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Beale

(54) BETA FREE PISTON STIRLING ENGINE IN FREE CASING CONFIGURATION HAVING POWER OUTPUT CONTROLLED BY CONTROLLING CASING AMPLITUDE OF RECIPROCATION

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(52) **U.S. Cl.**
USPC **60/518**; 60/645

(57) **ABSTRACT**

The power output of a free piston Stirling engine mounted in a free casing configuration is controlled by having a spring drivingly linking the displacer to the casing and controllably varying the amplitude of reciprocation of the casing. A variable casing reciprocation restraint is linked to the casing for applying a variable restraining force to the casing. The restraining force is increased for decreasing the displacer amplitude of reciprocation and thereby decreasing the power output from the Stirling engine and the restraining force is decreased for increasing the displacer amplitude of reciprocation and thereby increasing the power output from the Stirling engine.

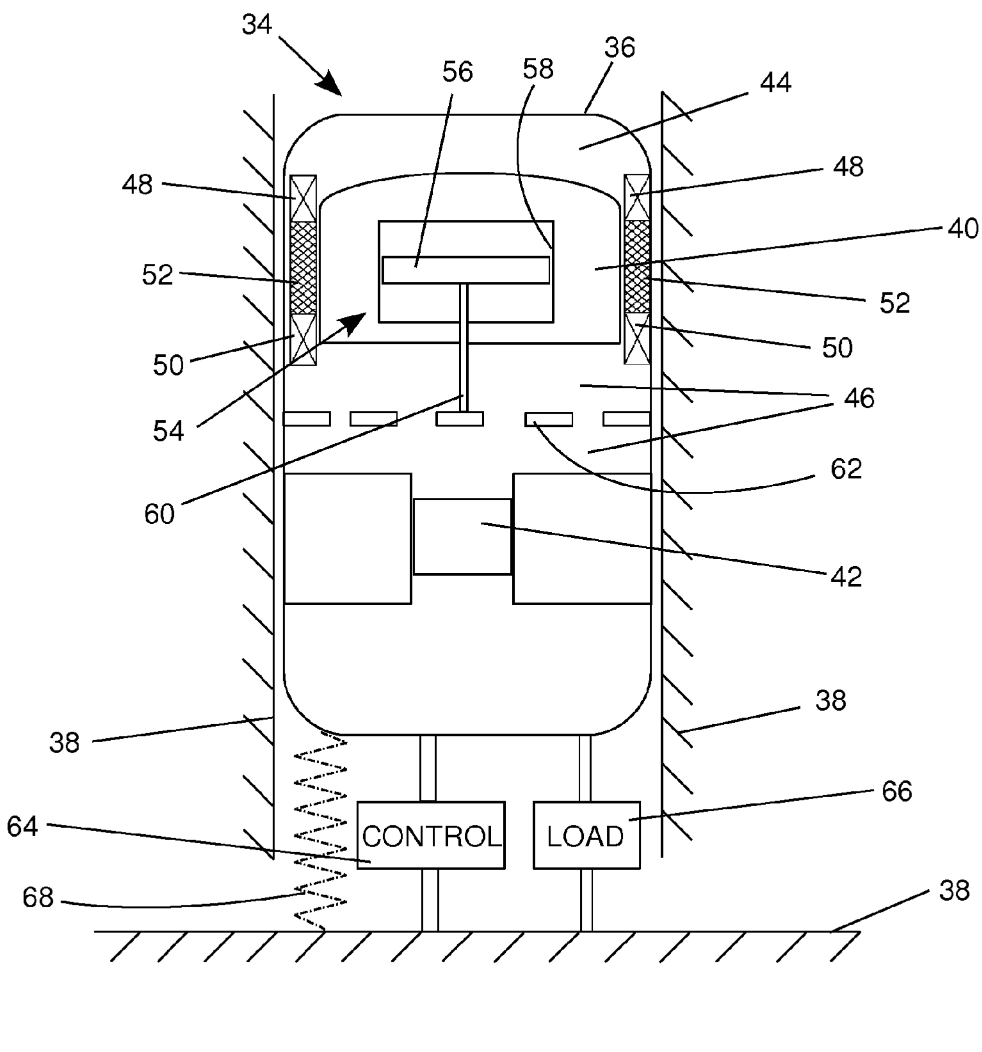


Fig. 1
Prior Art

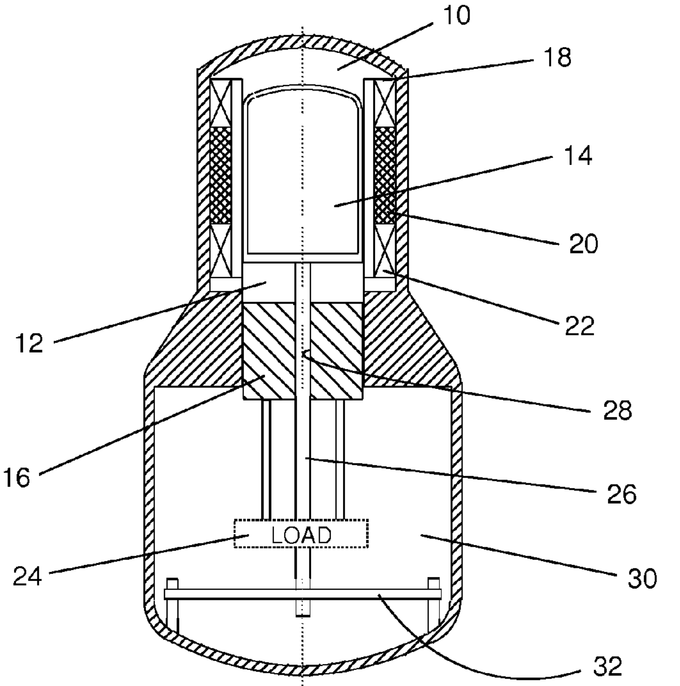


Fig. 2

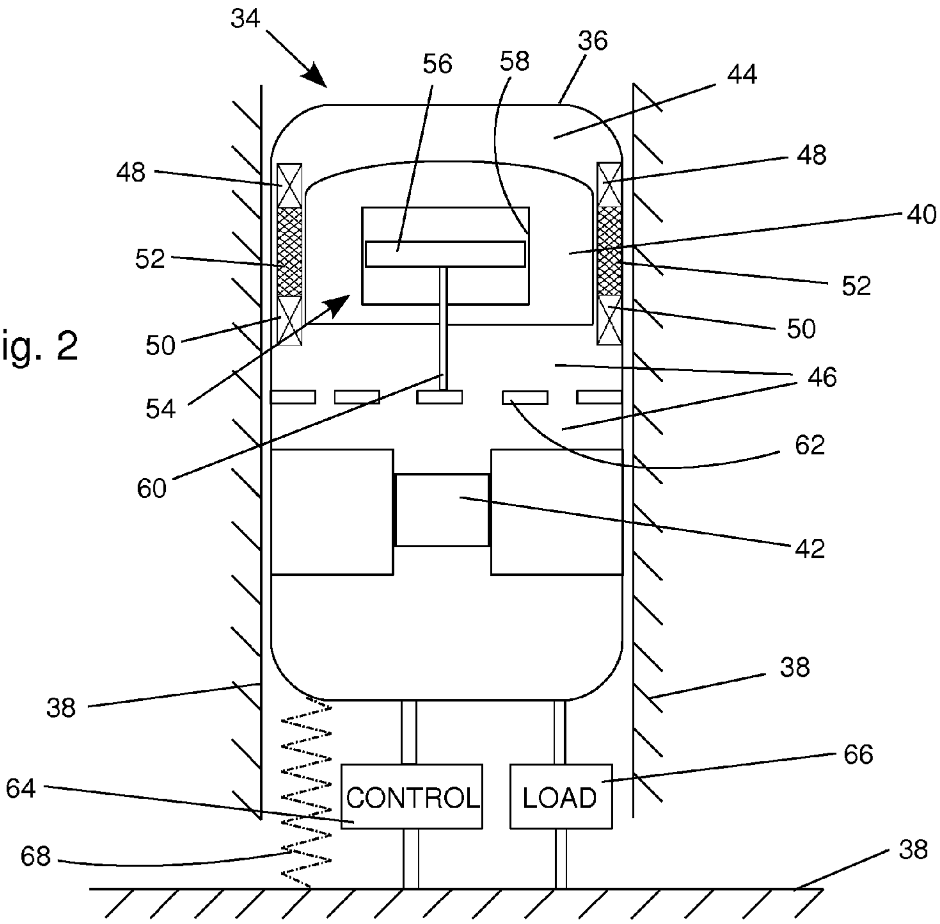
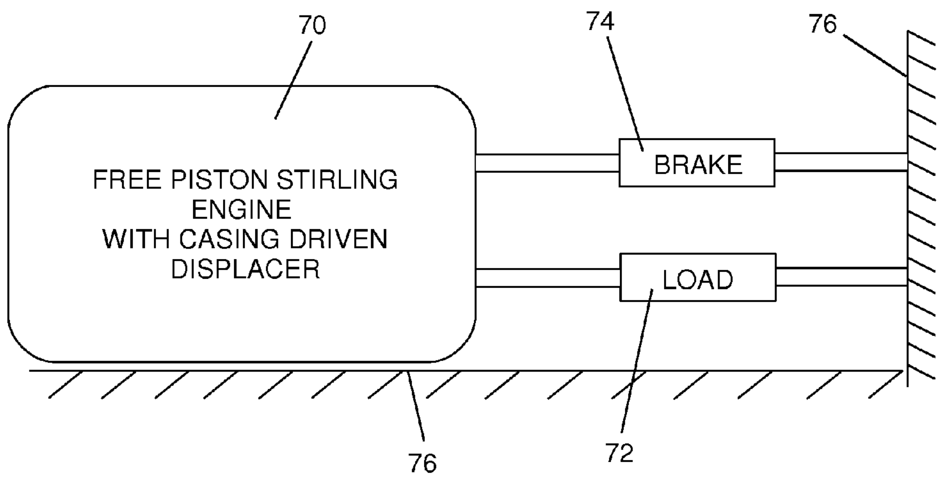


Fig. 3


70
74
76
FREE PISTON STIRLING
ENGINE
WITH CASING DRIVEN
DISPLACER
BRAKE
LOAD
76
72

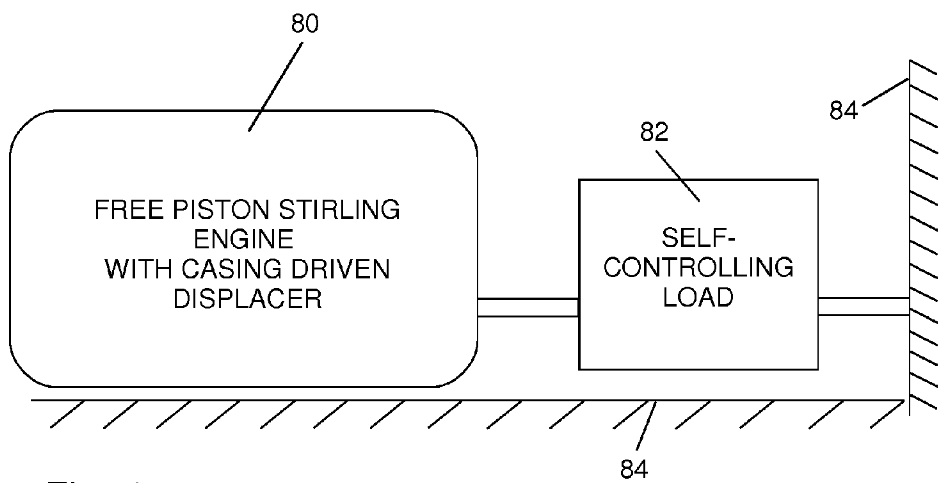
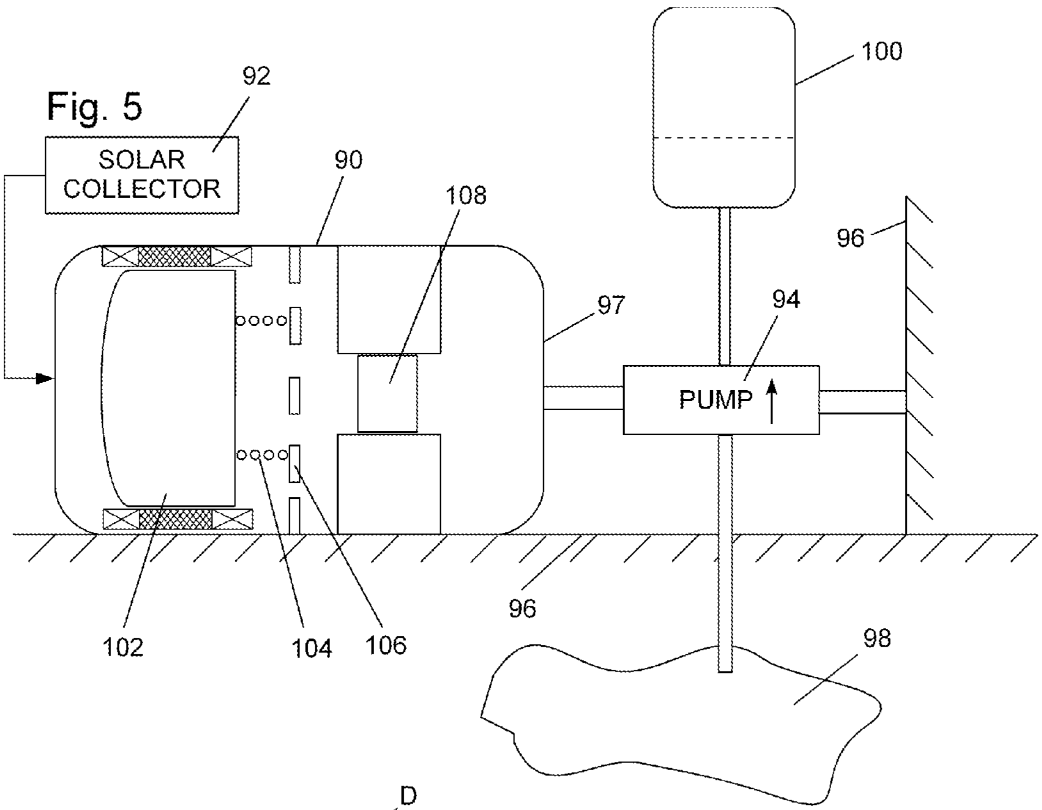

80
84
82
FREE PISTON STIRLING
ENGINE
WITH CASING DRIVEN
DISPLACER
SELF-
CONTROLLING
LOAD
84

Fig. 4

Fig. 5



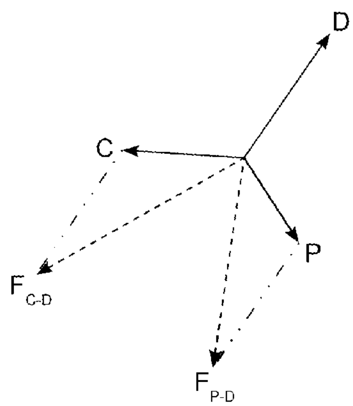


Fig. 6

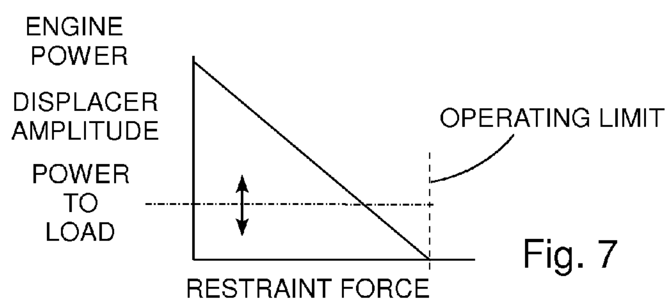


Fig. 7

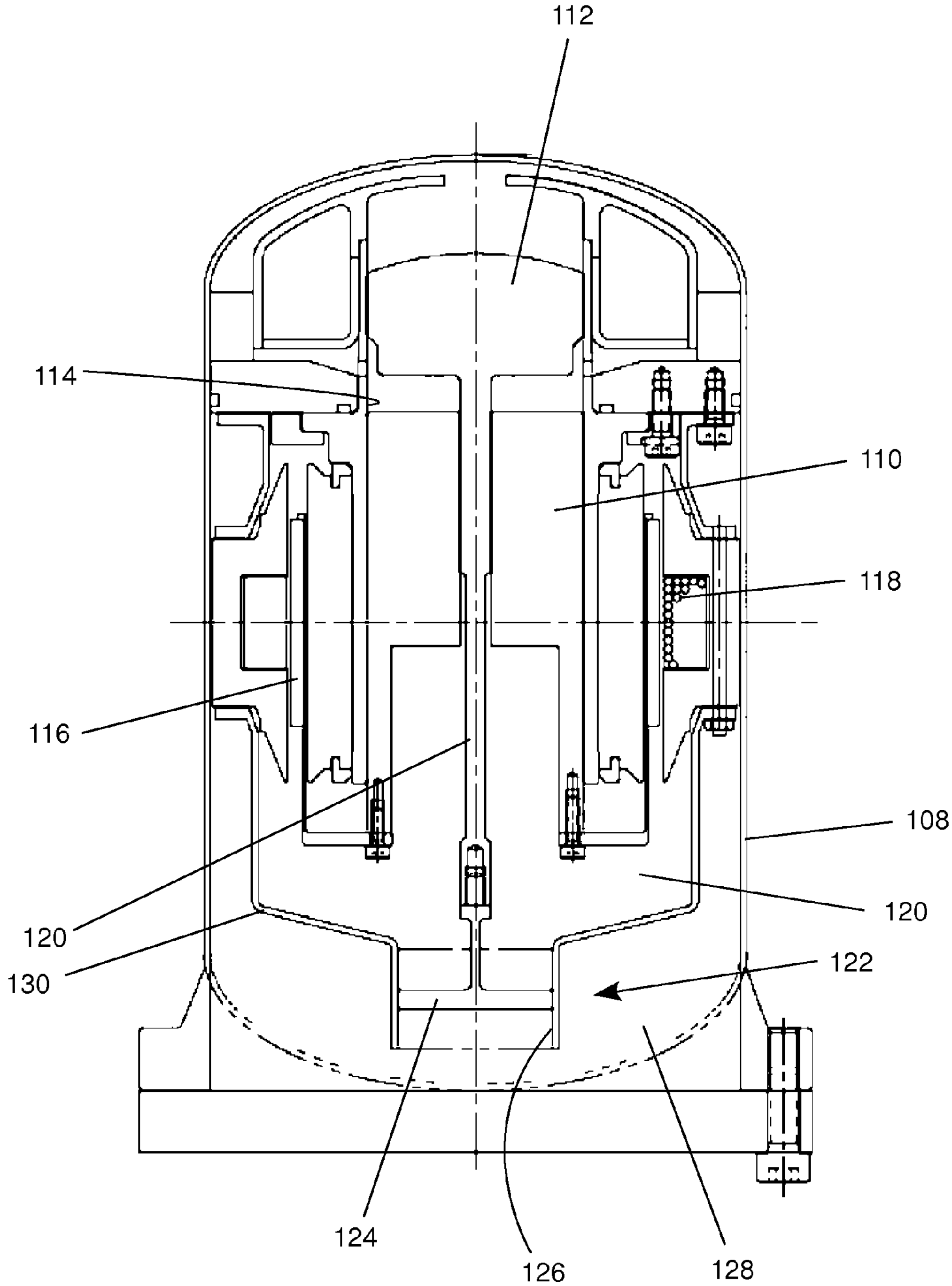


Fig. 8

Fig. 9

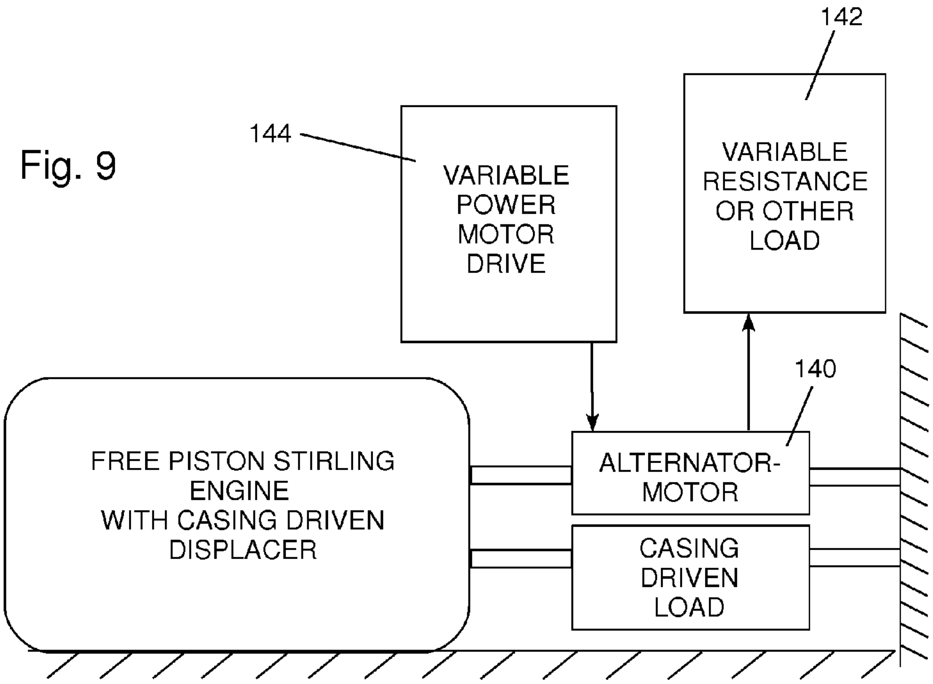
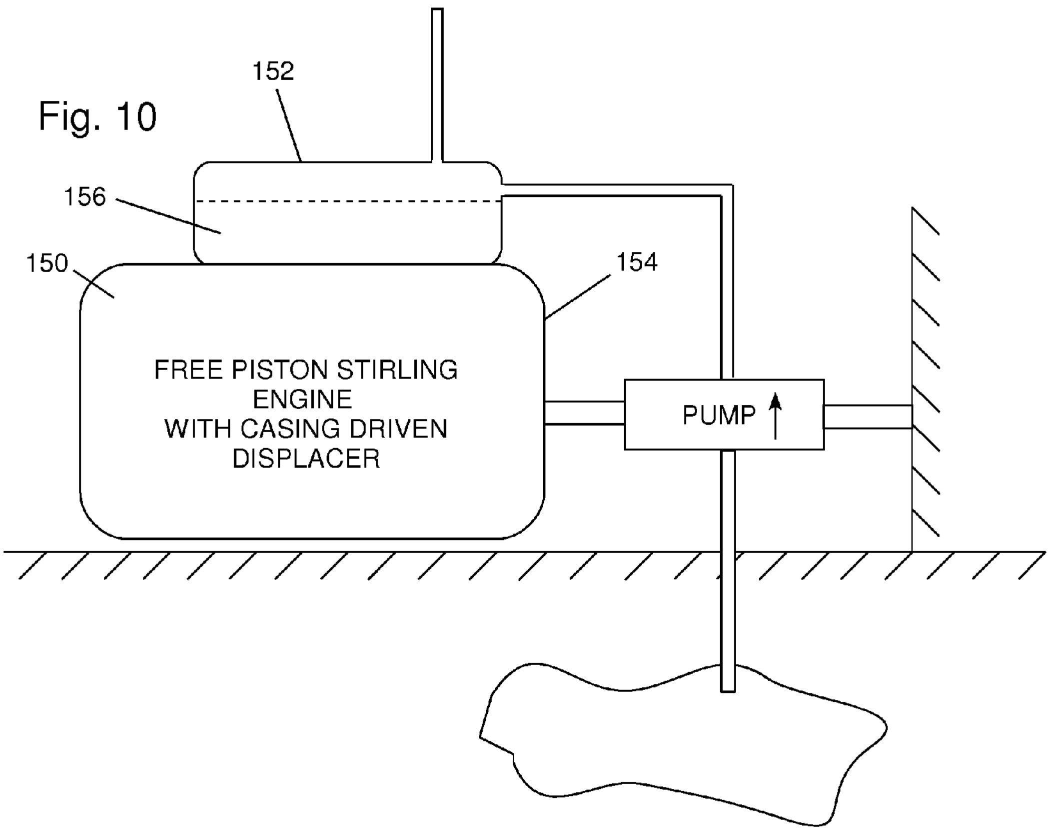

144
VARIABLE
POWER
MOTOR
DRIVE
142
VARIABLE
RESISTANCE
OR OTHER
LOAD
140
FREE PISTON STIRLING
ENGINE
WITH CASING DRIVEN
DISPLACER
ALTERNATOR-
MOTOR
CASING
DRIVEN
LOAD

Fig. 10


152
156
150
154
FREE PISTON STIRLING
ENGINE
WITH CASING DRIVEN
DISPLACER
PUMP

BETA FREE PISTON STIRLING ENGINE IN FREE CASING CONFIGURATION HAVING POWER OUTPUT CONTROLLED BY CONTROLLING CASING AMPLITUDE OF RECIPROCATION

CROSS-REFERENCES TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 61/586,280 filed 13 Jan. 2012.

STATEMENT REGARDING FEDERALLY-SPONSORED RESEARCH AND DEVELOPMENT

[0002] (Not Applicable)

REFERENCE TO AN APPENDIX

[0003] (Not Applicable)

BACKGROUND OF THE INVENTION

[0004] This invention relates to free piston Stirling engines and more particularly relates to a new manner of controlling the output power of such engines that gives the advantageous results of reducing manufacturing costs by easing alignment and concentricity tolerance requirements and of providing a new engine power output modulation characteristic by which a load modulates the output power of the engine with the characteristic that the power output from the engine is an increasing function of the difference between a desired load operating limit and the current load.

[0005] Stirling machines have been known for nearly two centuries but in recent decades have been the subject of considerable development because they offer important advantages. Modern versions have been used as engines and heat pumps for many years in a variety of applications.

[0006] The prior art has numerous examples of prior art, free piston Stirling engines including U.S. Pat. Nos.: 7,640,740; 7,692,339; 7,775,041; 7,827,789; and 8,011,183. Explanation can be found at http://www.sunpower.com/services/technology/stirling.php. FIG. **1** diagrammatically illustrates an example of a prior art Stirling engine in a beta configuration. In a Stirling machine, a working gas is confined in a working space comprised principally of an expansion space **10** and a compression space **12**. The working gas is alternately expanded and compressed in order to either do work or to pump heat. Each beta Stirling machine has a pair of pistons, one referred to as a displacer **14** and the other referred to as a power piston **16** and often just as a piston **16**. The reciprocating displacer **14** cyclically shuttles a working gas between the compression space **12** and the expansion space **10** which are connected in fluid communication through a heat accepter **18**, a regenerator **20** and a heat rejecter **22**. The shuttling cyclically changes the relative proportion of working gas in each space. Gas that is in the expansion space **10**, and gas that is flowing into or out of the expansion space **10** through a heat exchanger (the heat accepter **18**) between the regenerator **20** and the expansion space **10**, accepts heat from surrounding surfaces. Gas that is in the compression space **12**, and gas that is flowing into or out of the compression space **12** through a heat exchanger (the heat rejecter **22**) between the regenerator **20** and the compression space **12**, rejects heat to surrounding surfaces. The gas pressure is essentially the same in both spaces at any instant of time because the spaces are interconnected through a path having a relatively low flow resistance. However, the pressure of the working gas in the work space as a whole varies cyclically and periodically. When more of the working gas is in the compression space **12**, there is a net heat rejection from the working gas. When more of the working gas is in the expansion space **10**, there is a net heat acceptance into the working gas. This is true whether the machine is working as a heat pump or as an engine.

[0007] Until about 1965, Stirling machines were constructed as kinematically driven machines meaning that the piston and displacer are connected to each other by a mechanical linkage, typically connecting rods and crankshafts. The free piston Stirling machine was then invented by William Beale. In the free piston Stirling machine, the pistons are not connected to each other by a mechanical drive linkage. A free-piston Stirling machine is a thermo mechanical oscillator and the displacer **14** is, in the prior art, driven by the working gas pressure variations and pressure differences in spaces or chambers within the machine. The piston **16** is either driven by a reciprocating prime mover when the Stirling machine is operated in its heat pumping mode or drives a reciprocating mechanical load **24** when the Stirling machine is operated as an engine. Free piston Stirling machines offer numerous advantages including the ability to control their frequency, phase and amplitude, the ability to be hermetically sealed from their surroundings and their lack of a requirement for a mechanical fluid seal between moving parts to prevent the mixing of the working gas and lubricating oil.

[0008] The function of the displacer **14** is to alternately displace working gas in the expansion space **10** and the compression space **12** and thereby cyclically vary the proportion of working gas in each of those spaces. A characteristic of a free piston Stirling engine is that the power out produced by the engine is an increasing function of the amplitude of the displacer reciprocation. The greater the amplitude of the displacer reciprocation, the greater the heat that is transferred into and out of the working gas during each operating cycle and therefore the greater the heat energy input to the engine and the mechanical energy output from the machine during each cycle.

[0009] The recognized and preferred manner of driving the displacer **14** in reciprocation is based upon the pressure differential that exists because a connecting rod **26** typically extends through a cylindrical bore **28** in the piston **16** and into a back space **30** and sometimes to a planar spring **32** which centers the connecting rod **26**. The back space **30** usually has a large volume relative to the working space so that the cyclical gas pressure variations in the back space **30** are relatively small compared to the cyclical gas pressure variations in the working space. The gas pressure in the working space applies a cyclically varying force on the displacer **14** and its connecting rod **26**. The instantaneous value of that force is equal to the product of the instantaneous pressure in the working space multiplied by the cross sectional area of the connecting rod **26**. The gas in the back space **30** applies an oppositely directed force that is equal to the product of the instantaneous pressure in the back space **30** multiplied by the cross sectional area of the connecting rod **26**. Consequently, the net force driving the displacer is the difference between the two oppositely directed forces. That is true whether the back space **30** pressure never appreciably varies or the back space has a smaller volume that acts like a gas spring and therefore undergoes pressure variations. In addition to the pressure differential method for driving the displacer, displacers have also been driven by a separate prime mover and by a mechanical drive linkage connected to the piston but both of these methods have been largely discarded in current technology.

[0010] The use of the pressure differential method for driving the displacer not only requires a displacer connecting rod and a bore, which usually extend into and most commonly through the piston, but also requires that the connecting rod have a cross sectional area that is large enough to provide a sufficient drive force for driving the displacer at desired amplitudes. These requirements add considerably to the cost of manufacturing a free piston Stirling engine because of the extremely close tolerance manufacturing and assembly that are required. One reason for the increased cost is the need for a tight gas seal between the connecting rod and the piston bore through which the rod extends. Consequently, both must be precision machined to minimize the clearance between them and yet permit their relative reciprocation. Additionally, the rod and bore also introduce substantial concentricity and alignment problems. Both the piston bore and the displacer rod not only must be precisely concentric in their position but also they must be aligned precisely coaxially along the central axis of the displacer cylinder and the piston cylinder. Otherwise they would interfere during reciprocation. Furthermore, as the connecting rod diameter becomes larger, the concentricity and alignment problems become larger. In summary, the combination of the need for a close fit of the rod within the bore through the piston and the need for precise alignment and concentricity make both manufacturing and assembly a significant part of the cost of fabricating such free piston Stirling engines.

[0011] It is therefore an object and feature of the present invention to provide a free piston Stirling engine that permits the connecting rod and its mating bore in the piston to be totally eliminated or, in the alternative if retained, allows them to be considerably smaller in diameter and thereby reduces the concentricity and alignment requirements and their corresponding manufacturing costs.

[0012] There are a variety of methods and apparatus for controlling a free piston Stirling engine. Many are complicated and involve sophisticated electronic circuitry typically with digital processors. Control is necessary because, if the demand of a load that is driven by a free piston Stirling engine is reduced during operation, the piston and displacer amplitude can increase to the extent that the piston and displacer collide with internal structures and become damaged or destroyed. It is an object and feature of the invention that the invention permits control by technically simple structures that are readily accessible outside the casing of the engine.

[0013] It would be desirable for some applications to have a free piston Stirling engine that has an operating characteristic that the power output from the engine is reduced as the load approaches some desirable, selected operating limit and becomes zero power output when that limit is reached. For example, that characteristic would be desirable for a domestic water supply system in which a water pump is driven by a free piston Stirling engine and the engine receives its power from a solar collector. In a domestic water system, a supply of water is pumped into a reservoir, such as a pressure tank, until a suitable upper pressure limit is reached, commonly 50 psi. It would be desirable that the Stirling engine stop operating the pump when the upper pressure limit is reached and also desirable that the drive power from the Stirling engine increase as the pressure drops below the upper pressure limit. In particular it would be desirable that the engine power output be an increasing function of the difference between the upper pressure limit and the current pressure in the system. That would provide the characteristic that the engine and pump would stop when the pressure reaches the upper pressure limit but water would be pumped at a rate that is proportional to (or some other increasing mathematical function of) the extent to which the current water pressure is below the upper limit pressure so that the greater the need for pump operation, the greater the drive power that is applied to the pump. It is an object and feature of the invention to provide an engine and load configuration that exhibits such an operating characteristic.

[0014] Although unusual or rare, free piston Stirling engines have been shown in a free casing configuration sometimes known as free-cylinder. The free casing Stirling engine offers a means by which mechanical power extraction devices (e.g. a water pump) may be coupled externally to a pressurized, sealed engine. The cyclically repetitive acceleration and deceleration of the moving displacer and piston masses, along with masses connected to them, apply f=ma forces to the engine casing. The result is usually regarded as undesirable vibration of the casing and the vibrations are often reduced by use of a vibration balancer or vibration damper. However, if the casing is mounted so that it is free to reciprocate with respect to a reference ground, a load can be linked between the casing and the ground and the casing motion used to drive the load. Unlike the free piston engine having its load coupled directly to its piston, the free casing configuration has the ability to start at any value of load. In the free casing configuration of the prior art, the load is coupled externally between the engine casing and a reference ground. So far as known, a free piston Stirling engine has never had its power output controllably modulated, or otherwise controlled, by controlling the amplitude of the casing reciprocation.

[0015] In fact, if a water pump is driven by a free casing, and the free piston Stirling engine has its displacer driven in the usual manner by means of a displacer connecting rod using the above described pressure differential to drive the displacer, an increase in the water pressure causes an increase in power applied to drive the displacer and a consequent increase in piston and displacer amplitude and therefore in the force applied to the pump. If the pump pressure rises high enough to entirely stop the casing motion, the displacer and piston reciprocate at an excessive amplitude that is likely to cause internal collisions. Conventional free casing configurations generate more thermodynamic power as a result of more casing constraint. If the load increases enough to completely restrain the casing and stop casing motion, the additional thermodynamic power must go somewhere. The additional power is not transferred to the load if the load motion is stopped. So that additional thermodynamic power is transferred to self-destructive internal behavior such as increased amplitude of piston and displacer motion. The present invention does the opposite. With the invention, as the reciprocation is restrained, the generated thermodynamic power decreases. Therefore, if the invention is used for the water pump example, as the pump pressure rises, the amplitudes of reciprocation of the displacer and piston are reduced, thereby avoiding damaging collisions.

BRIEF SUMMARY OF THE INVENTION

[0016] In a free piston Stirling engine, the power output from the engine is an increasing function of the amplitude of the displacer's amplitude of reciprocation. The basic concept of the invention is that the displacer is sprung to the casing so that the displacer is driven, at least in dominant part, by the motion of the casing and the power output from the free piston Stirling engine is controlled by controlling the casing amplitude of reciprocation and thereby controlling the displacer amplitude of reciprocation. The displacer is desirably driven only by power coupled through the spring from the casing in which case a displacer connecting rod can be entirely eliminated along with the concentricity and alignment problems it causes. Alternatively, a displacer rod of smaller diameter can be used and the displacer driven in minor or inconsequential part by the above-described pressure differential used in the prior art. With the invention, because the casing applies the principal proportion of the displacer drive power, the displacer motion can be controlled by controlling the casing motion (e.g. by a brake). Power output can be taken from the reciprocating piston or from the reciprocating free casing. Regardless of whether power output is from the piston, the casing or both, engine power output is still controlled by controlling casing amplitude and thereby controlling displacer amplitude.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0017] FIG. **1** is a diagrammatic view of a free piston Stirling engine that is typical of the prior art.

[0018] FIG. **2** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with the invention.

[0019] FIG. **3** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with another arrangement of the invention.

[0020] FIG. **4** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with an embodiment of the invention with a self controlling load.

[0021] FIG. **5** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with another alternative embodiment of the invention.

[0022] FIG. **6** is a phasor diagram for an embodiment of the invention.

[0023] FIG. **7** is a simplified graphical illustration of a principle of the invention.

[0024] FIG. **8** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with an alternative embodiment of the invention.

[0025] FIG. **9** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with still another alternative embodiment of the invention.

[0026] FIG. **10** is a diagrammatic view of a free piston Stirling engine configured and controlled in accordance with yet another embodiment of the invention.

[0027] In describing the preferred embodiment of the invention which is illustrated in the drawings, specific terminology will be resorted to for the sake of clarity. However, it is not intended that the invention be limited to the specific term so selected and it is to be understood that each specific term includes all technical equivalents which operate in a similar manner to accomplish a similar purpose.

DETAILED DESCRIPTION OF THE INVENTION

[0028] FIG. **2** illustrates an example of an improved free piston Stirling engine **34** according to the present invention. The engine **34** is mounted in a free casing configuration permitting reciprocating movement of its casing **36** with respect to a reference ground **38**. The reference ground **38** is a mass, such as the earth, with respect to which the casing is free to reciprocate. The freedom to reciprocate is accomplished by suitable bearings, a wheeled carriage, slides or other structures usually mounted in a support frame that permit the casing **36** to reciprocate along its longitudinal axis while being confined against motion in other directions. Contained within the casing **36** are a displacer **40** and a piston **42**, that reciprocate at the designed operating frequency of the engine, and the usual expansion space **44** and compression space **46**. Also contained in the casing are the usual heat accepting heat exchanger **48**, heat rejecting heat exchanger **50** and regenerator **52**.

[0029] The casing **36** is drivingly linked to the displacer **40** by a double acting gas spring **54**. This gas spring **54** is formed by a gas spring piston **56** that sealingly reciprocates within an enclosed cylinder **58**. A gas spring piston connecting rod **60** extends slidingly through the displacer **40** to a perforate support plate **62** in the compression space **46**. The perforate support plate **62** extends to and is fixed to an interior wall of the engine, such as directly to the casing **36**. The support plate **62** has openings or perforations to permit working gas to flow through it. Consequently, the gas spring piston **56**, its piston rod **60** and the support plate **62** are all stationery with respect to the casing **36**. Therefore, when the displacer **40** reciprocated, it is sprung to the casing by the gas spring **54**.

[0030] During operation, this gas spring **54** applies a drive force to the displacer **40** from the reciprocation of the casing which drives the displacer **40** in reciprocation. In this manner drive power is applied to the displacer from the casing. In the embodiment of FIG. **2**, this spring **54** is the only displacer drive for driving the displacer **40** in reciprocation. As will be seen in connection with FIG. **5**, a mechanical spring can be substituted for the gas spring **54**. As will be seen in connection with FIG. **8**, it is possible have the displacer driven by two component drives, a principal component drive from the casing and a secondary or minor component drive by a conventional displacer rod pressure differential drive that is known in the prior art. Importantly, however, in the invention the drive power from the casing is greater than the sum of any and all other drive power applied to the displacer.

[0031] As stated above, the power output from a free piston Stirling engine is an increasing function of the amplitude of the displacer reciprocation. A power output control **64** is linked to the casing **36** and, in the embodiment of FIG. **2**, between the casing **36** and the ground **38**. A load **66** to be driven by the Stirling engine is also connected between the casing **36** and the ground **38**. The power output control **64** is a variable reciprocation restraint that is capable of applying an increased restraining force on the casing for decreasing the amplitude of reciprocation of the casing and of applying a decreased restraining force on the casing for permitting the amplitude of reciprocation of the casing to increase. One example of a control **64** is a friction brake that can be adjustably varied to vary the restraining force between the casing **36** and the ground **38**. Such a friction brake has movable brake pads or shoes that engage against a frictional surface with a variable force. The brake applies a restraining force from the ground to the casing and increases the restraining force by increasing the braking; that is, increasing the force of engagement of the brake pads with the moving surface.

[0032] The power output control that is a variable reciprocation restraint used with the invention acts on the casing to variably and controllably restrain the reciprocation of the casing. The variable reciprocation restraint is drivingly linked to the casing, usually between the casing and the reference ground. Typically a reciprocation restraint is a reciprocation damper that has variable damping so that the quantity of power that it absorbs is variable. Another example of a variable reciprocation restraint is an electromagnetic generator or alternator with an energy absorbing load such as a variable resistance. A characteristic of the variable restraint is that it varies the restraining force it is capable of exerting on the casing so that it restrains the casing more tightly against reciprocation. As a reciprocation restraint becomes capable of exerting more force, it first exerts more force and becomes more effective in reducing casing reciprocation. As casing reciprocation is reduced, the displacer drive power and displacer amplitude are reduced and therefore engine power decreases. As engine power is reduced, the force and power output from the engine is reduced so the force actually applied by the variable restraint is reduced. Another example of a reciprocation restraint is a fluid pump that pumps fluid through a variable orifice allowing a controllably variable fluid flow resistance. Since an alternator and a motor are both essentially a moving magnet that reciprocates within, or is otherwise magnetically coupled to an armature coil, a linear motor/alternator may be connected in a circuit that can be controlled to alternatively consume power in a variable resistance or other load or operate the linear motor/alternator as a motor to drive the casing in reciprocation to increase the amplitude of reciprocation of the casing and thereby increase the power output of the Stirling engine. In other words, the reciprocation restraint can be a variable power absorber or a variable power transducer. Another type of reciprocation restraint is an apparatus which can vary the mass drivingly linked to the casing. Varying a mass that is mechanically connected to the casing increases or decreases the restraining force applied to the casing by the mass because F=ma.

[0033] Because increasing and decreasing the restraint to control the reciprocation amplitude of the casing decreases or increases the power output of the Stirling engine, the load, which is being driven by the Stirling engine and to which its output power is coupled, can be driven by the casing, by the piston or by both. The designer has the options to position a load, such as an alternator, inside the casing and connected to the piston or outside the casing and driven by the casing or have a load in both locations. If the load is only outside the casing and driven by the casing, the piston can be fixed to or itself have a sizeable mass and operate as an inertia reactor. Optionally, the designer may also want to include a spring **68** between the casing **36** and the reference ground **38**.

[0034] FIG. **3** illustrates a simple embodiment of the invention in which the free piston Stirling engine **70** has both its load **72** and a variable reciprocation restraint in the form of a brake **74** connected between the engine **70** and a reference ground **76**.

[0035] FIG. **4** is a simplified drawing introducing the concept of a self controlling load. A self controlling load functions as a load doing useful work and also functions as the variable reciprocation restraint that itself controls the power output of the free piston Stirling engine in a desirable manner. A self controlling load is a load that requires an increasing force to drive the load as the load approaches closer to a selected operating limit. This means that the load requires increasing power to maintain the same amplitude of reciprocation. Of course the power from an engine always equals the power transmitted to the load. With the invention, the increasing force required by the load increases the restraint of the casing and therefore decreases the amplitude of reciprocation of the casing. As a consequence, the power produced by the engine is decreased so that the power output from the free piston Stirling engine that is transmitted from the casing to the load is decreased as the load approaches closer to a selected operating limit. For the application of this concept, a free piston Stirling engine **80** is drivingly connected to a self-controlling load **82** which in turn is also connected to a reference ground **84**.

[0036] An example of a useful application of the self controlling load concept is a solar powered domestic water system illustrated in FIG. **5**. A free piston Stirling engine **90** is driven by the heat from a solar collector **92**. A water pump **94** is a self controlling load that is drivingly connected between the engine **90** and a reference ground **96** and is driven by reciprocation of the engine casing **97**. The pump **94** pumps water from a water source **98** into a vessel **100**. The fluid pressure in the vessel **100** increases as the vessel fills with water, either because the vessel is sealed and the air above the water is compressed as the vessel **100** is filled or because the water level rises to a higher level in the vessel as the vessel **100** is filled with water, or both. When the water pressure reaches the maximum pressure desired for the domestic water system, it is desirable to stop the pumping. Otherwise the pressure would exceed the maximum and the pump would wear needlessly. In the embodiment of FIG. **5**, as the water pressure at the output side of the pump **94** increases, the restraint force on the engine casing increases. Consequently, the pump **94** is a self controlling load having the operating characteristic of increasing the force required to drive the load as the load approaches closer to the selected operating limit. More specifically, the engine **90** and the pump **94** increasingly restrain the reciprocation of the casing as the water system approaches closer to a selected operating limit which is the maximum water system pressure. The power output from the engine is an increasing function of the difference between the operating limit and the current load. Therefore, the usual mechanical engineering design principles and algorithms can be applied so that the restraint by the pump stops the engine at the desired maximum water system pressure. Consequently, the system self regulates the water pressure by not only providing more engine power and pumping more water when the vessel is less filled and a higher water pumping rate is desirable but also applying less power as the water pressure approaches closer to the limit pressure.

[0037] In that manner, the invention generally provides the capability of an engine operating characteristic for any load for which the drive force, which is required to drive the load, increases as the load approaches closer to a selected operating limit and for which load it is desirable to decrease the drive power applied to that load as the load approaches and reaches that operating limit. In other words, this concept is useful when it is desirable to have the power output from the engine be an increasing function of the difference between the operating limit and the current load. FIG. **7** is a graphical representation for that relationship, although the relationship is shown as linear for simplicity.

[0038] FIG. **5** also shows a displacer **102** that is sprung to the casing **97** by a coil spring **104**. One end of the spring **104** is attached to the displacer **102** and the opposite end is attached to a perforate support plate **106** that is like the perforate plate **62** in FIG. **2**. A planar spring would be a suitable alternative substitute for the coil spring **104** and its support plate **104**. 1. There is no displacer rod so that the displacer is driven only by the casing reciprocation. The displacer **102** has a diameter that is larger than the diameter of the piston **108**. The reason is that a mechanical spring is only capable of a short stroke because its maximum amplitude without excess stress and fatigue damage is low. Therefore, in order to for the displacer to provide a sufficiently large gas displacement from the displacer reciprocation within its limited amplitude range, the displacer is made with a large diameter relative to the piston and designed to operate with a relatively short stroke.

[0039] FIG. **8** illustrates an embodiment of the invention in which the displacer is driven in major part by the casing motion and in minor part by the pressure differential applied to the cross sectional area of a displacer rod in the prior art manner so that drive power that is applied to the displacer by the spring from the casing is greater than the sum of any and all other displacer drive power applied. In FIG. **8** the drive power from the casing motion is greater than the drive power from the pressure differential applied to the cross sectional area of the displacer connecting rod.

[0040] Referring to FIG. **8**, a free piston Stirling engine drives an electrical alternator both contained within a casing **108**. A piston **110** and a displacer **112** reciprocate in a cylinder **114**. The piston **110** drives permanent magnets **116** in reciprocation within armatures coils **118**. The displacer **112** has a connecting rod **120** extending from a fixed connection to the displacer **112**, through the piston **110**, and into a back space **120** of the engine. The displacer **112** is sprung to the casing by a gas spring **122** formed adjacent the back space **120**. The gas spring **122** comprises a gas spring piston **124** fixed to the end of the displacer connecting rod **120**, sealingly reciprocating within a cylinder **126** and with an enclosed gas spring volume **128**. The gas spring volume **128** is separated from the back space **120** by a wall **130** so that their are no passages between them.

[0041] FIG. **8** illustrates that, although the invention is to control engine power output by driving the displacer from the casing of an engine in a free casing configuration and varying a restraining force applied to the casing by a variable reciprocation restraint in order to control displacer amplitude, it is not necessary that the prior art displacer drive system be eliminated. With the invention, at least a majority component of displacer drive is from the casing so varying the casing restraint will significantly control piston amplitude and therefore power out. As known to those skilled in the art, force summation and other equations that describe the operation of free piston Stirling engines are used by those skilled in the art to create computer simulations of the operation of free piston Stirling engines. Driving the displacer by casing motion and then using variable restraint of the casing to control engine power provides an additional degree of freedom to the designer even if some displacer drive power comes from the pressure differential applied to the displacer connecting rod. The larger the proportion of displacer drive power from the casing, the greater the control by variation of the casing reciprocation restraint. Additionally, the larger the proportion of displacer drive power from the casing, the smaller the displacer connecting rod can be made and therefore the more the concentricity and alignment problems reduced. The displacer connecting rod can be vanishingly small or nonexistent.

[0042] Although the casing drive power should be dominant (that is, greater than the sum of any other displacer drive power applied to the displacer more than 50%) for many applications that can benefit from the advantage of controlling power output by controlling the casing amplitude of reciprocation, the casing drive power should be a considerably higher proportion of the total displacer drive power. It is preferred that the displacer drive power from casing control be at least 70% of the total casing drive. An example would be a displacer drive that has a 50 watt drive power from the casing and 2 watts drive power from the pressure differential drive. Most preferred for some applications is that the proportion of drive power from the casing be greater than 99% so that the displacer drive power from the differential pressure variations is an inconsequential or trivial proportion of the total displacer drive power.

[0043] FIG. **9** illustrates a previously briefly mentioned variable reciprocation restraint in the form of a linear motor/alternator **140** that is electrically connected to a circuit that can be controlled to alternatively consume power in a variable resistance **142** or other load or electrically connected to a variable electrical drive source **144** to power the linear motor/alternator **140** as a motor. When the motor/alternator **140** is operated as an alternator and power is consumed in a variable resistance **142**, the reciprocation restraint operates as an electromagnetic brake and reduces the reciprocation amplitude of the casing. When the motor/alternator **140** is driven by the variable drive power source **144**, the motor/alternator is operated as a linear motor and drives the casing in reciprocation to increase the amplitude of reciprocation of the casing and thereby increase the power output of the Stirling engine. Consequently, the invention provides a method of power output control that includes an option of applying a drive force on the casing in phase synchronism with the casing reciprocation that is caused by the reciprocation of the displacer and piston. This drive force increases the amplitude of reciprocation of the casing and thereby increases the power output from the Stirling engine.

[0044] FIG. **10** illustrates an example of yet another possible way of applying a variable reciprocation restraint that was previously briefly mentioned and can control the power output from the Stirling engine **150**. The casing reciprocation can be varied by increasing and decreasing the effective mass of the casing, such as by drivingly connecting a variable mass to the casing. The example is a variable mass in the form of a container **152** that is mechanically connected to the engine casing **154** and containing a liquid **156**. The mass connected to the casing **154** is varied by varying the volume of the liquid in the container. The greater the volume of liquid **156** in the container **152** the greater the restraint of the reciprocation amplitude of the casing and therefore the less the engine power output.

[0045] FIG. **6** is a phasor diagram illustrating the phase relationship, for an embodiment of the invention, of the respective displacements of the displacer D, the piston P and the casing C. FIG. **6** also shows the phase relationship of the respective force components that drive the displacer in reciprocation in an embodiment in which the displacer is driven by both the casing motion and the pressure differential. Those component forces are the casing drive force F_{C-D} and the pressure differential drive force F_{P-D}.

[0046] This detailed description in connection with the drawings is intended principally as a description of the presently preferred embodiments of the invention, and is not intended to represent the only form in which the present invention may be constructed or utilized. The description sets forth the designs, functions, means, and methods of implementing the invention in connection with the illustrated embodiments. It is to be understood, however, that the same or equivalent functions and features may be accomplished by different embodiments that are also intended to be encompassed within the spirit and scope of the invention and that various modifications may be adopted without departing from the invention or scope of the following claims.

1. A method for controllably varying the power output of a free piston Stirling engine contained within a casing and mounted in a free casing configuration permitting reciprocating movement of the casing with respect to a reference ground, the engine including a displacer and a piston that reciprocate at an operating frequency, the displacer having a spring drivingly linking the displacer to the casing, the method comprising:

controllably varying the amplitude of reciprocation of the casing with respect to the reference ground by applying and varying a restraining force applied to the casing, the restraining force being increased for decreasing the displacer amplitude of reciprocation and thereby decreasing the power output from the Stirling engine and the restraining force being decreased for increasing the displacer amplitude of reciprocation and thereby increasing the power output from the Stirling engine.

2. A method according to claim **1** wherein drive power is applied to drive the displacer by the spring from the casing and that drive power is greater than the sum of any other displacer drive power applied to the displacer.

3. A method according to claim **2** wherein the spring drives the displacer with at least 70% of the displacer drive power driving the displacer in reciprocation.

4. A method according to claim **3** wherein the spring drives the displacer with at least 99% of the displacer drive power driving the displacer in reciprocation.

5. A method according to claim **1** and further comprising applying the restraining force from the ground to the casing by braking the reciprocation of the casing and increasing the restraining force by increasing the braking.

6. A method according to claim **1** wherein the restraining force is applied by drivingly coupling a mass to the casing.

7. A method according to claim **1** and further comprising increasing the restraining force as a load driven by the engine approaches closer to a selected operating limit so that the power output from the engine is an increasing function of the difference between the operating limit and the current load.

8. A method according to claim **7** wherein the restraining force is applied by a self controlling load connected between the casing and the reference ground, the self controlling load increasing the force required to drive the load as the load approaches closer to a selected operating limit.

9. A method according to claim **8** wherein the self controlling load is a fluid pump that is pumping fluid into a vessel and the fluid pressure increases as the vessel fills with the fluid.

10. A method according to claim **1** and further comprising applying a drive force on the casing in phase synchronism with the reciprocation of the casing as driven by the reciprocation of the displacer and piston for increasing the amplitude of reciprocation of the casing and thereby increase the power output from the Stirling engine.

11. An improved free piston Stirling engine contained within a casing and mounted in a free casing configuration permitting reciprocating movement of the casing with respect to a reference ground, the engine including a displacer and a piston that reciprocate at an operating frequency, the improvement comprising:

(a) a spring drivingly linking the casing to the displacer and, during operation, applying a drive force to the displacer from the reciprocation of the casing for driving the displacer in reciprocation, wherein drive power applied to the displacer from the casing is greater than the sum of any other drive power applied to the displacer; and

(b) a power output control that is a variable reciprocation restraint drivingly linked to the casing, the reciprocation restraint being capable of applying an increased restraining force on the casing for decreasing the amplitude of reciprocation of the casing and of applying a decreased restraining force on the casing for permitting the amplitude of reciprocation of the casing to increase.

12. An improved free piston Stirling engine according to claim **11** wherein the spring is the only displacer drive for driving the displacer in reciprocation.

13. An improved free piston Stirling engine according to claim **11** wherein the variable reciprocation restraint is connected between the casing and the reference ground.

14. An improved free piston Stirling engine according to claim **13** wherein the variable reciprocation restraint is a brake.

15. An improved free piston Stirling engine according to claim **13** wherein the variable reciprocation restraint is a self controlling load driven by the casing, the self controlling load having the operating characteristic of increasing the force required to drive the load as the load approaches closer to a selected operating limit.

16. An improved free piston Stirling engine according to claim **15** wherein the self controlling load is a fluid pump connected for pumping fluid into a vessel and the fluid pressure increases as the vessel fills with the fluid.

17. An improved free piston Stirling engine according to claim **11** wherein the spring drives the displacer with at least 70% of the displacer drive power driving the displacer in reciprocation.

18. An improved free piston Stirling engine according to claim **17** wherein the spring drives the displacer with at least 99% of the displacer drive power driving the displacer in reciprocation.

19. An improved free piston Stirling engine according to claim **11** wherein the variable reciprocation restraint is a variable mass that is drivingly linked to the casing.

20. An improved free piston Stirling engine according to claim **11** wherein the spring is a gas spring within the displacer, the gas spring having a connecting rod extending from a gas spring piston within the displacer to a perforate support formed in a compression space of the free piston Stirling engine and fixed to an interior wall of the engine.

21. An improved free piston Stirling engine according to claim **11** wherein the displacer has a connecting rod extending from the displacer, through the piston into a back space of the engine and the spring is a gas spring formed adjacent the back space.

22. An improved free piston Stirling engine according to claim **11** wherein the displacer has a diameter that is larger than the diameter of the piston.

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