insulating sheets disposed between pairs of oppositely charged plates of the stacks.

17. An electromechanical battery, comprising:

a parallel plate capacitor, comprising,

a first foil, having a fixed position, and

a second foil, disposed with its surface in proximity to the first foil, the second foil being in a rolled up state when no voltage is applied across the capacitor, the unrolling of the second foil being constrained by a mechanical spring having a constant force-displacement characteristic,

wherein unrolling of the second foil as a result of increased electrostatic attraction to the first foil because of an increase in the charge held by the capacitor, results in an increase in the capacity of the parallel plate capacitor, such that the voltage across the capacitor remains constant in spite of the change in the charge held by the capacitor.

18. An electromechanical battery according to claim 17, wherein the constant force spring is generated by the flexing tension within the rolled up foil.

19. An electromechanical battery according to claim 17, wherein the spring is an external spring having a constant force as a function of displacement, and is attached to an axis around which the rolled up foil is curled.

20. An electromechanical battery according to claim 17, wherein the constant force spring is generated by alignment of the parallel plate capacitor out of the horizontal plane such that the rolled up section of the second foil must operate against gravity as it unrolls.

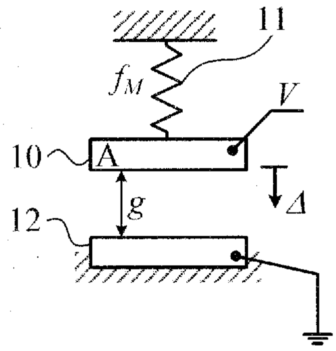


FIG. 1a

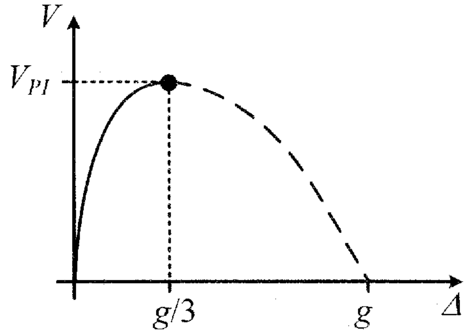


FIG. 1b

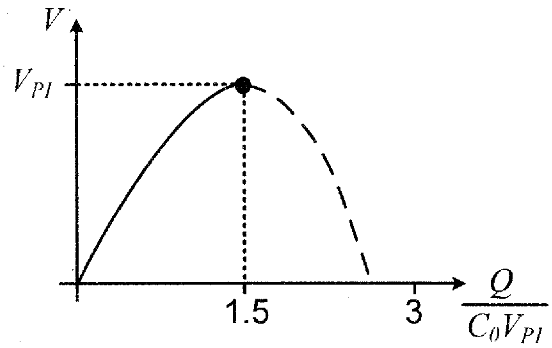


FIG. 2a

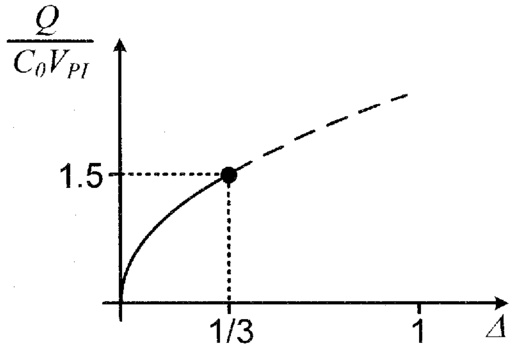


FIG. 2b

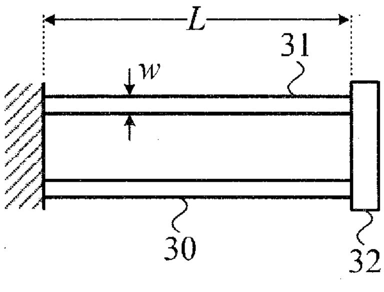


FIG. 3a

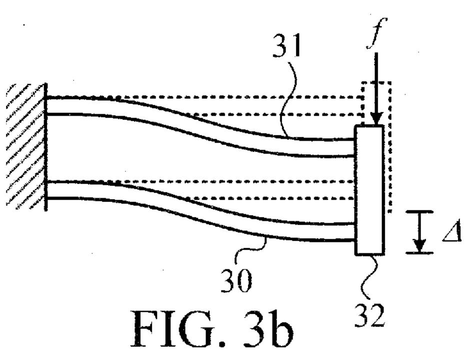


FIG. 3b

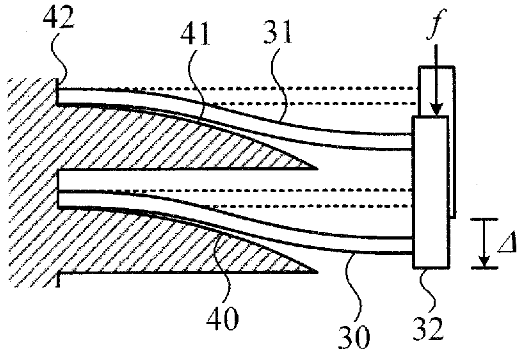


FIG. 4a

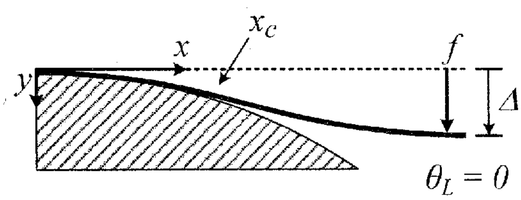
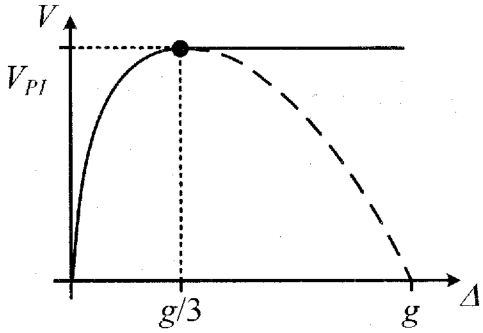


FIG. 4b

FIG. 5a



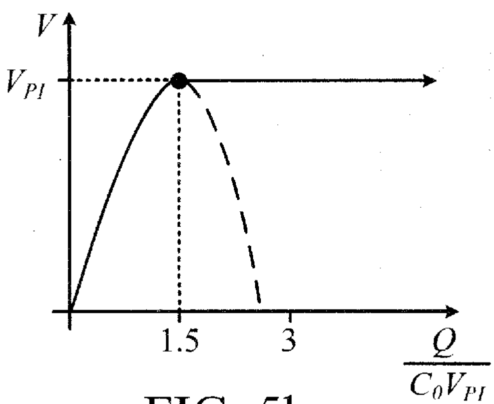


FIG. 5b

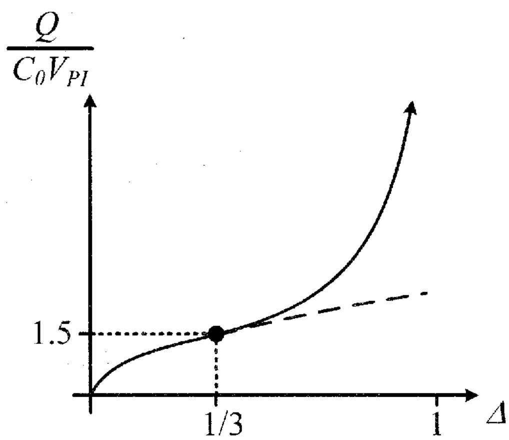


FIG. 5c

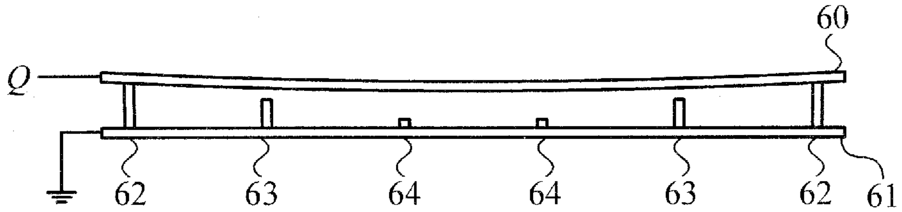


FIG. 6a

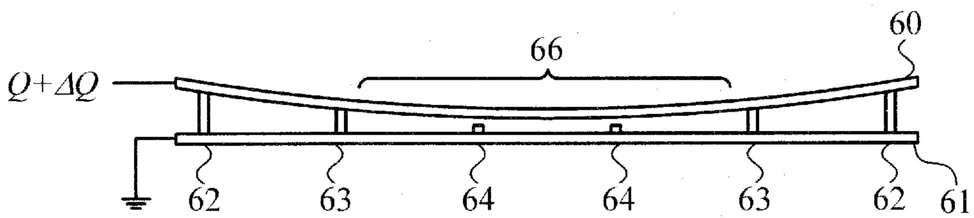


FIG. 6b

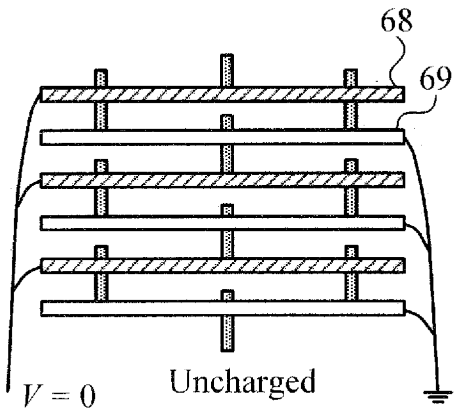


FIG. 6c

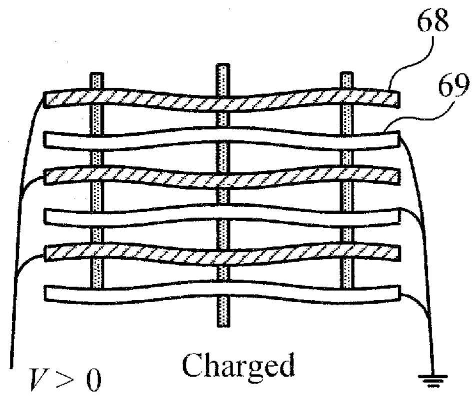


FIG. 6d

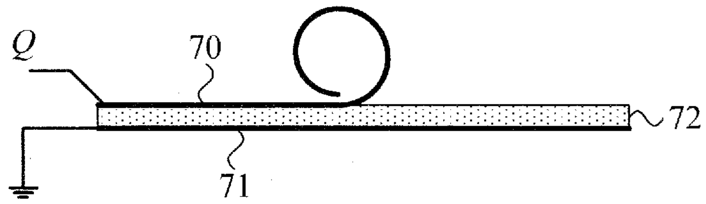


FIG. 7a

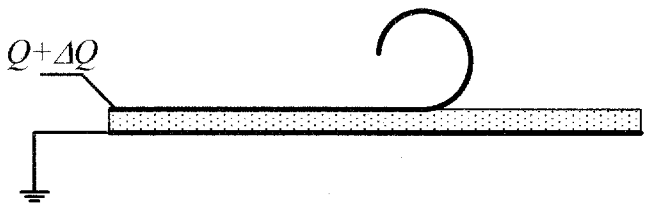


FIG. 7b

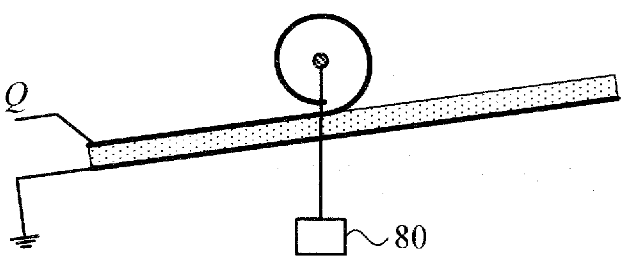


FIG. 8

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2013/050852

A. CLASSIFICATION OF SUBJECT MATTER
IPC (2013.01) H01M 10/04

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)
IPC (2013.01) H01M 10/04, B81B

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)
Databases consulted: THOMSON INNOVATION, Esp@cenet, Google Patents, Google Scholar, FamPat database
Search terms used: electromechanical, battery, capacitore, elastic, spring, folding, flexible, deformable, moving, plate, electrode

C. 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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[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
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"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
15 Jan 2014	28 Jan 2014

Name and mailing address of the ISA:	Authorized officer
Israel Patent Office Technology Park, Bldg.5, Malcha, Jerusalem, 9695101, Israel Facsimile No. 972-2-5651616	COHAY Matan Telephone No. 972-2-5651611

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IL2013/050852

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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Information on patent family members

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