A tunable pendulum comprises a rotatable mass which is balanced about the axis of rotation 5, and means for moving portions of the rotatable mass to and from the axis with the balance maintained. The pendulum also comprises an eccentric mass and means for moving the eccentric mass to and from the axis. The pendulum further comprises means for capturing the motion of the pendulum to enable conversion to electrical power. The rotatable mass may comprise first and second arms 8, 9 of equal length, and first and second masses 2, 3 of equal size and slidable along the arms by screw jacks 18, 19, the masses being kept equidistant from the axis of rotation. The eccentric mass may comprise a third arm 4 fixed to pivot at right angles to the first and second arms, and a third mass 1 slid able along the third arm by a screw jack 20. The pendulum can be used in a wave energy converter, or for damping oscillations in ocean vessels, sea-mounted platforms or high-rise buildings.
Patent Application

Balanced and Eccentric Mass Pendulum with Dynamic Tuning
Description

The present invention may be applied to:

- Capture of ocean wave energy and the conversion of this energy to electric power;
- Damping of oscillations, for example in ocean vessels or sea-mounted platforms or in wind-affected high-rise buildings;
- Energy harvesting for example to provide power to distributed wireless devices.

Balanced and eccentric mass pendulum (BEMP)

Figure 1a is a schematic side view, not to scale, of a pendulum combining an eccentric mass (1) with two equal balanced masses (2) and (3). Figure 1b is a schematic plan view of the same device.

The first balanced mass (2) and the second balanced mass (3) are slidably attached to a first rigid arm (8) and a second rigid arm (9) respectively. The arms (8) and (9) are of equal length and fixed in alignment to each other to opposite sides of a horizontal axial shaft (5). The first and second balanced masses (2) and (3) are equidistant from shaft (5).

The eccentric mass (1) is slidably attached to a third rigid arm (4) that is vertical when at rest. One end of the arm (4) is fixed to the horizontal axial shaft (5) at right angles to the first arm (8) and second arm (9) at the junction of these arms (8) and (9). The shaft (5) is held by, and rotates inside, a pair of roller bearings (6) and (7) that are fixed to the enclosing structure (not shown).

The first arm (8) comprises two rigid smooth parallel outer rails (10) and (11) along which the first balanced mass (2) slides and an inner parallel threaded rod (12). The rails (10) and (11) and the rod (12) are rigidly fixed to each other by a cross-member (16). The second arm (9) has the same arrangement of two rigid smooth parallel outer rails (13) and (14) along which the second balanced mass (3) slides and an inner parallel threaded rod (15). The rails (13) and (14) and the rod (15) are rigidly fixed to each other by a cross-member (17).

The third arm (4) has the same arrangement of two parallel outer rails and an inner parallel threaded rod (not shown).

Two electrically powered self-locking screw jacks (18) and (19) are attached to the balanced masses (2) and (3) respectively and ride on the threaded rods (12) and (15) respectively, so moving the balanced masses (2) and (3) respectively and always keeping the balanced masses (2) and (3) equidistant from the axis of rotation.

An electrically powered self-locking screw jack (20) rides on the threaded rod (not shown) incorporated into the third arm (4) and so moves the eccentric mass (1) up and down the third arm (4).
The screw jacks (18), (19) and (20) are powered via trailing cables (not shown).

**Power absorption and take-off**

In a wave-power application the BEMP absorbs energy by resonating at the same frequency as the dominant wave in the plane of rotation of the pendulum.

Power is extracted from the motion of the BEMP by fixing a toothed wheel to the shaft (5) so that the toothed wheel rotates with the shaft. The toothed wheel drives an arrangement of gear-train, one-way clutches and fly-wheel to deliver high-speed uniform rotation to a rotary electrical generator. This arrangement is not shown.

**Operation of pendulum**

The BEMP can behave in a manner that is the opposite of a conventional pendulum.

In the case of the conventional pendulum a single arm is attached at one end to a fixed pivot and at the other end to a mass. The period of oscillation of the mass of the conventional pendulum is increased by moving the mass away from the pivot, so increasing the radius of oscillation. Where a long period is required, for example to tune the pendulum to the typical period of an ocean swell, the radius of oscillation required becomes large: up to 60m.

By contrast, the BEMP can increase the oscillation period by **reducing** the radius of oscillation, so enabling a compact construction.

This effect can be understood using figures 2a to 2c, which show in simplified schematic form the side views of different positions of the eccentric mass (1) and the balanced masses (2) and (3).

The period of oscillation of the BEMP is given by:

1. \( T_p = 2\pi \sqrt{I/(MgL)} \) where:

   \( T_p \) is the oscillation period in seconds  
   \( I \) is the moment of inertia around the rotational axis in mass x meters\(^2\)  
   \( M \) is the total mass of the pendulum in kg  
   \( g \) is the gravitational constant (=9.81 meters/sec\(^2\))  
   \( L \) is the distance of the center of mass of the pendulum from the rotational axis in meters

   In the case illustrated in Figures 1a, 1b

2. \( I = 2MbR^2 + MeRe^2 + I_1 \) where:
Mb = each balanced mass (2) and (3) including the mass of the attached screw jacks (18) and (19) respectively in kg
Rb = the radius from the axis to the centre of mass of each balanced mass (2) and (3) in metres
Me = the eccentric mass (1) including the mass of the attached screw jack (20) in kg
Re = the radius from the axis to the centre of mass of the eccentric mass (1) in metres.
Ia = moment of inertia of the arms ((4), (8) and (9)) around the rotational axis

To an approximation, assuming Mb and Me are large compared with the mass of the arms (4), (8) and (9):

3. \[ L = \frac{Re \cdot Me}{(2Mb + Me)} \]

Combining equations 1, 2 and 3 we get:

4. \[ Tp = 2.01 \sqrt{\left( (2MbRb^2 + MeRe^2 - Ia)/(2Mb + Me) \times ReMe/(2Mb + Me) \right)} \]

Using the equation for the moment of inertia of a rod rotated about its end:

1. \[ Ia = 3Ma \cdot La^2/3 \text{ where} \]

Ma is the mass of each arm and La is the length of each arm in metres.

If we let Ma = fMb then from equation 4:

6. \[ Tp = 2.01 \sqrt{(2Mb/Me \times (Rb^2 \cdot Re + fLa^2/Re) + Re)} \]

In the special case of the conventional pendulum, which is assumed to have negligible mass apart from the pendulum bob, Mb = 0 and equation 6 becomes:

7. \[ Tp = 2.01 \sqrt{(Re)} \]

It is evident from equation 6 that we can increase Tp by:

- Increasing the ratio Mb/Me
- Increasing the ratio of Rb/Re

As Re is reduced to zero, Tp becomes infinitely large.

Figure 2a shows Rb at a minimum and Re at a maximum

Assume that:

Mb/Me = 1
f = 0.1
Rb = 0.5 m
Re = 5m
La = 5m

From equation 6, \[ Tp = 2.01 \sqrt{(0.1 + 5/Re + 5)} = 5 \text{ seconds} \]

Where Rb is small, Tp is determined by Re.

If Re is reduced to 2m, then from equation 6:

\[ Tp = 2.01 \sqrt{(0.125 + 2.5 + 2)} = 4.3 \text{ seconds} \]

Figure 2b shows the masses Me and Mb at midway positions

Assume that:

Rb = 4.0m
Re = 2.5m

From equation 6, \[ Tp = 2.01 \sqrt{(12.8 + 2 + 2.5)} = 8.4 \text{ seconds} \]

Where Rb is large, Tp is determined by Rb.

Figure 2c shows the mass Me close to the axis and the masses Mb at the furthest position from the axis

Assume that:

Rb = 5.0m
Re = 0.5m

From equation 6, \[ Tp = 2.01 \sqrt{(100.0 + 10 + 0.5)} = 21.1 \text{ seconds} \]

The described BEMP is therefore capable of a wide and dynamic variation in period. By suitable choice of Mp, Mb and Rp, Rb, a range of periods can be achieved in a compact pendulum that matches the characteristic range of periods of ocean swells: namely 5 to 15 seconds.

If Rb is fixed (ie the balanced masses (2) and (3) do not move along the first and second arms (8) and (9) respectively), then the range of Tp may be restricted.

For example, in the case given, if Rb is fixed at 5m, then:

8. \[ Tp = 2.01 \sqrt{(50/Re + 5/Re + Re)} \]

And for Re = 5m to 0.5m.
$T_p = 8$ seconds to $21.2$ seconds

This range of result can be shifted by, for example, by reducing the ratio of $M_b/M_e$ to $0.5$ so that:

9. $T_p = 2.01 \sqrt{(25/Re + 2.5/Re + Re)}$

So that:

$T_p = 6.5$ seconds to $15$ seconds

This is close to the range required for wave-power application.

If $Re$ is fixed (ie the eccentric mass does not move along the third arm (4)) then $T_p$ is again restricted.

For example, in the case given, if $Re$ is fixed at $2m$, then:

10. $T_p = 2.01 \sqrt{(Rb^2 + 2.5 + 2)}$

And for $R_b = 0.5m$ to $5m$

$T_p = 4.4$ seconds to $10.9$ seconds

This range of result can be shifted by, for example, by increasing the ratio of $M_b/M_e$ to $1.5$ so that:

11. $T_p = 2.01 \sqrt{(1.5Rb^2 + 3.75 + 2)}$

So that:

$T_p = 5$ seconds to $13.2$ seconds

This is also close to the range required for wave-power application.

**Alternative modes of suspension**

Roller bearings (6) and (7) are available that enable construction of a multi-megawatt BEMP of many thousand tonnes total mass. For example, the largest standard Timken spherical roller bearing (outer diameter 1.95m) can carry a dynamic load up to 3,000 tonnes. In principle, a set of four such bearings can support a total mass of 10,000 tonnes. Where $M_b/M_e = 1$, the eccentric mass $M_e = 10000/3 = 3,300$ tonnes (ignoring the mass of the arms).

The present invention also describes alternative methods of suspension that do not use conventional bearings and enable the economical use of very large masses.
Axle rolling on surface.

Figure 3a shows in 3D schematic form an alternative suspension. For simplicity the detail of the arms (4), (8) and (9) is omitted. The horizontal cylindrical axial shaft (5) rolls inside a pair of support tubes (21) and (22) that are fixed to the enclosing structure (not shown). This arrangement does not permit full rotation of the eccentric mass (1) but such rotation is not required and is prevented by progressive rate buffers (not shown).

Provided that the diameter of the axial shaft (5) is small compared with the radius of the centre of mass of the BEMP, the path of the centre of mass approximates to a circular arc and the BEMP displays the same periodicity as a conventional pendulum. In general the path is a prolate cycloid.

In a similar arrangement (not shown), the axial shaft (5) is hollow and inside the hollow shaft is a cylindrical shaft fixed at each end to the enclosing structure. The hollow axial shaft rolls on the internal fixed shaft.

Wheel rolling on surface.

Figure 3b shows in 3D schematic form another alternative suspension. For simplicity the horizontal arms (8) and (9) are omitted. The horizontal axial shaft (5) is fixed at each end to identical vertical wheels (23) and (24). The two wheels (23) and (24) roll on a surface (25) that is fixed to the enclosing structure. The eccentric mass (1) slides on two parallel rails (26) and is moved by a screw jack (not shown) fixed to the mass (1) and mounted on a threaded rod (27).

The wheels (23) and (24) in themselves comprise a balanced mass. The moment of inertia of the wheels (23) and (24) varies with wheel mass and the square of the wheel radius. The largest moment of inertia is obtained when the wheel mass is concentrated in the rim.

As indicated by equation 7, a compact long period pendulum of variable period suitable for wave-power application can be constructed by concentrating sufficient mass into the rims of a wheels (23), (24) and by constructing wheels (23), (24) of sufficient radius.

It is not obvious that the rolling variant of the BEMP will show uniform behaviour as a pendulum since the centre of mass of the device follows a cycloidal path. However, provided that the centre of mass is at 60% or less of the radius of the rolling wheel and provided that rotation is less than a round 90% of full rotation, then the path of the centre of mass traces a curvate cycloid that closely approximates the circular arc followed by the mass of a conventional pendulum. As a result the periodicity of the rolling BEMP approximates the periodicity of a conventional pendulum.
Continuously variable curvature rolling surface

The curvature of the rolling surface (25) can be continuously varied so that the oscillation period of the rolling wheel variant of the BEMP can be held nearly constant over a wide range of oscillation amplitudes.

Figure 4a shows a schematic side view of a wheel (23) rolling on a flexible rolling surface. The surface is a flexible rectangular sheet (28) made of spring steel or a similar material. The sheet (28) rests on a flat horizontal surface (29) of the enclosing structure and is fixed to the surface (29) along the centre-line of the flexible sheet (28) where the centre-line is at right-angles to the rolling path of the wheels (23 and 24).

Two sides of the sheet are parallel to the rolling path and two sides are at right angles to the rolling path. The narrow end of a first wedge (30) projects under the edge of the first of the latter sides. The narrow end of a second wedge (31) projects under the edge of the second of the latter sides. Each wedge (30) and (31) is as wide as the flexible sheet (28) and is slidably fixed to rails (not shown) that are embedded in the flat surface (29) parallel to the rolling path. The wedges (30) and (31) are fixed to screw jacks (32) and (33) respectively that move the wedges symmetrically to and from the centre-line, so increasing or reducing the curvature of the flexible sheet (28).

Alternative means of moving masses

In the described invention, the eccentric mass (1) and the balanced masses (2) and (3) are moved by screw jacks. In alternative embodiments of the invention, the masses are moved by rack and pinion devices or by hydraulic or pneumatic rams or by an arrangement of winches and pulleys. The masses (1), (2) and (3) can be containers of solid shot that is moved by Archimedian screws. The masses (1), (2) and (3) can be containers of liquid that is moved by pumps.

Alternative power take-off (PTO) systems

In the described invention, the PTO uses a cogged wheel fixed to the axial shaft (5). This cogged wheel drives a rotary electrical generator via a familiar arrangement of gear train, one-way clutches and flywheel, all fixed to the enclosing structure. In alternative embodiments of the invention, one or more arms (4), (8) (9) of the BEMP are attached to one or more hydraulic pumps or to one or more cable-driven spools.

Cable-driven spool PTO

The mechanism of the cable-driven spool PTO is shown in a schematic side view in Figure 4b. A cable (34) is looped round the axial shaft (5) or wheel (23) or (24). One end of the cable (34) is looped round a first spool (35) and then round a first pulley (36) and
is then fixed to the enclosing structure. The first pulley (36) is held by a first cable shock absorber (37) fixed to the enclosing structure. The shock absorber (37) comprises a progressive rate compression spring mounted on a progressive rate pneumatic damper. The other end of the cable (34) is looped round a second spool (38) and then round a second pulley (39) and is then fixed to the enclosing structure. The second pulley (39) is held by a second cable shock absorber (40) fixed to the enclosing structure. Each spool (35), (38) rotates on a shaft (not shown) that drives a rotary electrical generator via a an arrangement (not shown) of one-way clutches, gear train and flywheel to deliver high-speed uniform rotation to a rotary electrical generator.

The shock absorbers (37), (40) keep the cable (34) under tension at all times. The shock absorbers (37), (40) also progressively arrest the motion of the BEMP at the extremes of its rotation.

When the axial shaft (5) turns or moves, it pulls the cable (34) on one side and releases the cable (34) on the other side. The pulled cable (34) turns the first spool (35), which drives a rotary electric generator. The released cable (34) is pulled by the second shock absorber (40) so that the second spool (38) free-wheels.

When the axial shaft reverses its motion, the pulled cable (34) turns the second spool (38), which drives a rotary electric generator. The released cable (34) is pulled by the first shock absorber (37) so that the first spool (35) free-wheels. And so on.

An advantage of the cable-driven spool PTO is that it can be applied where the axial shaft (5) does not remain in a fixed position. In the case of the rolling wheel variant of the BEMP (Figure 3b) the axial shaft (5) moves from side to side and when rolling on a variable curvature surface (Figure 4a), the axial shaft also moves up and down. This motion of the shaft (5) is readily accommodated by cable links.

**Toothed wheel on frame**

The rolling wheel embodiment of the BEMP shown in Figure 3b can also use a toothed wheel fixed to the axial shaft (5) driving a rotary electrical generator via a familiar arrangement (not shown) of one-way clutches, gear train and flywheel. However, to accommodate the horizontal and vertical motion of the axial shaft (5) this drive arrangement must be fixed to a frame that moves with the axial shaft (5).

Figure 5 shows a schematic side view of a rigid cuboid frame (41) that is fixed by bearings (42) to the axial shaft (5) of the rolling BEMP. The frame (41) is slidably connected to parallel horizontal overhead rails (43) by vertical shock absorbers (45) each mounted on wheeled overhead chassis (44). The rails (43) are fixed to the enclosing structure. Movement of the frame (41) along the rails (43) is limited by progressive rate buffers (not shown). The PTO system (not shown) is carried on the upper part of the frame (41) and is driven by the rolling wheel (23 or (24) by engagement of a toothed wheel (46) with teeth (not shown) embedded in the rim of the rolling wheel (23) or (24).
The vertical shock absorbers (45) are always in compression, exerting a downward force. As the rolling BEMP moves along the curved rolling surface (25), the shock absorbers (45) accommodate the changes in height of the BEMP.

An advantage of the described frame (41) is that it restrains the rolling path of the rolling BEMP so that rails (which would inhibit flexing of the rolling surface (25)) are not required. The frame can be slidably connected to rails (not shown) on each side of the BEMP to further restrain sideways movement.

Other PTO methods

The frame (41) described above can operate an overhead rack and pinion drive.

The frame (41) described above can be attached to hydraulic pistons that drive pressurized fluid through an accumulator to a rotary hydraulic engine that drives a rotary electrical generator.

By embedding permanent magnets in the rim of the wheels (23) and (24) of the rolling variant of the BEMP and passing the rim between conducting coils, electric current can be generated directly.

Spherical BEMP

A variant of the BEMP is based on a rolling sphere. This is shown in schematic plan view in Figure 6a and in schematic side view in Figure 6b. In Figure 6a the top hemisphere is removed. In Figure 6b the front side hemisphere is removed and the bowl-shaped rolling surface (48) is cut away.

A hollow sphere (47) rolls on a bowl-shaped rolling surface (48) fixed to the enclosing structure. Inside the hollow sphere (47) are five arms of equal length. Four arms (49) are fixed in a plane that passes through the centre of the sphere (47). The four arms (49) join in a cross with the outer ends fixed to the inner wall of the sphere (47). The fifth arm (50) is at right angles to the four arms (49) and fixed at one end to the cross junction of the four arms (49) and at the other end fixed to the inner wall of the sphere (47). Equal masses (51) are slidably attached to each of the four arms (49) and kept equidistant from the centre of the sphere (47). An eccentric mass (52) is slidably attached to the fifth arm (50). The equal masses (51) and the eccentric mass (52) move along their respective arms (49) and (50) by sliding along rails (53) driven by screw jacks (54) mounted on threaded rods (55).

By sliding the balanced masses along each pair of arms, the period of rolling oscillation of the sphere be varied independently in directions at right angles to each other.

The PTO system for the rolling sphere is a variant of the system described in Figure 5a.
As shown in a schematic plan view (Figure 7a) and in a schematic side view (Figure 7b), the sphere (47) is gripped by an outer annular collar (56) that slides against the smooth outer surface of the sphere (47). The collar is attached to at least three radially symmetrical collar cables (57). In Figure 7 four radially symmetrical collar cables (57) are shown. The cables (57) connect to spools (58). The spools are anchored to the enclosing structure (not shown) and capture power as described under the prior section ‘cable-driven spool PTO’.

**Tuning**

In order to extract power from the BEMP in a wave power application, it is tuned to resonate with the dominant swell. As already described, the period of oscillation of the BEMP can be varied dynamically by varying the radii Rb and Re (see equation 5). Tuning can also be achieved by varying the rate of power take-off so that the amplitude of oscillation is controlled.

For a conventional pendulum, the period is almost constant for small angles of rotation. The percentage deviation of amplitude from the small angle period for a conventional pendulum can be derived from an infinite series:

\[
8. \% \text{ deviation} = 100\left(\frac{A^2}{16} + \frac{11A^4}{3072} + \frac{173A^6}{737280} + \ldots..\right)
\]

where \( A \) is the angle of displacement from the vertical.

For \( A = 45, 90, 135, 162 \) degrees (90% rotation)
the calculated \% deviation = 4, 18, 53, 100\% respectively

The \% deviation for the rolling BEMP varies moderately with the position of the centre of mass relative to the rolling axis. The average measured result for the same angles as above was 6.75, 15.8, 38.5, 92.2\% respectively.

The period of oscillation can be increased by reducing the rate of power take-off and so enabling larger amplitudes.

In a wave-power application, rapid variation in swell amplitude may make precise control of power take-off impractical, so that it is preferable for BEMP period to be made independent of amplitude.

This was achieved for the conventional pendulum by an invention attributed to Christian Huygens in 1658. His invention relies on suspending the pendulum mass from a cord that swings against shaped blocks, forcing the mass to follow a path that becomes steeper as amplitude increases.

An equivalent to the Huygens invention is a curved rolling surface for the rolling BEMP. The required surface is effectively flat for small amplitudes and becomes progressively steeper at higher amplitudes. Tests confirm that such a curved surface can provide a
period that is independent of amplitude. The curvature needed varies with the
collection of the BEMP, and so a dynamically variable curvature is required, as
described in Figures 4a and 4b.

Tests

Confirming tests of variation in oscillation period have been carried out with model
BEKnPs that include:

- Axial shaft mounted on bearings (Figures 1a and 1b)
- Axial shaft rolling on a flat and curved surface (Figure 3a)
- Axial shaft mounted on two rolling wheels (Figure 3b) rolling on a flat and on a
curved surface
- A hollow sphere with balanced and eccentric masses (Figures 6a and 6b).

Energy harvesting

The present invention is described here in terms that assume implementation using
thousands of tonnes of mass. It is also possible to use a BEMP on a micro scale with
applications in energy harvesting, for example to power remote sensors. The advantage of
a tunable pendulum is greatly improved efficiency in energy capture, assuming
predictability in the period of oscillation.

A micro version of the rolling variant of the BEMP can be constructed as single vertical
wheel with the axle turning on bearings mounted in blocks that slide in two parallel PTFE
grooves. The centre of mass of the wheel can be varied by using a miniature stepper
motor to move an eccentric mass to and from the axis of the wheel. Commercially
available stepper motors are available in packages as small as 7x8x8mm. New Scale
Technologies Inc of NY provide an even smaller linear motor: the Squiggle motor, in a
package as small as 2x2x6mm. Power can be extracted using the well-known kinetic
watch mechanism whereby the wheel rotates a small pinion at over 10,000 rpm and this
drives a small rotary electrical generator. Alternatively power can be extracted from
piezoelectric springs fixed at each end of the path of the wheel.
Advantages of invention

- Long period oscillations can be achieved without the large structures required for a conventional pendulum. For example, in a wave energy conversion system that requires resonance with sea swells from 5 to 15 seconds period the equivalent conventional pendulum requires a structure 60m high. A low-power BEMP can be less than one meter high. An equivalent one-megawatt BEMP can be under 12m high.
- The period of oscillation can be adjusted continuously and rapidly. For example, to adjust the period from 5 seconds to 15 seconds in a conventional pendulum requires the pendulum mass to be shifted over 50m along the pendulum arm. The same adjustment can be made in a one-megawatt BEMP by shifting the pendulum mass approximately 5m.
- In a wave-power application of a compact pendulum, commercial levels of power require large inertial masses. If these masses are suspended on conventional bearings the stresses on these components are large and the structural and maintenance costs can be high. The rolling variants of the BEMP do not require conventional bearings and so avoid these costs.
- In wave-power applications, the sideways stresses created by large inertial masses imply high structural and maintenance costs. These stresses on the BEMP can be mitigated by using long axial shafts and multiple points of support to the shaft. In the rolling variant of the BEMP, a multiple wheel embodiment provides increased lateral stability. In the spherical embodiment of the BEMP, the device is compliant with sideways forces and harvests energy from such forces so reducing the cost of sideways reinforcement.
Claims

1. A tunable pendulum with power take-off comprising:
   
   a. a rotatable mass that is balanced about the axis of rotation;
   b. means for moving portions of said rotatable balanced mass to and from said axis with the balance maintained;
   c. an eccentric mass attached to said rotatable mass;
   d. means for moving portions of said eccentric mass to and from said axis;
   e. means for capturing the motion of said rotatable mass to enable conversion to electrical power.

2. A pendulum as claimed in claim 1 wherein said rotatable mass comprises:
   
   a. first and second arms of equal length fixed to opposite sides of a pivot;
   b. first and second masses of equal size slidably fixed to said first and second arms respectively and said first and second equal masses kept equidistant from said axis of rotation.

3. A pendulum as claimed in claim 2 wherein said eccentric mass comprises:
   
   a. a third arm fixed to said pivot at right angles to said first and second arms;
   b. a third mass slidably fixed to said third arm.

4. A pendulum as claimed in claim 3 wherein means for moving portions of said balanced mass to and from said axis comprises:
   
   a. first and second electrical screw jacks fixed to said first and second equal masses respectively;
   b. first and second threaded rods fixed along the lengths of said first and second arms respectively and on said rods said first and second screw jacks respectively are mounted;
   c. first and second pair of parallel rails fixed along the lengths of said first and second arms respectively and on said rails slide said first and second equal masses respectively.

5. A pendulum as claimed in claim 4 wherein means for moving portions of said eccentric mass to and from said axis comprises:
   
   a. a third electrical screw jack fixed to said third mass;
   b. a third threaded rod fixed along the length of said third arm and on said third rod said third screw jack is mounted;
   c. a third pair of parallel rails fixed along the length of said third arm and on said rails said third mass slides.
6. A pendulum as claimed in claim 5 wherein said pivot is a horizontal pivot shaft held at each end inside bearings fixed to the enclosing structure.

7. A pendulum as claimed in claim 6 wherein means for capturing the motion of said rotatable mass comprises:
   
   a. a first toothed wheel fixed to said pivot shaft and rotating with said pivot shaft;
   b. a second toothed wheel that rotates on a drive shaft and engages with said first toothed wheel;
   c. said drive shaft drives a combination of gear train and one-way clutches and flywheel to deliver uniform, high-speed rotating motion to a rotary electrical generator.

8. A pendulum as claimed in claim 5 wherein said pivot is a horizontal pivot shaft supported at each end inside horizontal open-ended tubes fixed to the enclosing structure.

9. A pendulum as claimed in claim 5 wherein said pivot is a horizontal pivot shaft fixed at each end to the axis of identical vertical wheels that roll on a rolling surface fixed to the enclosing structure.

10. A pendulum as claimed in claim 9 wherein said rolling surface is substantially flat over a central distance equal to around 30% of the circumference of said wheels and curves upwards with increasing steepness at each extreme.

11. A pendulum as claimed in claim 9 wherein said rolling surface comprises:
   
   a. a flexible sheet fixed to the enclosing structure along a line at right angles to the direction of rolling and at the midpoint of said sheet;
   b. a first and second wedge each with a sloping upper surface and with a horizontal lower surface that is slidably attached to a pair of parallel rails aligned with the direction of rolling of said wheels and embedded in said enclosing structure under said sheet;
   c. the low ends of said first and second wedges projecting under the opposite edges of said sheet;
   d. the high ends of said first and second wedges each attached to one or more screw jacks mounted on threaded rods that are each fixed at one end to the enclosing structure.

12. A pendulum as claimed in claims 8 and 9 wherein means for capturing the motion of said rotatable mass comprises:
   
   a. a cable wrapped round the pivot shaft;
b. the first end of said cable extending in the first direction of oscillation of said pendulum;
c. said first end of cable wrapped round a first spool that rotates on a spool shaft on bearings fixed to said enclosing structure;
d. said first end of cable extends from said first spool via a first pulley to a fixing on said enclosing structure;
e. said first pulley is mounted on a first shock absorber with progressive rate compression spring and pneumatic damper and said first shock absorber is fixed at the base to the enclosing structure;
f. the second end of said cable extending in the second direction of oscillation of said pendulum;
g. said second end of cable wrapped round a second spool that rotates on a spool shaft on bearings fixed to said enclosing structure;
h. said second end of cable extends from said second spool via a second pulley to a fixing on said enclosing structure;
i. said second pulley is mounted on a second shock absorber with progressive rate compression spring and pneumatic damper and said second shock absorber is fixed at the base to the enclosing structure;
j. said shafts of said first and second spools each drive a combination of gear train and one-way clutches and flywheel to deliver uniform, high-speed rotating motion to a rotary electrical generator.

13. A pendulum as claimed in claim 9 wherein means for capturing the motion of said rotatable mass comprises:

a. a rigid cuboid frame surrounding the pendulum and fixed to bearings round both ends of said pivot shaft;
b. said frame attached slidably to parallel overhead rails that are fixed to said enclosing structure;
c. said frame attached to said overhead rails by vertical shock absorbers under permanent compressive load;
d. a toothed wheel on a drive shaft carried on bearings fixed to said frame;
e. said toothed wheel engaged with teeth embedded in the rim of said rolling wheel;
f. said drive shaft driving a combination of gear train and one-way clutches and flywheel to deliver uniform, high-speed rotating motion to a rotary electrical generator.

14. A pendulum as claimed in claim 1 wherein:

a. said rotatable mass comprises a hollow sphere inside which are fixed to the wall of the sphere four identical arms forming a cross in the same plane, all joined at the centre of said sphere and on each of said four arms an identical mass is slidably attached;
b. said eccentric mass is a fifth arm inside said sphere, fixed at one end to the wall of the sphere and fixed at the other end to said four other arms at the centre of said sphere and on said fifth arm a fifth mass is slidably attached;
c. said four arms and said fifth arm each comprise a central threaded rod and two parallel outer rails held together by cross-members;
d. said means for moving portions of said rotatable balanced mass is an electrical screw jack attached to each of said identical masses and mounted on each said threaded rod and the identical mass sliding on said rails;
e. said means for moving portions of said eccentric mass is an electrical screw jack attached to said fifth mass and mounted on the threaded rod of said fifth arm and said fifth mass sliding on the rails of said fifth arm;
f. said means for capturing motion of said sphere is a sliding collar around the upper surface of said sphere and said collar being held by at least three radially symmetrical cables each wound around a spool and then round a pulley mounted on a shock absorber, with the shaft of said spool driving a PTO system as claimed in claim 12.

15. A means of dynamically tuning a pendulum as claimed in claim 1 by:

a. moving portions of said balanced mass to and from said axis of rotation;
b. moving portions of said eccentric mass to and from said axis of rotation.

16. A means of dynamically tuning a pendulum as claimed in claim 1 by varying the power take-off to change the amplitude and thereby the period.

17. A means of dynamically tuning a pendulum as claimed in claim 9 by varying the curvature of said rolling surface.

18. A means of varying the curvature of said rolling surface as claimed in claim 17 by:

a. using as said rolling surface a flexible sheet fixed at its middle to a floor of the enclosing structure;
b. sliding wedges under said flexible sheet in the direction of rolling of said pendulum wheel.
Application No: GB1103508.6
Claims searched: 1-18
Examiner: Alex Swaffer
Date of search: 20 July 2011

Patents Act 1977: Search Report under Section 17

Documents considered to be relevant:

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<td>GB189905508 (De Vlbiess): See masses 12, 18 in figure 4.</td>
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Field of Search:

Search of GB, EP, WO & US patent documents classified in the following areas of the UKC:

B63B; B63J; E04B; F03B; F03G; F16F; G04B

The following online and other databases have been used in the preparation of this search report:

EPODOC, WPI

International Classification:

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