United States Patent

[11] 3,610,217

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[21] Appl. No. 868,008
[22] Filed Oct. 21, 1969
[45] Patented Oct. 5, 1971

[54] BALANCED-FREE PISTON ENGINE
14 Claims, 10 Drawing Figs.

[52] U.S. Cl. 123/46, 123/46 A, 123/46 SC, 123/192, 290/1, 417/364, 417/380
[51] Int. Cl. F02b 71/00, H02p 9/04, F04b 35/00
[50] Field of Search 123/46, 46 B, 46 SA, 46 A, 46 H, 46 E, 64 SC, 192, 193, 321; 417/380; 7/364; 290/1

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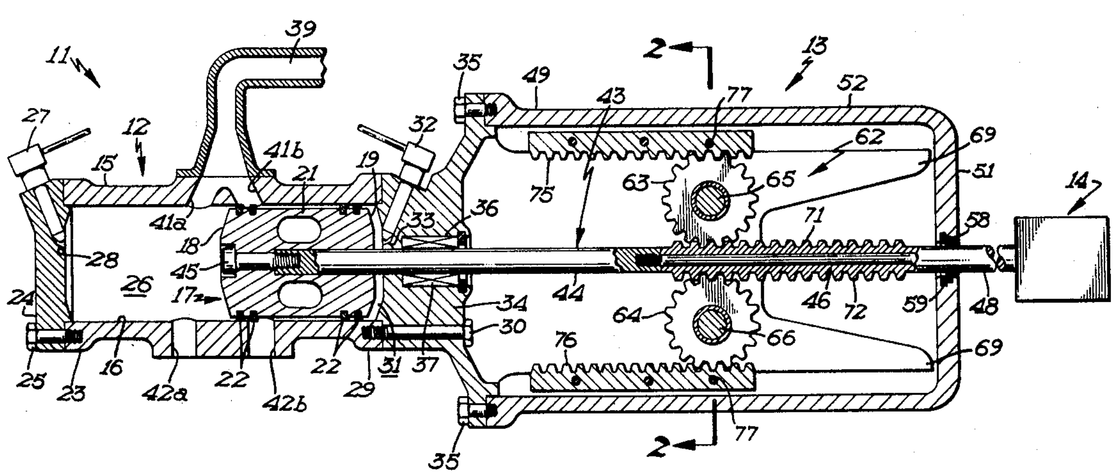
ABSTRACT: Unsymmetrical, synchronized, balanced, free piston engines are disclosed in which a pair of alternately acting power pistons are interconnected to form a double-acting power piston, in which the power piston is connected to the movable member of an energy absorbing device to be driven by the engine in order to provide the reciprocatory power input to that energy absorbing device, the double-acting power piston, the movable member, and the connection between them defining a power assembly, and in which the movement of the power assembly in the engine is balanced by the oppositely directed translational movement, with respect to the engine housing, of a counterbalancing movable weight associated with a synchronizer-balancer. Engines incorporating energy absorbing devices in the form of a pump, an electrical generator, and a double-acting reciprocal compressor are specifically shown. Also specifically shown are two single-acting power sections which may be used together in place of the one double-acting power section.



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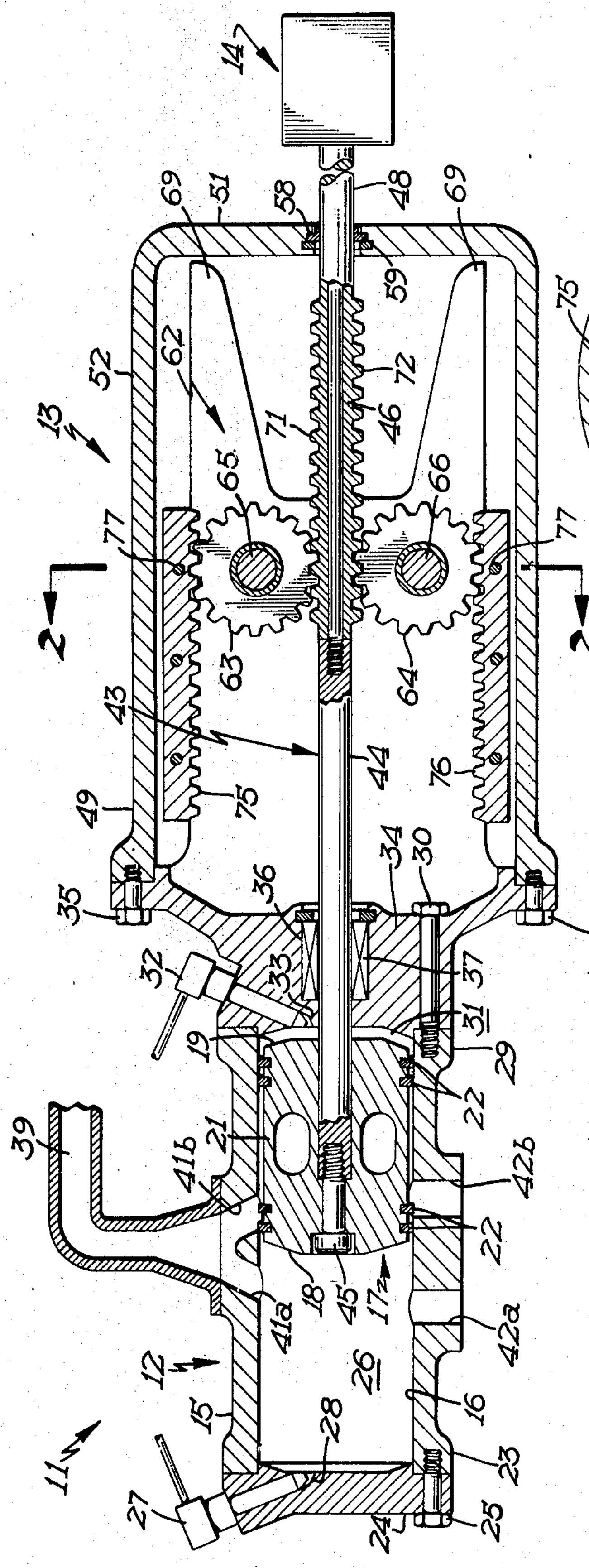

FIG 1

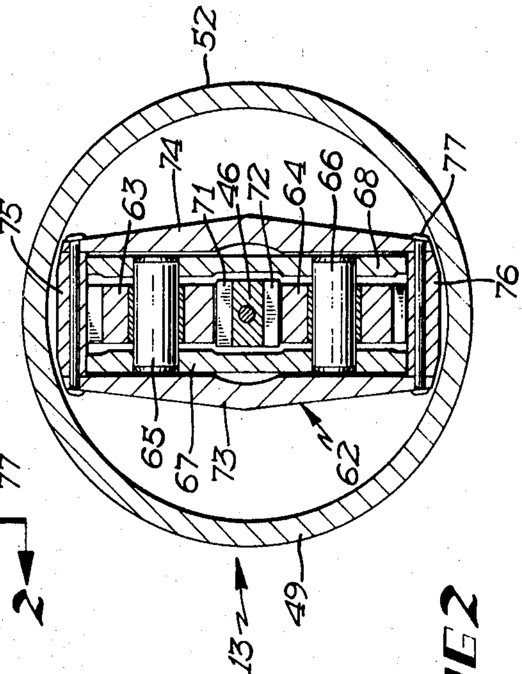

FIG 2

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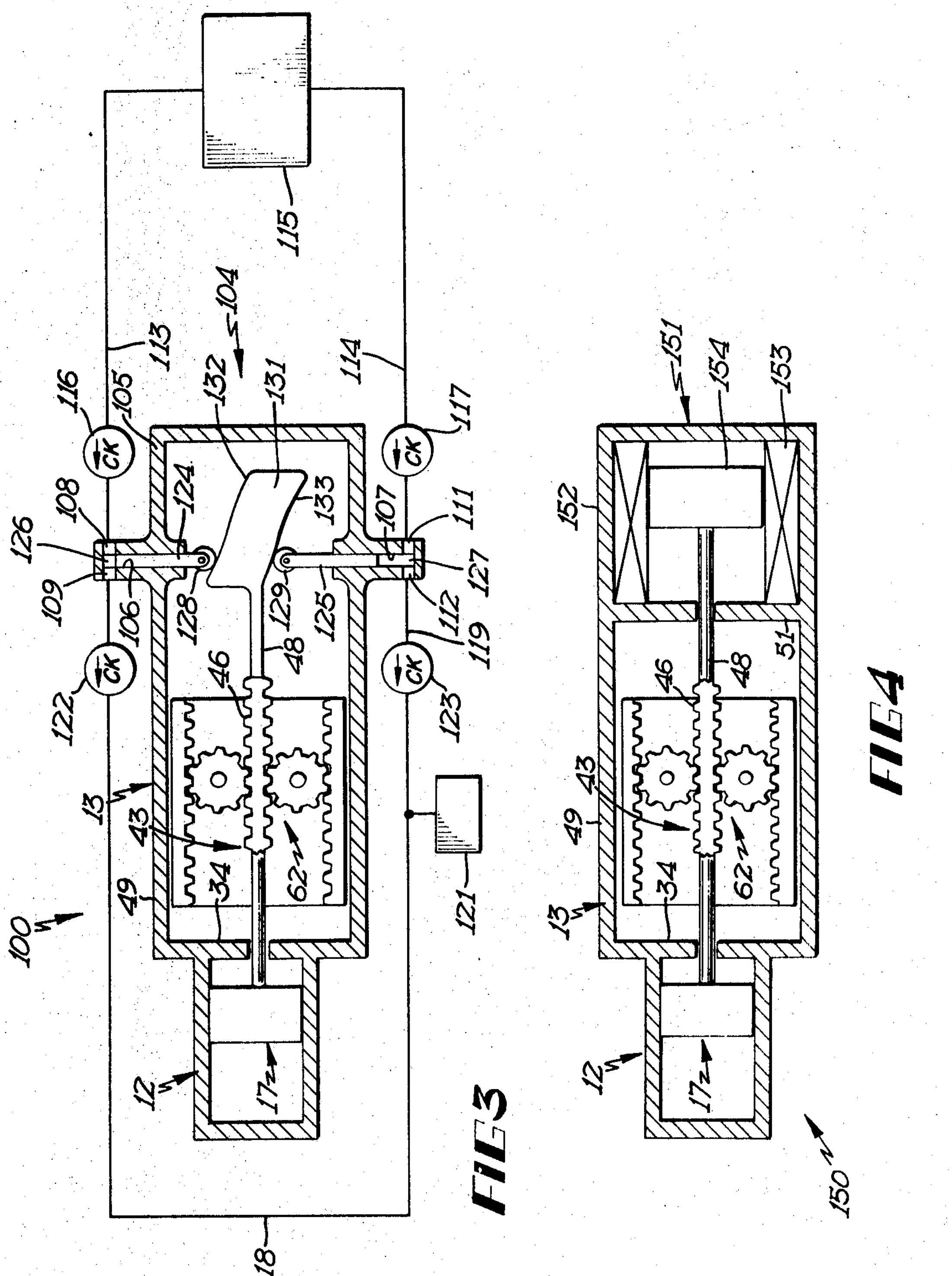

FIG 3

FIG 4

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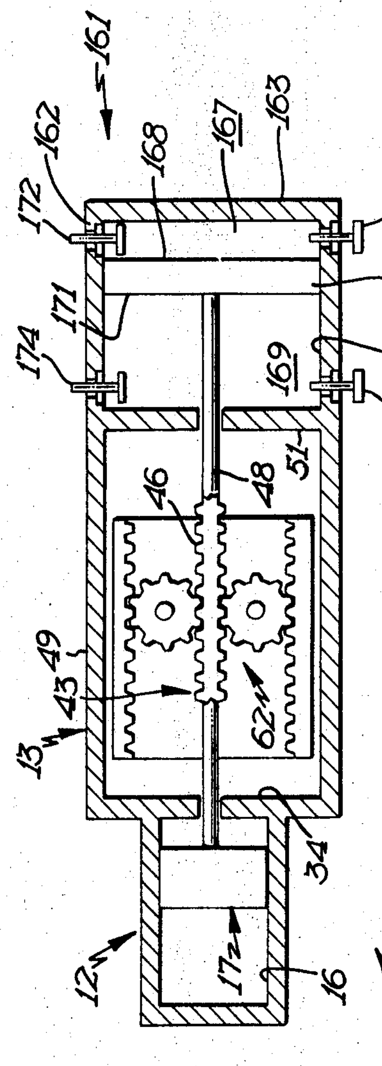

FIG 5

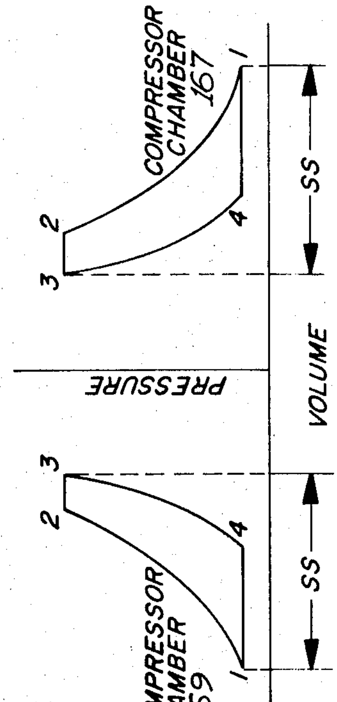

FIG 7

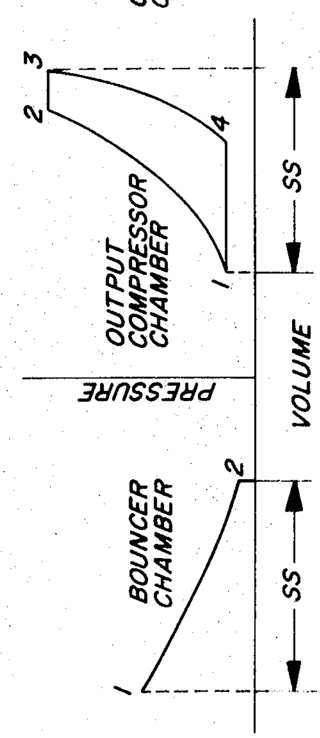

FIG 6

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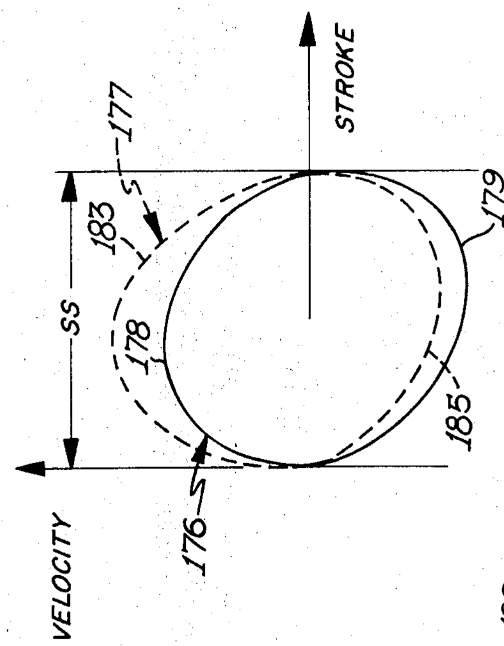

FIG 8

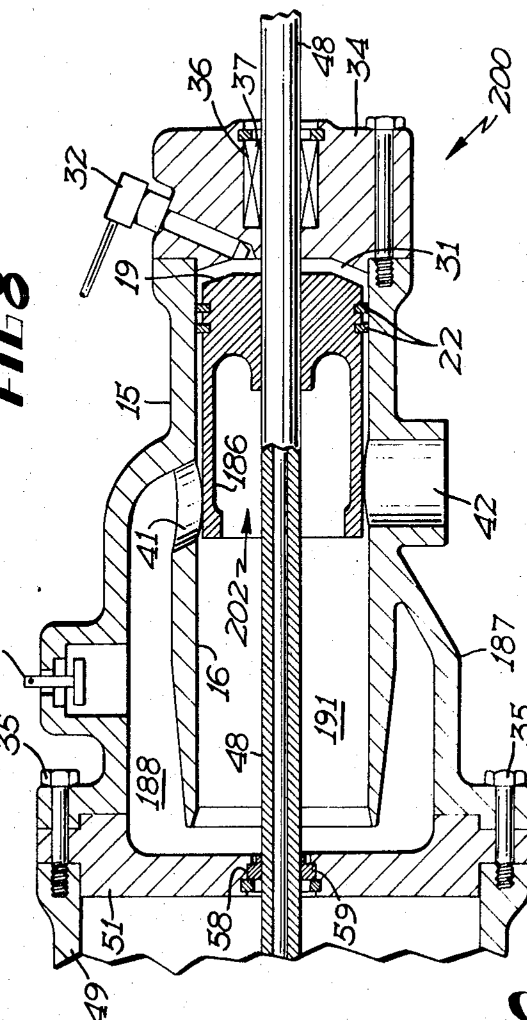

FIG 10

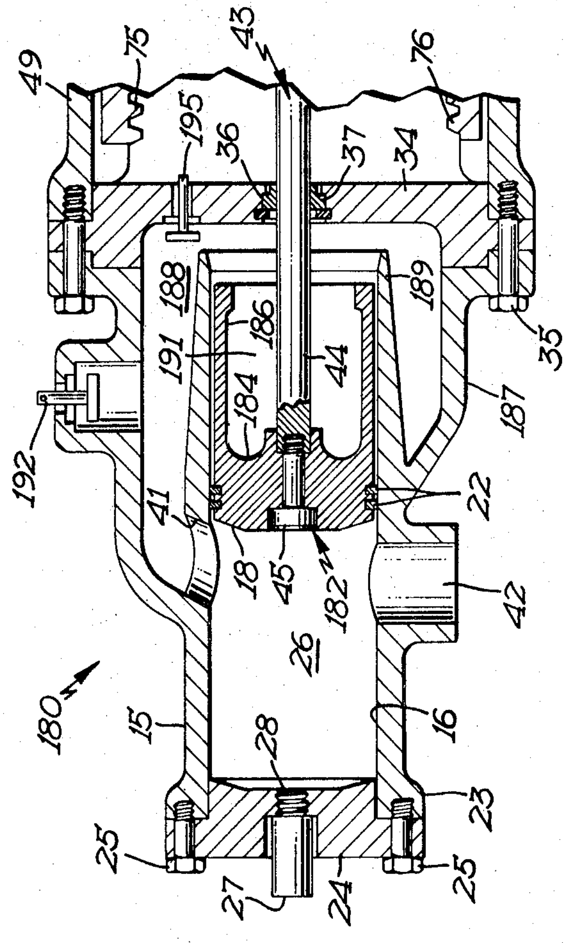

FIG 9

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BALANCED-FREE PISTON ENGINE

BACKGROUND

This invention relates to free piston engines, and particularly to unsymmetrical, synchronized, balanced, free piston engines, and more particularly to unsymmetrical, synchronized, balanced, free piston engines in which at least two alternately acting power pistons provide the power necessary to drive the reciprocally movable member of an energy absorbing device.

Prior free piston engines exist which are unsymmetrical, synchronized, and balanced and which use a power section to provide power to the reciprocally movable member of an energy absorbing device and a bouncer section to return the power piston to a point in the power cylinder where repetitive combustion can occur. A bouncer compressor may be a disadvantage, however, in that stagnant air within a bouncer compressor may become fouled by lubricating oil and present a control problem. Further, an engine using a bouncer compressor to return the power piston does not have a naturally equal stroke-time function on both strokes of the movable member of the energy absorbing device.

Other prior synchronized, balanced, free piston engines have had alternately acting power pistons, but these engines were balanced by the counter movement of a working cylinder, such as a power cylinder or a compressor cylinder, and the movement of these working cylinders complicated the engine and presented a control problem in providing the fuel to the moving cylinder and allowing exhaust gases and compressed air output to escape from the moving cylinder. Also, these engines were not readily adaptable to perform as a power package and provide power to various types of energy absorbing devices which accept a reciprocatory power input.

Other symmetrical prior free piston engines using alternately acting power pistons also used countermoving piston assemblies to balance the engine. These engines were more complicated than the present invention and they were also not readily adaptable for use with an energy absorbing device other than the device they were specifically designed to operate.

SUMMARY

In contrast to these prior free piston engines, free piston engines according to the present invention are unsymmetrical, synchronized, balanced, free piston engines wherein at least two alternately acting power sections, that is, two power sections where one section is providing power on its power stroke while the other section is accepting power on its compression stroke provide power to the engine, wherein each power section is connected with the movable member of an energy absorbing device to be driven by the engine to form a power assembly such that the power piston within each power section is connected to move together as a unit with the movable member of the energy absorbing device and the remaining parts of the power assembly, and wherein the engine is balanced by the mechanically synchronized movement of a counterbalancing movable weight arranged to have translational movement with respect to the housing of the free piston engine in a direction opposite to the direction of movement of the power assembly.

Free piston engines of the present invention are simple and compact engines which provide twice the work output per cycle with the same capacity synchronizer and with significantly less than a factor of two increase in the overall size and weight of the engine as compared to prior engines using bouncer compressors to return the power piston. The bouncer compressor is, in fact, eliminated in engines according to the present invention since a high rate of pressure rise occurs alternately in each combustion chamber as the respective power piston approaches its top-deadcenter position. This high rate of pressure rise in the combustion chamber renders the engine relatively "stiff" at both ends of its stroke; that is, the power pistons traveling in one direction are caused to stop and "return" or to travel in the opposite direction by force which increases at a very high rate as the power pistons approach their top-deadcenter positions, all without a bouncer compressor. This "stiff" characteristic of the engine is particularly useful when the energy absorbing device is a double acting reciprocal compressor because the "stiff" characteristic prevents any significant compressor piston travel beyond the desired nominal point, i.e. it permits a low overstroke requirement to be adopted in the compressor which, in turn, results in the compressor being able to have a small clearance volume per given output, or a high volumetric efficiency.

Free piston engines according to the present invention also have a naturally equal stroke-time function on both strokes of the movable member of the energy absorbing device driven by the engine. Where a hydrostatic pump is the energy absorbing device driven by the engine, large dampers or accumulators would be needed to smooth the flow without this naturally equal stroke-time function provided by engines of the present invention. Engines of the present invention allow the smallest damper size for any given pump. Where an AC generator is the energy absorbing device driven by the engine, an unacceptably high DC component would be provided from the AC generator because of the asymmetry of the output waveform without this naturally equal stroke-time function provided by engines of the present invention. Engines of the present invention allow the smallest DC component for any given electrical generator.

Also, the unsymmetrical, synchronized, balanced, free piston engines of the present invention may be used as a simple, compact, relatively small and lightweight power unit for operating various types of energy absorbing devices, such as reciprocal compressors, pumps, generators, and the like. That is, because of the flexible nature of the present invention, it is readily adaptable to perform as a power package and to provide power to various types of energy absorbing devices which accept a reciprocatory power input.

It is thus an object of the present invention to provide improved, unsymmetrical, synchronized, balanced, free piston engines which are simple and compact and flexible in their nature to accept various kinds of energy absorbing devices.

It is a further object of the present invention to provide improved unsymmetrical, synchronized, balanced, free piston engines which use alternately acting power sections which are interconnected with each other and with the movable member of an energy absorbing device driven by the engine to provide the reciprocatory power input to that energy absorbing device.

These and further objects and advantages of the present invention will become clearer in the light of the following detailed description of illustrative embodiments of this invention described in connection with the drawings.

DESCRIPTION OF THE DRAWINGS

FIG. 1 is a vertical cross-sectional view of an embodiment of the improved, free piston engine of the present invention shown with a double-acting power section connected with an energy absorbing device.

FIG. 2 is a vertical cross-sectional view taken along the section line 2—2 of FIG. 1.

FIG. 3 is a schematic, vertical, cross-sectional view of another embodiment of the improved, free piston engine of the present invention shown as connected with an energy absorbing device in the form of a fluid pump.

FIG. 4 is a schematic, vertical, cross-sectional view of still another embodiment of the improved, free piston engine of the present invention shown connected with an energy absorbing device in the form of an electrical generator.

FIG. 5 is a schematic, vertical, cross-sectional view of still another embodiment of the improved, free piston engine of the present invention shown connected with an energy absorbing device in the form of a double-acting reciprocal compressor.

FIGS. **6** and **7** are pressure-volume curves illustrating a major advantage of engines according to the present invention.

FIG. **8** is a graphical representation of velocity plotted versus stroke to illustrate another major advantage of engines according to the present invention.

FIGS. **9** and **10** show vertical cross-sectional views of two single-acting power sections which together may be advantageously used with engines according to the present invention in place of the one double-acting power section shown in FIG. **1**.

Where used in the various figures of the drawings, the same reference numerals designate the same or similar parts or elements in the various embodiments of the engine shown. Furthermore, when the terms "right," "left," "right end," and "left end" are used herein, it should be understood that these terms have reference only to the structure shown in the drawings as it would appear to a person viewing the drawings, and are utilized only to facilitate describing the invention.

DESCRIPTION

FIG. 1 Embodiment

An improved, balanced, free piston engine **11** of the present invention is generally shown in FIGS. **1** and **2**. The free piston engine **11** includes a power section **12**, and a synchronizer-balancer section **13**. An energy absorbing device, shown diagrammatically at **14**, is spaced from the right end of the synchronizer-balancer section **13**. The energy absorbing device **14** may be a liquid pump, an electrical generator, a double-acting reciprocal compressor, or any other device which utilizes or absorbs reciprocatory power.

The power section **12** includes a cylindrical housing **15** which has a power cylinder **16** formed therein. A double-acting power piston **17** is positioned within the cylinder **16** for reciprocal movement therein substantially parallel to the longitudinal axis of the cylinder **16**. The piston includes a first or outer power face **18**, a second or inner power face **19** and a generally annular portion **21** interconnecting the outer power face **18** and the inner power face **19** such that they reciprocate together as a unit and form a single, alternately acting, double-acting, power piston. Piston rings **22** are carried in grooves formed in the piston **17** for minimizing the leakage of gases between cylinder **16** and the piston **17**.

The left end **23** of the housing **15** is closed by a cylinder head **24** which is bolted to the end **23** of the housing **15** by a plurality of bolts, one of which is shown at **25**. The cylinder head **24** together with the outer power face **18** of the piston **17** define a first or outer combustion chamber **26** in the cylinder **16**. A conventional fuel injector unit **27** is positioned in an aperture **28** formed in the cylinder head **24** so that its inner end communicates with chamber **26**.

Similarly, the right end **29** of the housing **15** is closed by a cylinder head **34** which is bolted to the end **29** of the housing **15** by a plurality of bolts, one of which is shown at **30**. The cylinder head **34** together with the inner face **19** of the piston **17** define a second or inner combustion chamber **31** in the cylinder **16**. A further conventional fuel injector unit **32** is positioned in an aperture **33** formed in the cylinder head **34** so that the inner end of fuel injector **32** communicates with the inner combustion chamber **31**.

The inner cylinder head **34** also forms a wall between the power section **12** and the synchronizer-balancer section **13**, and, in order to provide a connection between the power section and the synchronizer-balancer section, the cylinder head **34** has a central aperture **36** formed therein so that the central longitudinal axes of the aperture **36** and the cylinder **16** are coaxial. Conventional combustion chamber shaft seals **37** are positioned in the aperture **36**, for reasons hereinafter explained. Shaft seals **37** must withstand the temperature and pressure of the combustion chamber **31**, but seals of this kind are well known in the art.

A duct **39** is shown connected with housing **15** to provide communication between a plurality of peripherally spaced duel inlet ports, one of which dual ports is shown formed in the housing **15** at **41***a* and **41***b*, and a source of air or fuel-air mixture, not shown. A plurality of peripherally spaced duel exhaust ports or openings, one of which dual ports is shown formed in housing **15** at **42***a* and **42***b*, permit combustion gas in the combustion chambers **226** and **31** to be exhausted from cylinder **16**. To insure proper "blowdown" the outermost edges of the ports **41***a* and **41***b* are positioned such that the projection of these outermost edges on the central longitudinal axis of cylinder **16** is within the projection of the outermost edges of the ports **42***a* and **42***b* on the central longitudinal axis of cylinder **16**. The ports **41** and **42** are further arranged, relative to the combustion chambers **26** and **31**, so that the chambers will be properly scavenged during normal operation of the engine. That is, as the power piston **17** approaches its rightmost position, exhaust ports **42***a* are opened, and exhaust gases can "blowdown" to the approximate pressure of the fresh charge of air or fuel-air mixture that exists in duct **39** at the time inlet ports **41***a* are opened. As the inlet ports **41***a* are opened by piston **17**, the air or fuel-air mixture from the source, not shown, can enter chamber **26** through duct **39** and ports **41***a*, and this fresh charge of air or fuel-air mixture can scavenge chamber **26** to provide a fresh charge for the next power stroke in chamber **26**. With the piston **17** traveling towards its leftmost position, exhaust gases within combustion chamber **31** can similarly "blowdown" through exhaust ports **42***b*, and chamber **31** can be similarly scavenged through duct **39**, inlet ports **41***b*, and exhaust ports **42***b*.

The power piston **17** and all other main pistons within the engine are a part of and move with a power assembly **43** that includes, in addition, all other parts of the engine which move with and are connected with power piston **17**. These parts include the movable member of the energy absorbing device **14**, and the means for connecting the main pistons together and for interconnecting the main pistons with the movable member of the energy absorbing device. Thus, the main pistons and the movable member of the energy absorbing device form parts of the power assembly and always move together as a unit within the engines of the present invention.

In this connection, piston **17** is fastened to the left end of a shaft **44** by means of a bolt **45**. The right end of shaft **44** is connected with the left end of a double rack member **46**. A second shaft **48**, arranged in axial alignment with shaft **44**, is connected to the right end of double rack member **46** and interconnects the rack member **46** with the reciprocally movable portion of the energy absorbing device **14**. Thus, in engine **11**, the power assembly **43** includes the power piston **17**, the shaft **44**, the double rack member **46**, the shaft **48**, and the reciprocally movable portion of the energy absorbing device **14**, together with the bolt **45**, and any other fastening means utilized to interconnect the aforementioned parts, and the piston rings **22** carried by the piston. The component parts of the power assembly **43** are described more fully hereinafter.

More specifically, the shaft **44** interconnecting the power piston **17** and the double rack member **46** extends into the synchronizer section **13** of the engine through the aperture **36** formed in the cylinder head **34** and is sealed by the conventional combustion chamber shaft seals **37** positioned in this aperture **36** so as to minimize the leakage of gas and lubricant between the shaft and the aperture.

The synchronizer section **13** includes housing **49**, which, as noted above, has its left end closed by cylinder head **34**. Bolts **35**, two of which are shown in FIG. **1**, are used to fasten the housing **49** to cylinder head **34**. An end wall **51** closes the right end of the housing **49** and is formed integrally with a sidewall **52** of the housing **49**, as shown in FIG. **1**. Of course, if desired, the end wall **51** could also be a separate member attached to the housing **49** by a plurality of bolts.

The end wall **51** has a central aperture **58** positioned so that its central axis is coaxial to the central axis of shaft **44**. The second shaft **48** extends through the aperture **58** formed in the wall 51, and a conventional shaft seal 59 is mounted in the aperture 58 so as to minimize the leakage of gas and lubricant between the shaft 48 and the aperture 58.

As will be appreciated from the foregoing, since all the parts of the power assembly 43 move in the same direction, the engine 11, without more, would be dynamically unbalanced and thus would be subject to serious vibrational problems. To achieve a dynamically balanced engine, the engine 11 includes a synchronizer-balancer assembly 62 mounted within the housing 49.

The synchronizer-balancer assembly 62 is connected with the power assembly 43 through a double rack member 46 which may also be termed a first means of the balancing and synchronizing assembly. The balancing and synchronizing assembly 62 also includes a pair of pinions 63 and 64 which are mounted for rotation about fixed axes on a pair of shafts 65 and 66, respectively. The ends of the shafts 65 and 66 are supported by a pair of fixed sideplates 67 and 68, which are positioned on opposite sides of the double rack member 46. One end of each of the plates 67 and 68 is secured to the right face of the cylinder head 34 and the other ends 69 thereof project to the right from the cylinder head 34 towards the end wall 51 of the housing 49. The plates 67 and 68 are spaced an equidistance from the double rack member 46 so that the member 46 can slide freely between the plates 67 and 68, and are positioned so that the plates are substantially parallel to each other and to the longitudinal central axis of the power assembly 43.

The shafts 65 and 66 are supported by the plates 67 and 68 approximately midway between the cylinder head 34 and the end wall 51 and are positioned vertically on opposite sides of the longitudinal central axis of the double rack member 46 and equidistant from the member 46, with the central longitudinal axes of the shafts 65 and 66 being arranged at 9° to the central longitudinal axis of the power assembly 43. The distance between the plates 67 and 68 is sufficient so that the pinions 63 and 64 can rotate freely between the plates.

The double rack member 46 includes upper and lower racks 71 and 72 which are formed in back-to-back fashion so that the teeth thereof project substantially radially outwardly from the member 46. The teeth of the racks 71 and 72 are arranged so that there is always engagement between the teeth of the racks 71 and 72 and the teeth of the pinions 63 and 64, respectively, whereby reciprocatory movement of the power assembly, and thus the racks 71 and 72, causes corresponding rotary movement of the pinions 63 and 64.

The synchronizer-balancer assembly 62 further includes a pair of movable wall members 73 and 74 which are positioned adjacent to and parallel with the fixed sideplates 67 and 68, respectively, with the movable members 73 and 74 being positioned a greater distance from the double rack member 46 than the plates 67 and 68 so that the movable members 73 and 74 can slide freely with respect to the fixed plates 67 and 68. A pair of racks 75 and 76 are carried by and positioned between the upper and lower ends of the movable wall members 73 and 74, as shown in FIG. 2. A plurality of pins or rivets, two of which being shown at 77, extend through the racks 75 and 76 and the ends of the movable members 73 and 74 and are used to secure the racks 75 and 76 to the movable members 73 and 74. The racks 75 and 76 are positioned so that the teeth thereof project toward the teeth of the racks 71 and 72, respectively, i.e., project substantially radially inwardly relative to the double rack member 46, and engage the pinions 63 and 64, respectively, substantially diametrically opposite the points of engagement between the teeth of the pinions 63 and 64 and the racks 71 and 72, respectively.

Also, as best shown in FIG. 2, the synchronizer-balancer assembly 62, and more specifically the counterbalancing part of assembly 62 which includes racks 75 and 76 and the members 73 and 74, can reciprocate freely along its central longitudinal axis with respect to the housing 49 and to any relatively fixed member therein and with respect to any parts of the power assembly 43. Moreover, because the racks 75 and 76 are secured together by the movable members 73 and 74 so as to prevent relative movement therebetween and because the racks 71 and 72 are integrally formed in a back-to-back relationship on the double rack member 46, the normal components of the forces created by the transmission of forces between the teeth of the racks and pinions are balanced. This arrangement of the racks and pinions eliminates a major cause of frictional losses and minimizes the energy loses, due to friction, resulting from the transfer of forces between the counterbalancing part of the synchronizer-balancer assembly 62 and the power assembly 43. Furthermore, frictional losses and dynamic loading of the gear teeth, due to manufacturing errors, are further reduced by the fact that racks 71 and 72 tend to "float" between, and the racks 75 and 76 tend to "float" about the pinions 63 and 64 and are self-aligning in that they inherently seek a position, relative to the pinions 63 and 64, in which the dynamic forces created by the engagement between the teeth of the racks 71, 72, 75, and 76 and the pinions 63 and 64 are minimized.

To achieve dynamic balance, the product of the sum of the weight associated to move with the counterbalancing movable weight part (also referred to herein as the second means or the counterbalancing means) of the synchronizer balancer assembly 62 times the distance the counterbalancing movable weight part associated with assembly 62 moves during a stroke of the engine must be equal to the product of the sum of the weight associated to move with the power assembly 43 times the length of the corresponding stroke of the assembly 43 in the opposite direction to the motion of the counterbalancing part of assembly 62. As noted above, the counterbalancing movable weight part of the synchronizer balancer assembly 62 includes the weight of the movable members 73 and 74, the pins 77, and the weight of the racks 75 and 76.

As noted above, the engine 11 is suitable for use with various different energy absorbing devices, and thus the weight of the element of the energy absorbing device 14 which is attached to and carried by the right end of the shaft 48 may vary depending on what type of energy absorbing device is being driven by the engine. For this reason, the movable members 73 and 74 have been designed so that they can be readily removed and replaced by movable wall members of different weights so that the counterbalancing movable weight of the balancing and synchronizing assembly 62 may be easily varied without affecting structure or operation of the engine. Alternately, weight may easily be removed from or added to movable wall members 73 and 74 without replacing them. In this way, standard movable members 73 and 74 may serve for a multiple of different energy absorbing devices.

Moreover, the unique structure and structural arrangement of the engine permits the total length of the engine to be substantially equal to four times the swept stroke of the piston 17, plus the length required for the energy absorbing device 14.

OPERATION

Briefly, the operation of engine 11 is as follows: combustion occurs in chamber 26 near the top-deadcenter position of piston 17, i.e. when the piston 17 has moved to its leftmost operating position, and such combustion, together with any other energy in the engine 11 or the device 14 available to support the rightward movement of the power assembly 43, causes the piston 17 and the rest of power assembly 43 including the connecting part of the synchronizer-balancer assembly, rack member 46, to be moved to the right with respect to the engine housing, in a translational manner. Due to the rack and pinion arrangement 63, 64, 71, 72, 75 and 76, this translational movement to the right of the assembly 43, and thus the double rack member 46, causes the counterbalancing movable weight of assembly 62, including the racks 75 and 76 and the movable wall members 73 and 74, to move to the left with respect to the housing 49 also in a translational manner. As the power assembly 43 moves to the right, the pressure in combustion chamber 31 increases due to the decreasing volume of combustion chamber **31**. That is, air is compressed in combustion chamber **31** by the rightward movement of piston **17** until the air pressure and temperature in chamber **31** have been raised beyond the auto ignition point, at which time the fuel introduced into the chamber **31** by the fuel injector unit **32** will effectively burn in accordance with the principles of operation of conventional diesel engines. Of course, by using a conventional ignition system and a conventional carburetor or fuel injector system, the power sections can also be operated in accordance with the principles of conventional spark ignition or stratified charge engines.

Due to the increasing pressure of the gas within combustion chamber **31**, and other energies available to support the leftward movement of power assembly **43**, the rightward movement of power assembly **43** is stopped and again caused to move to the left. During the leftward movement of piston **17** in cylinder **16**, first the exhaust ports **42*b*** are uncovered to allow the "blowdown" of the combustion gases within chamber **31**, then the intake ports **41*b*** are uncovered by piston **17** so that the chamber **31** can be properly scavenged and a new charge of air or fuel-air mixture introduced into chamber **31**.

Also during the leftward movement of power assembly **43** and thus the piston **17**, the ports **41*a*** within combustion chamber **26** are blocked by the piston **17**, thereafter the ports **41*b*** are blocked by the piston **17**, and the air or fuel-air mixture in chamber **26** is compressed until combustion again occurs in chamber **26** and the cycle of operation is repeated.

Thus, combustion chamber **26** and combustion chamber **31** are alternately acting in that gas within combustion chamber **26** is expanding and providing energy to the engine while gas within combustion chamber **31** is being compressed and accepting energy from the engine, and vice versa.

As noted above, during the rightward translational movement of the power assembly **43**, with respect to the engine housing, the counterbalancing means of assembly **62**, including the racks **75**, **76** and the movable wall members **73**, **74** is translationally moved to the left with respect to housing **49**. Conversely when the power assembly **43** translationally moves to the left, the counterbalancing means of assembly **62**, including the racks **75**, **76** and the movable wall members **73**, **74**, moves to the right. Moreover, as explained hereinabove, if the weights of the movable wall members **73**, **74** are selected so that the product of the sum of the weight moving with the power assembly **43** times the length of the stroke of the assembly **43** is equal to the product of the sum of the weight of the counterbalancing means of assembly **62**, including the racks **75**, **76** and the movable wall members **73**, **74**, times the distance through which the counterbalancing means of assembly **62** moves in the opposite direction of the piston **17**, then dynamically balanced operation of the engine **11** can be achieved.

FIG. 3 Embodiment

The engine **100**, shown schematically in FIG. 3, includes a power section **12** and synchronizer-balancer section **13** which are substantially identical in structure and mode of operation to the power section **12** and the synchronizer-balancer section **13**, respectively, of engine **11**. Engine **100** is substantially identical to engine **11** of FIG. **1** except that energy absorbing device **14**, represented diagrammatically in FIG. **1**, is specifically shown as a hydrostatic pump **104** driven by engine **100**.

The pump **104** includes a pump housing **105** which may be integrally formed with the synchronizer housing **49**, or may be separated from the engine as shown in FIG. **1**. The housing **105** includes a pair of main bores **106** and **107** which are formed on opposite sides of the central longitudinal axis of the power assembly **43** and which have their central longitudinal axes aligned and disposed at an angle of substantially 90° with respect to the central longitudinal axis of the power assembly **43**. The bore **106** is closed at its radially outer end, with respect to the central longitudinal axis of the power assembly **43**, except for transverse inlet and outlet bores **108** and **109** which communicate with the bore **106** adjacent to its outer end. Similarly, bore **107** is closed at its radially outer end except for transverse inlet and outlet bores **111** and **112** which communicate with the bore **107** adjacent to its outer end. Conduits **113** and **114** connect the inlet bores **108** and **111**, respectively, and thus the bores **106** and **107**, respectively, with a source **115** of liquid to be pumped. Conventional check valves **116** and **117** are positioned in conduits **113** and **114** so as to permit flow of liquid only from the source **115** to the bores **106** and **107**. Conduits **118** and **119** connect outlet bores **109** and **112**, respectively, and thus the bores **106** and **107**, respectively, with means **121** for utilizing or storing liquid under pressure. Conventional check valves **122** and **123** are positioned in conduits **118** and **119** so as to prevent liquid from returning to the bores **106** and **107** from means **121**.

Plungers **124** and **125** are positioned for reciprocal movement in the bores **106** and **107**, respectively, and conventional seals, not shown, are used to prevent leakage therebetween. Pumping chambers **126** and **127** are defined in the bores **106** and **107**, respectively, between the radially outer ends of the bores and the radially outer ends of the plungers **124** and **125**. As the plungers reciprocally move within their respective bores, liquid may be alternately "sucked" into and expelled from the pumping chambers through their inlet and outlet bores, respectively, in a conventional manner.

Cam followers **128** and **129** are mounted on the radially inner ends of plungers **124** and **125**. A cam member **131** is mounted within the housing for reciprocal movement therein in a direction substantially parallel to the central longitudinal axis of the power assembly **43**. The cam **131** has a pair of cam surfaces **132** and **133** formed thereon and is designed so that the cam followers **128** and **129** remain in contact with the surfaces **132** and **133**, respectively, at all times and so that the plungers **124** and **125** always move in the opposite directions in their respective bores during the operation of the pump **104**. This reduces the pressure waves in the discharge of the pump. Moreover the cam surfaces **132** and **133** can be designed so that relatively uniform fluid velocities may be achieved in the discharge from the pump. The cam **131** constitutes a part of the power assembly **43** of engine **100**. More specifically, the shaft **48** connects the left end of the cam **131** with the rack member **46**.

FIG. 4 Embodiment

The engine **150**, shown schematically in FIG. 4, includes a power section **12** and a synchronizer-balancer section **13** which are substantially identical in structure and mode of operation to the power section **12** and synchronizer-balancer section **13**, respectively, of engine **11**. Engine **150** is substantially identical to engine **11** of FIG. **1** except that energy absorbing device **14**, represented diagrammatically in FIG. **1**, is specifically shown as an electrical generator **151** driven by engine **150**.

The generator **151** includes the generator housing **152** which, like pump housing **105**, may be integral with the synchronizer housing **49**. An annular stator arrangement **153**, including a conventional core of magnetic material with windings of conductive material formed thereon, is positioned within the housing **152**, and a conventional armature **154** is mounted for reciprocal movement within the stator arrangement **153** to conventionally magnetically coact with stator arrangement **153**. Armature **154** is connected with the shaft **48** to form a part of the power assembly **43**.

Since the generator **151** may be of conventional design, further description thereof is not included herein. Again however one of the principle advantages of generator **151** as used with engines of the present invention is that the shape of the electrical wave or waves produced by the generator **151** during the leftward stroke of the armature **154**, and thus the leftward stroke of the power assembly **43**, is substantially identical to the shape of electrical wave or waves produced by the generator **151** during the rightward stroke of the armature **154**.

FIG. 5 Embodiment

The engine **160**, shown schematically, in FIG. **5**, includes a power section **12** and a synchronizer section **13** which are substantially identical in structure and mode of operation to power section 12 and synchronizer section 13, respectively, of engine 11. The engine 160 is substantially identical to engine 11 of FIG. 1 except that energy absorbing device 14, represented diagrammatically in FIG. 1, is specifically shown as a double acting reciprocal compressor 161 driven by engine 160.

The compressor 161 includes a housing 162 which again may be integral with the synchronizer housing 49. Housing 162 has a wall 163 forming one end thereof with wall 163 shown schematically as integrally formed with housing 162. A compressor cylinder 164 is formed within housing 162 such that the central longitudinal axis of compressor cylinder 164 is coaxial with the central longitudinal axis of power cylinder 16 of power section 12, and thus of power assembly 43. A compressor piston 165 is positioned in the compressor cylinder 164 for reciprocal movement within the compressor cylinder 164 with respect to the housing 162. A first compressor chamber 167 is formed between a right face 168 of compressor piston 165 and end wall 163. A second compressor chamber 169 is formed in the compressor cylinder 164 between a left face 171 of compressor piston 165 and and end wall 51 of synchronizer section 13. A set of intake and discharge valves, two of which are shown at 172 and 173, respectively, are positioned in the housing 162 adjacent chamber 167 to permit the ingress of fluid to be compressed into chamber 167 and egress of compressed fluid from chamber 167. Similarly, a set of intake and discharge valves, two of which are shown at 174 and 175, respectively, are positioned in housing 162 adjacent chamber 169 to permit the ingress of fluid to be compressed into chamber 169 and the egress of compressed fluid from chamber 169.

Thus, during the leftward stroke of power assembly 43, gas or fluid within chamber 169 is compressed and discharged through valve 175 while, simultaneously, gas or fluid is being "sucked" into chamber 167 through intake valve 172. On the rightward stroke of power assembly 43, the gas or fluid in chamber 167 is compressed and discharged through discharge valve 173 while, simultaneously, gas or fluid is "sucked" into chamber 169 through intake valve 174, and the cycle is repeated.

As noted above, a major advantage of the engines according to the present invention is that they can provide twice the work output per cycle with the same capacity synchronizer and with substantially less than a factor of two increase in overall size and weight, as compared to prior engines needing a bouncer compressor to supply return energy. This illustrated by FIGS. 6 and 7. FIG. 6 shows pressure-volume curves for a prior engine having an output compressor and a bouncer compressor providing at least a portion of the return energy necessary for sustained operation of the engine. FIG. 7 shows pressure-volume curves for the engines of the present invention. The notation "*ss*" represents the length of the swept stroke of the engine.

With respect to the output compressor curve of FIG. 6, at point 1 the compressor piston begins to compress fluid within the output compressor chamber, and the compressor piston continues to compress this fluid until point 2. At point 2, the output compressor discharge valves open and the continued movement of the compressor piston forces the compressed fluid from the output compressor at substantially constant pressure. At point 3, the compressor piston is caused to reverse direction, and the output compressor discharge valves close. Between 3 and point 4 the pressure in the output compressor chamber rapidly drops as the volume increases behind the returning compressor piston. At point 4, the pressure within the output compressor chamber falls below atmospheric pressure, and the compressor inlet or suction valves open to admit the air which will be compressed and expelled during the next compressor stroke. As is well known in the art, the work done on the air by the compressor piston during the compressor-compression stroke is proportional to the area under the curve 1, 2, 3. The work returned to the system by the compressor piston during the compressor-expansion stroke is the area under the curve 3, 4, 1. Thus the area enclosed by the curve 1, 2, 3, 4 is a measure of the output work done by the output compressor piston during a single cycle.

With reference to the bouncer compressor curve of FIG. 6, the pressure within the bouncer compressor increases as the volume decreases along curve 2, 1. Also, the pressure within the bouncer compressor decreases as the volume increases, along curve 1, 2. Thus, the work done by the bouncer compressor piston during a single cycle is the area beneath the curve 2, 1 while the work returned to the system by the bouncer compressor piston during the same cycle is the area beneath the curve 1, 2. Thus, no network output is provided by the bouncer compressor piston since the area beneath these curves is substantially equal under the assumed ideal conditions.

Thus, in FIG. 6, one side of a compressor piston acts as an output compressor piston and the other side acts as a bouncer piston, and the network output per cycle is proportional to one times the area enclosed by the curve 1, 2, 3, 4.

FIG. 7, by contrast, shows that if both sides of a compressor piston, such as sides 168 and 171 of piston 168, each act as output compressor pistons, as allowed by engines of the present invention, the network output per cycle is proportional to two times the area enclosed by the curve 1, 2, 3, 4 which is twice the network output as in the case represented by FIG. 6.

Therefore, other factors equal, balanced, free piston engines according to the present invention provide twice the work output per cycle with substantially less than a factor of two increase in the overall size and weight.

An additional advantage of the present invention, as described above, may now be graphically represented. FIG. 8 shows the velocity versus stroke relationship between the power assemblies of engines according to the present invention, in solid line 176, and prior engines, in dashed line 177, both with respect to the swept stroke of the engine. Both curves start at the origin, as it represents the left endpoint of the power assembly where the power assembly is at zero velocity. Both curves return to the axis at the right endpoint of their power assemblies where again the velocities are zero. As can bee seen from a comparison of the two representations, the velocity upon the rightward stroke of engines according to the present invention, represented by the top half 178 of curve 176, is substantially identical to the velocity upon the leftward stroke, represented by the bottom half 179 of curve 176. As can also be seen, the velocity upon the leftward stroke of prior engines using bounce compressors, represented by the top half 183 of curve 177, is not equal to the velocity upon the leftward stroke, represented by the bottom half 185 of curve 177. Thus, engines according to the present invention have a naturally equal stroke-time function.

This naturally equal stroke-time function may be particularly important in association with certain energy absorbing devices. For example, with respect to the energy absorbing device in the form of the electrical generator 151 associated with engine 150, it was noted above that substantially identical waveforms were produced upon the rightward and the leftward stroke of the engine. As discussed, this is particularly important in alternating current wave generators, such as used with engine 150, to minimize the DC component of the generator output and in pumps, such as used with engine 100, to minimize the size of the dampers of accumulators used with the pump. Similarly, this naturally equal stroke-time function may be important for compressors such as used with engine 160.

FIGS. 9 and 10 Embodiments

FIGS. 9 and 10 show two single-acting power sections which may be placed on opposite ends of synchronizer housing 49 to provide power to the engine in place of the one double-acting power section 12 shown connected to one end of synchronizer housing 49 in FIG. 1.

In FIG. 9, a single-acting power section **180** is shown connected to the left end of housing **49** of engine **11**. Power section **180** is substantially identical in mode of operation to one-half of power section **12** of FIG. **1**, and thus the operation of power section **180** will only briefly be discussed here. One difference between power section **180** and power section **12** is that only a single-acting power piston **182** is positioned within power cylinder **16** of power section **180** instead of the double-acting power piston **17** positioned in power cylinder **16** of power section **12**. Power piston **182** again has an outer face **18**, and, in addition, power piston **182** has a recessed inner face **184** and a skirted sidewall **186**. Another distinction between power section **12** and power section **180** is that power section **180** includes single-acting intake ports **41** and single-acting outlet ports **42** rather than the dual ports **41***a*, **41***b* and **42***a*, **42***b* of power section **12**.

Further, the power section **180** includes an integral, radially outwardly extending portion **187** which has a generally annular chamber **188** formed about the right end **189** of cylinder **16**. The chamber **188** communicates with the end portion **191** of cylinder **16** to the right of the inner face **184** of the piston **182**. The right end of housing portion **187**, and thus the housing **15**, are fastened to a wall **34** by a plurality of bolts, two of which are shown at **35**, so the wall closes both the right end of chamber **188** and the left end of the synchronizer section **13**.

Conventional one-way valves, one of which is shown schematically at **192**, are positioned in the housing **15** and control the ingress of the air or fuel-air mixture into the chamber **188** of power section **180**.

Communication between the end portion **191** of the cylinder **16** and the chamber **188** permits the piston **182** to provide a scavenging pump action for the engine section **180**. In other words, as the piston **182** moves to the left, from the position shown in FIG. 9, air or air-fuel mixture is drawn through the valve **192** into the chamber **188** and into the end portion **191** of the cylinder **16**. After combustion within chamber **26** drives or forces the piston **182** to move to the right, the piston compresses the air or mixture in the end portion **191** of the cylinder **16** and thus in the chamber **188** so that when the ports **41** and **42** are uncovered by the piston **182**, the chamber **188** is a source of pressurized air or air-fuel mixture to scavenge the chamber **26**.

A second single-acting power stage is shown in FIG. **10** in the form of a single-acting power section **200** having a penetrated cylinder head **34**. Power section **200** includes a single-acting power piston **202** which is again arranged for reciprocal motion within cylinder **16**. Power section **200** is substantially identical in construction and mode of operation to power section **180**, except as noted herein and except that power section **200** is arranged to be alternately acting with power section **180**. That is, power section **200** provides power to the engine on the power stroke of power piston **202** at the same time that power section **180** accepts power from the engine on the compression stroke of power piston **182**.

Housing **187** of power section **200** is arranged to be connected to the right end of synchronizer housing **49**. End wall **51** is shown as a separate piece and no longer integrally formed with sidewalls **52** of housing **49** of synchronizer section **13**. Instead, end wall **51** and the remainder of housing **187** of power section **200** are arranged to be attached to sidewalls **52** of housing **49** in the same fashion as housing **15** and wall **34** of power section **180** are attached to housing **49**. Piston **202** is then attached to move with shaft **48**. Shaft **48** penetrates cylinder head **34** of power section **200**, as shaft **44** penetrates cylinder head **34** in FIG. **1**, and shaft **48** is again available to attach to the reciprocally movable member of an energy absorbing device.

Thus, engines according to the present invention may have single-acting power section **180** attached to the left end of synchronizer section **13** and single-acting power section **200** coaxially attached to the right end of synchronizer section **13** and yet function in the same fashion as does engine **11**. Further, the positions of power sections **180** and **200** may be reversed. Also, single-acting power sections, such as power section **180**, may be placed coaxially upon both extreme ends of the engine, beyond the energy absorbing device, and yield the benefit that identical power sections may be used.

CONCLUSION

From the foregoing, it is apparent that a relatively lightweight, balanced, free piston engine of simple design can be constructed utilizing the principles of this invention. As noted above, one of the principal advantages of this invention is that the same basic engine may perform as a power package to operate a variety of energy absorbing devices.

Also, it should again be noted that the term "main pistons" as used herein is meant to include only those pistons which perform the main or principal operating functions of the free piston engines of the present invention. The main pistons should be distinguished from so called auxiliary pistons such as oil pump pistons, water pump pistons, fuel pump pistons, and the like which may also be used in or on engines of the present invention and which may move either with or in the opposite direction to the main pistons during operation of the engines of the present invention. For example, an auxiliary oil pump piston could be attached to and moved with the walls **73, 74** of the synchronizer-balancer assembly **62**, in the opposite direction to the main pistons, or the same oil pump piston could be attached to and moved with power assembly **43**, in the same direction as the main pistons. Of course the weight of such an auxiliary piston must be considered as a part of the weight of the balancing and synchronizing assembly or the power assembly, as the case may be, in order to balance the engine.

Lastly, it should be noted that the term "main pistons" as used herein should be distinguished from the term "power assembly." The term "power assembly" as used herein, includes the main pistons, the movable member of the energy absorbing device, and the means for connecting the main pistons together and for interconnecting the main pistons with the movable member of the energy absorbing device. Thus, the main pistons and the movable member of the energy absorbing device form parts of the power assembly and always move together as a unit within the engine of the present invention.

It should also be obvious to those skilled in the art that the engines specifically described herein could be modified without affecting the principles of the present invention. For example, other types of gears, linkages, or other mechanisms could be utilized in place of the preferred embodiment of the synchronizer-balancer assembly **62** shown. Also, by an appropriate connection, the length of the stroke and weight of the counterbalancing part of assembly **62** could be different from the length of the stroke and weight of power assembly **43**.

Further, cam **131** of pump **104** shown in FIG. **3** may be designed to cause more than one pump stroke per power stroke of the free piston engine. Cam **131** may also include more than two cam surfaces which may be arranged in such a phase relationship as to require a minimum accumulator size. Many other pump configurations may be used in place of the preferred arrangement shown in FIG. 3.

Furthermore, other forms of electrical generators or alternators may be used in place of the specific embodiment described in association with FIG. 4.

Moreover, power sections **180** and **200** may both be double acting if the synchronizer-balancer is designed to have substantially twice the strength.

Thus, since the invention disclosed herein may be embodied in other specific forms without departing from the spirit or the general characteristics thereof, the embodiments described herein are therefore to be considered in all respects as illustrative and not restrictive; the scope of the invention being indicated by the appended claims, rather than the foregoing descriptions, and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced therein.

What is claimed is:

1. An unsymmetrical, synchronized, balanced, free piston engine adapted to drive a reciprocally movable member of an energy absorbing device comprising, in combination: an engine housing; means for defining a first power cylinder in the engine housing; means for defining a second power cylinder in the engine housing, with the second power cylinder being substantially coaxial to the first power cylinder; main piston means including a first power piston mounted in the first power cylinder for reciprocal movement therein along an axis substantially parallel to the central longitudinal axis of the first power cylinder, the first power piston defining a first combustion chamber with the first power cylinder, and including a second power piston mounted in the second power cylinder for reciprocal movement therein along an axis substantially parallel to the central longitudinal axis of the second power cylinder, the second power piston defining a second combustion chamber with the second power cylinder, the second combustion chamber being arranged to be alternately acting with the first combustion chamber; connection means, including shaft means, for connecting the main piston means, including the first power piston and the second power piston, to the movable member of an energy absorbing device, the main piston means, the connecting means, and the movable member of the energy absorbing device defining a power assembly wherein all components of the power assembly always move together as a unit; a synchronizer-balancer assembly having first means connected to move with the power assembly and having a counterbalancing means arranged for translational movement as a unit with respect to the engine housing in a direction opposite to the direction of movement of the power assembly in response to movement of the first means, the counterbalancing means having a preselected weight such that the absolute product of the weight associated to move with the counterbalancing means of the synchronizer-balancer assembly multiplied by the stroke of the counterbalancing means of the synchronizer-balancer assembly is substantially equal to the absolute product of the sum of the weight associated to move with the power assembly multiplied by the corresponding stroke length of the power assembly.

2. The improved free piston engine of claim 1, wherein the central longitudinal axes of the shaft means, the first power cylinder, the second power cylinder, and the counterbalancing means of the synchronizer-balancer assembly are coaxial and their paths of movement are parallel to their central longitudinal axes.

3. The improved free piston engine of claim 2, wherein the counterbalancing means of the synchronizer-balancer assembly comprises counterbalancing movable weight, with the weight arranged for translational movement with respect to the engine housing.

4. The improved free piston engine of claim 3, wherein the energy absorbing device is a pump.

5. The improved free piston engine of claim 4, wherein the pump includes at least one pumping chamber, wherein the movable member includes at least one pumping plunger associated with the pumping chamber and a cam which causes the pumping plunger to move reciprocally within the pumping chamber in response to movement of the cam.

6. The improved free piston engine of claim 3, wherein the energy absorbing device is an electrical generator.

7. The improved free piston engine of claim 6, wherein the movable member of the electrical generator is an electrical armature.

8. The improved free piston engine of claim 3, wherein the energy absorbing device is a double-acting reciprocal compressor having a compressor housing with a compressor cylinder formed therein, and wherein the movable member is a compressor piston which is mounted in the compressor cylinder for reciprocal movement therein in a direction substantially parallel to the longitudinal axis of the compressor cylinder, the compressor piston defining at least first and second compressor chambers with the compressor housing and the compressor cylinder.

9. The improved free piston of claim 3, wherein the means for defining the second power cylinder in the housing defines the second power cylinder to be adjacent to, coaxial with, and interconnected with the first power cylinder to form a double-acting power cylinder, wherein the connection means interconnects the first power piston and the second power piston to form a double-acting power piston, and wherein the combination of the double-acting power cylinder and the double-acting power piston comprises a double-acting power section.

10. The improved free piston engine of claim 3, wherein the first power piston and the first power cylinder comprise a first single-acting power section, wherein the first single-acting power section is positioned adjacent an end of the engine, and wherein the second power piston and the second power cylinder comprise a second single-acting power section.

11. The improved free piston engine of claim 10, wherein the first combustion chamber is defined in the first power cylinder between the outer face of the first power piston and the closed outer end of the first power cylinder, and wherein the second combustion chamber is defined in the second power cylinder between the outer face of the second power piston and the closed outer end of the second power cylinder.

12. The improved free piston engine of claim 10, wherein the shaft means connecting with the main piston means penetrates a portion of the engine housing forming one end of the second power cylinder to connect with the reciprocally movable member of an energy absorbing device, and wherein a combustion chamber shaft seal is positioned in the housing surrounding the shaft to minimize the leakage of gas and lubricant between the shaft and the housing.

13. The improved free piston engine of claim 10, wherein the second single-acting power section is positioned on the extreme end of the engine opposite from the first single-acting power section.

14. The improved free piston engine of claim 3, in which the first and second power cylinders and synchronizer-balancer assembly are located immediately adjacent each other along a common longitudinal axis with the first and second power pistons and the first means of the synchronizer-balancer assembly directly connected to each other by said shaft means, the connection means being adapted for connecting to the movable member of an energy absorbing device located along said axis at one end of the engine beyond said power pistons and synchronizer-balancer assembly.