March 17, 1970 A. BRAUN 3,501,088

BALANCED FREE PISTON ENGINE

Filed July 22, 1968 4 Sheets-Sheet 1

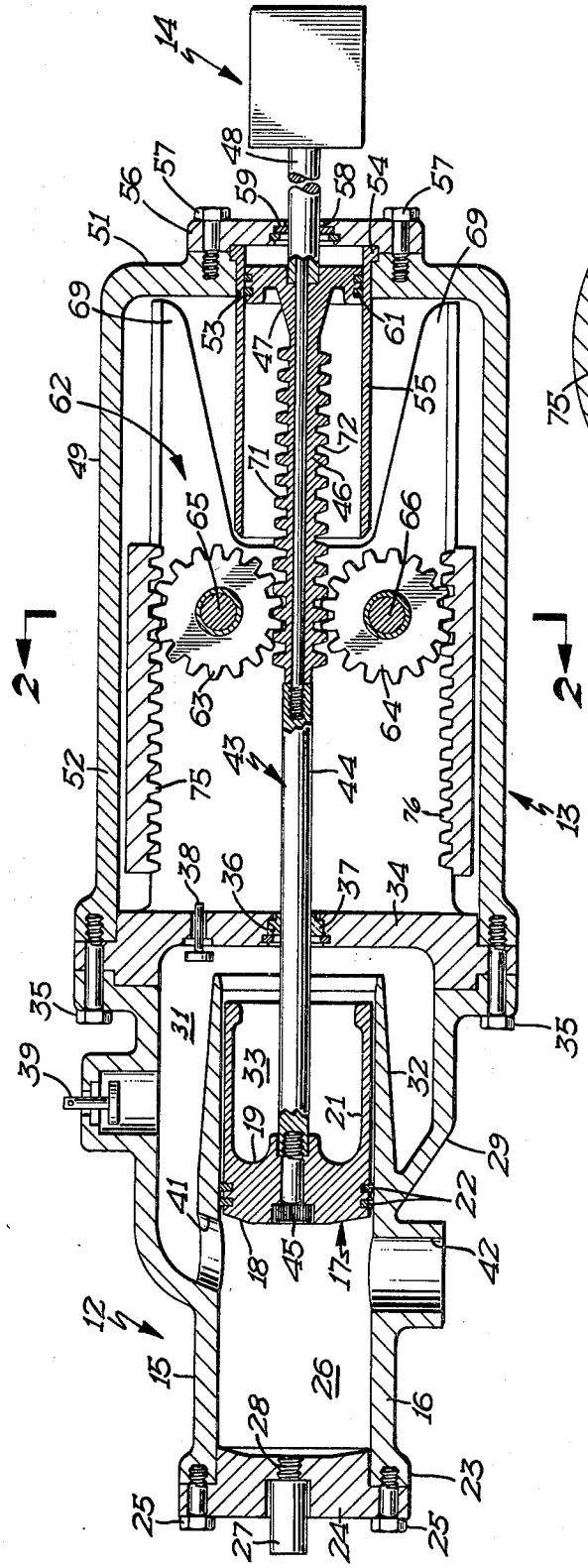


FIG 1

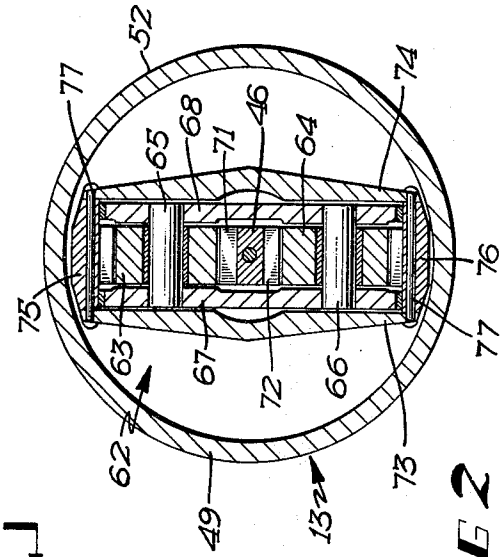


FIG 2

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BALANCED FREE PISTON ENGINE

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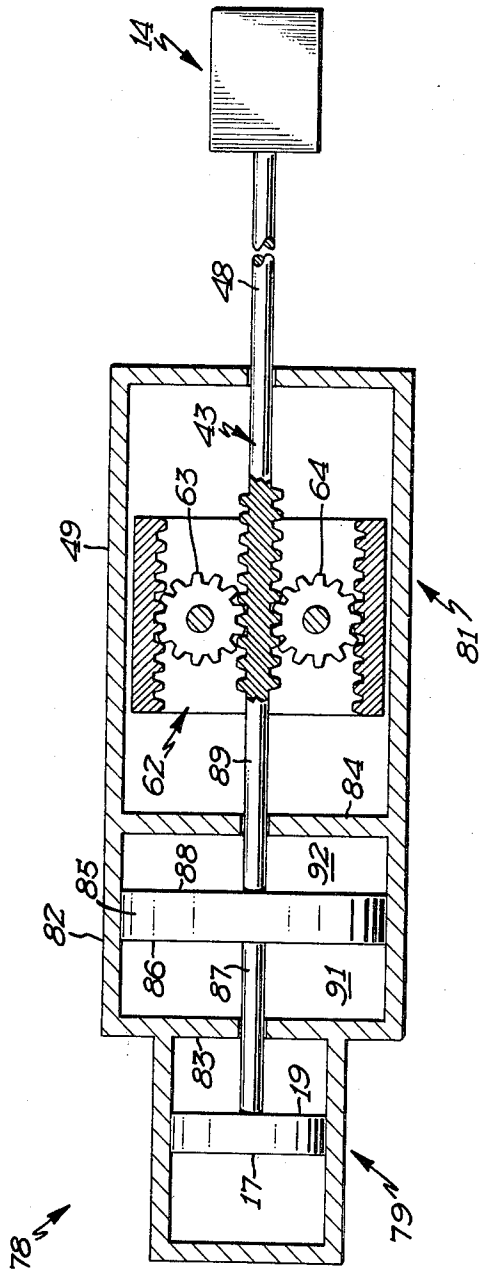


FIG 3

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March 17, 1970 A. BRAUN 3,501,088

BALANCED FREE PISTON ENGINE

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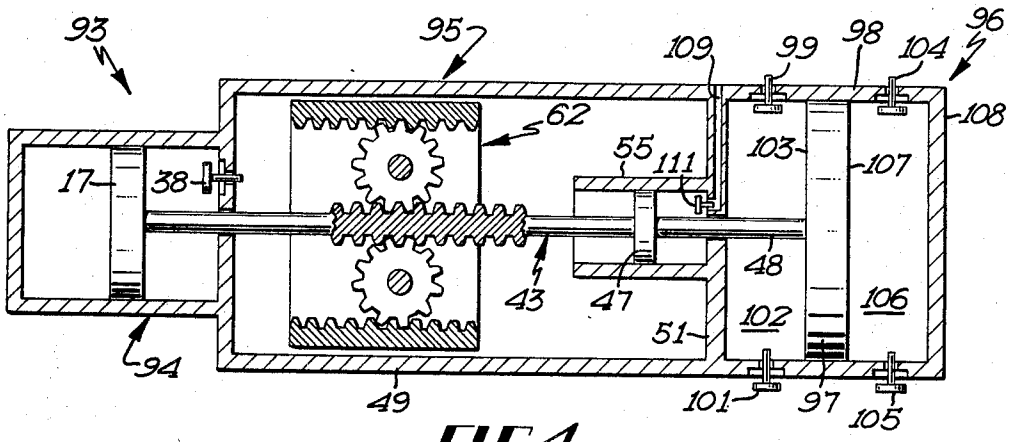


FIG 4

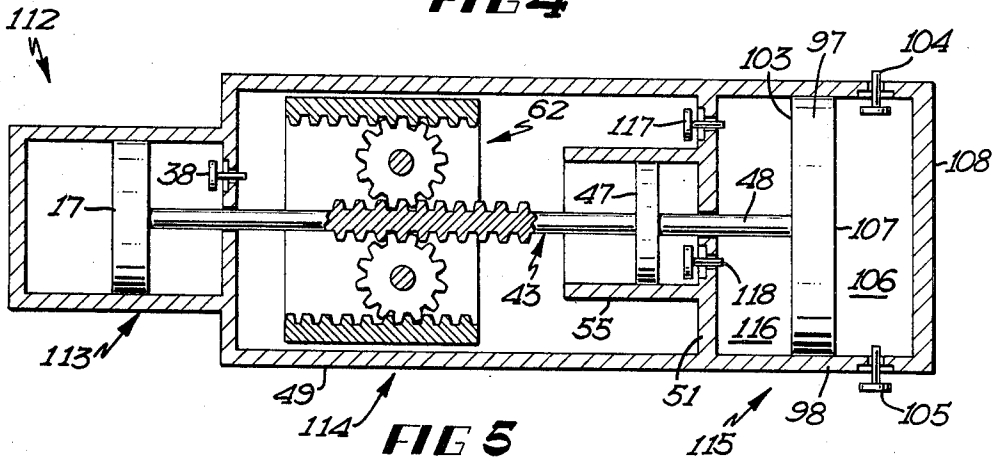


FIG 5

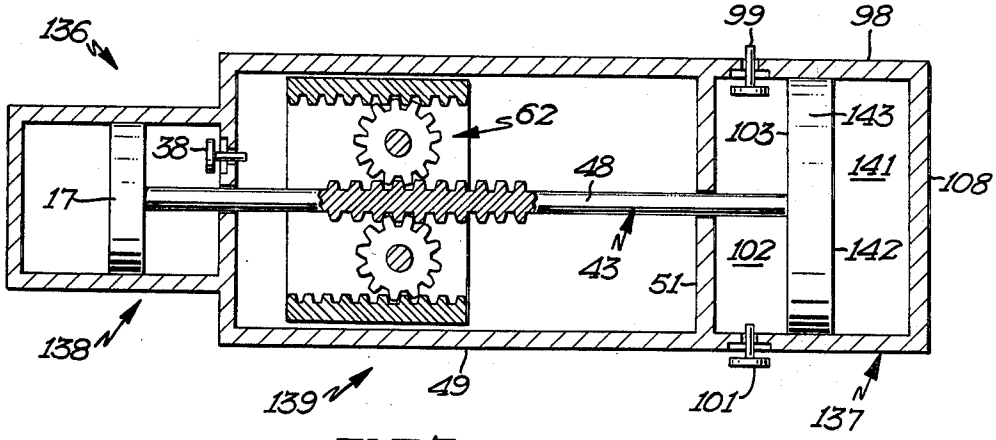


FIG 7

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March 17, 1970 A. BRAUN 3,501,088

BALANCED FREE PISTON ENGINE

Filed July 22, 1968 4 Sheets-Sheet 4

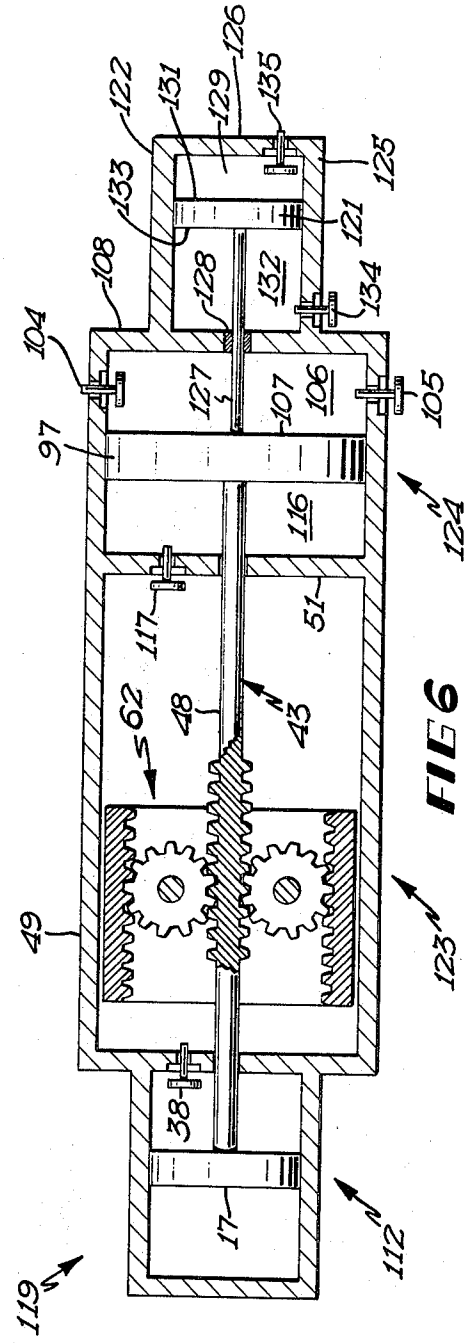


FIG 6

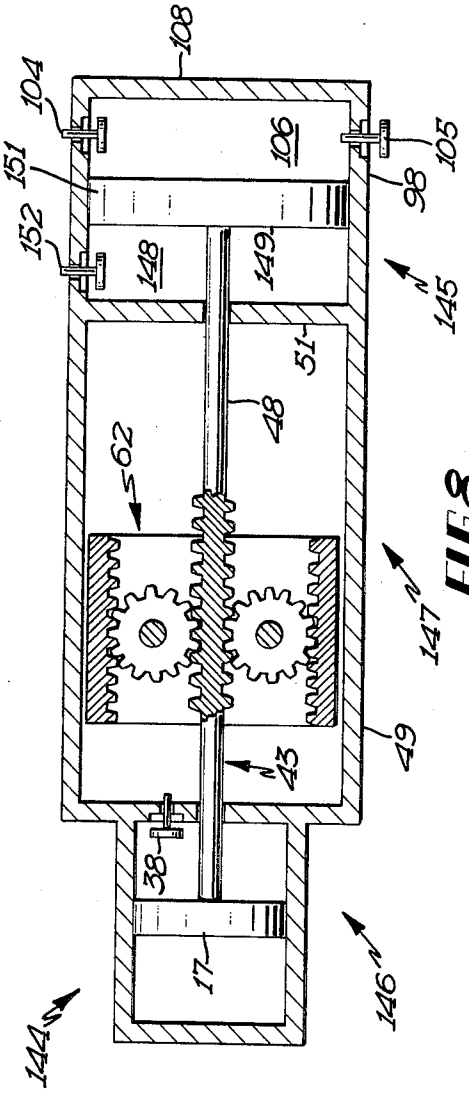


FIG 8

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United States Patent Office 3,501,088 Patented Mar. 17, 1970

3,501,088

BALANCED FREE PISTON ENGINE

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Filed July 22, 1968, Ser. No. 746,541
Int. Cl. F02b 71/06; F04b 31/00
U.S. Cl. 230—56 19 Claims

ABSTRACT OF THE DISCLOSURE

A balanced, free piston engine in which the power piston is connected to a reciprocally movable member of a driven energy absorbing device, such as the compressor piston in a gas compressor, so that all main pistons in the engine, including the power piston and the movable member move together as a unit during the operation of the engine. In some embodiments, a separate control piston is also connected with the power piston and is reciprocally movable therewith in a control cylinder so as to provide and/or regulate the energy necessary for satisfactory operation of the engine through a range of different operating conditions.

Dynamic balance of the engine is achieved by utilizing a balancing and synchronizing assembly having a counter-balancing movable weight which is arranged for translational movement with respect to the engine housing in an opposite direction to the power piston during the operation of the engine and which is constructed so that the absolute product of the weight of the counter-balancing movable weight of the balancing and synchronizing assembly times the length of its stroke is equal to the absolute product of the sum of the weights of the power assembly, i.e., the power piston and all other elements which are connected to and move with the power piston, times the corresponding length of the stroke of the power piston. The balancing and synchronizing assembly is connected with the power assembly by a rack and pinion arrangement, and is positioned and supported within the engine housing so that the losses, due to friction, resulting from the interconnection of the power assembly and the balancing and synchronizing assembly and from the movement of balancing and synchronizing assembly in the engine housing are minimized.

Background of the invention

This invention relates to an improved, balanced free piston engine, and more particularly to an improved dynamically balanced, free piston engine which may be used as a compact, relatively small and lightweight power unit for operating various types of energy absorbing devices, such as reciprocal compressors, pumps, generators and the like. Prior free piston engines have been designed to operate energy absorbing devices; however, these prior free piston engines were generally designed for use with only one energy absorbing device and usually were unadaptable for use with another.

In the past, balanced free piston engines have usually included at least a pair of piston assemblies which were mounted for reciprocal movement within axially aligned cylinders and which were caused to move in opposite directions within their respective cylinders. Each of the piston assemblies usually comprised a power piston and at least one compressor and/or bouncer piston, with the pistons of each piston assembly being connected together so that the piston assembly moved together as a unit. Dynamic balance was achieved in these engines by constructing the assemblies so that their weights were equal and so that the length of their strokes were equal. Also, as described in the Anton Braun United States patent application, Ser. No. 805,063, filed Dec. 17, 1968, dynamic balance can be achieved in such engines if the sum of the products of the weight of the piston assemblies times the length of their strokes is equal to zero.

Also in the past, a free piston engine has been constructed having a single power piston and a single compressor piston which reciprocally move together within their respective cylinders. However, this engine was not dynamically balanced and because of this, the engine experienced vibrational problems.

Summary

In accordance with the present invention, a balanced free piston engine is provided which may use only a single power piston and which has no counter-moving main pistons. In other words, in the free piston engines of the present invention all main pistons (i.e., power pistons, bouncer compressor pistons, or scavenge compressor pistons) move in one direction during each stroke, and only a counter-balancing movable weight translationally moves in the opposite direction with respect to the housing to balance the engines. This feature allows the balanced free piston engines of the present invention to be readily adaptable for use with a variety of energy absorbing devices which accept a reciprocatory power input. Briefly, the improved, balanced, free piston engine of the present invention includes a power piston which is connected with a reciprocally movable member in the energy absorbing device, for example, the compressor piston in a reciprocal compressor, that is being driven by the improved free piston engine. In some of the embodiments of the invention described herein, the improved free piston engine includes a separate control piston which reciprocates within a control cylinder, and which moves with the power piston so as to perform as a return means, i.e., to supply sufficient return energy for satisfactory operation of the engine through a range of different operating conditions or, in other words, to always supply the proper energy to return the power piston to the desired top-dead-center position. In still further embodiments, wherein the energy absorbing device is a compressor, the return energy may be supplied from the compressor itself rather than from a separate piston.

The improved engine of the present invention includes a novel balancing and synchronizing assembly. In the embodiments of the invention described herein, the counter-balancing movable weight of the balancing and synchronizing assembly is mounted adjacent a power assembly, i.e., the power piston and all other elements carried by and moving with the power piston, which moves parallel to, but in an opposite direction to the movement of the counter-balancing movable weight of the balancing and synchronizing assembly. The weight of the counter-balancing movable weight of the balancing and synchronizing assembly is selected so as to be substantially equal to the weight of the power assembly, and the distance through which the counter-balancing movable weight of the balancing and synchronizing assembly and the power assembly move during the operation are equal so that dynamic balance is achieved in the engine. One of the advantages of the novel balancing and synchronizing assembly is that its weight may be relatively easily changed so that dynamic balance may always be achieved, although the weights of the reciprocating portions of the energy absorbing devices connected with the engine may vary considerably. The balancing and synchronizing assembly is connected with the power assembly by means of a plurality of racks, carried by the power assembly and by the balancing and synchronizing assembly, and at least one pair of pinions mounted for rotation, about fixed axes, between the racks of the power assembly and the racks of the balancing and synchronizing assembly.

As noted above, the improved balanced free piston en-

gine of the present invention may be utilized, as a power package, to drive a variety of energy absorbing devices of the type using a reciprocatory power input for operation, since the engine may be constructed so that one end of a reciprocating shaft projects from the engine housing and may be attached to the movable member of an energy absorbing device to drive the same. In some embodiments described herein, the energy absorbing device, a compressor, is attached directly to the engine housing with one end of the shaft being directly attached to a compressor piston, although, of course, the engine and the energy absorbing device could be spaced apart, if desired.

In accordance with the foregoing, it is an object of the present invention to provide an improved, balanced, free piston engine wherein the power piston and a reciprocal movable member of an energy absorbing device, driven by the free piston engine, are connected and move together as a unit. A further related object of the present invention is to provide an improved, balanced, free piston engine wherein any and all main pistons (power pistons, scavenge compressor pistons, or bounce compressor pistons) in the engine translationally move together with respect to the engine housing and are balanced by the oppositely directed translational movement of a counterbalancing movable weight of a novel balancing and synchronizing assembly. A still further related object of the present invention is to provide an improved, balanced free piston engine including a control piston which is a part of and moves with the power assembly and which is arranged so as to supply substantially all, or a part of, the return energy necessary for the proper thermodynamic balance of the engine. A still further related object of the present invention is to provide an improved, balanced free piston engine having a separate control piston.

Another object of the present invention is to provide an improved, balanced, free piston engine which is relatively light weight and compact. A related object of the present invention is to provide an improved, balanced, free piston engine wherein the required overall length of the engine need not be substantially greater than four times the length of the swept stroke of the power piston utilized in the engine plus the length required for the energy absorbing device.

Another object of the present invention is to provide an improved, balanced free piston engine of the type described wherein the energy absorbing device is a compressor powered by the engine and wherein the compressor piston is connected with the power piston so that the compressor piston and the power piston move together as a unit.

Still another object of the present invention is to provide an improved, balanced, free piston engine wherein the power piston and the reciprocally movable member in the energy absorbing device driven by the engine are structurally interconnected and wherein dynamic balance of the engine is achieved by the utilization of a novel balancing and synchronizing assembly having a counterbalancing movable weight, the weight of which being easily changeable so that the engine may be used to power various different energy absorbing devices. The counterbalancing movable weight of the novel balancing and synchronizing assembly is arranged so as to be always translationally moved in the opposite direction to the power assembly with respect to the engine housing so that the product of the weight of the counter-balancing movable weight of the balancing and synchronizing assembly times its stroke plus the product of the weight of the power assembly times the corresponding stroke of the power assembly is equal to zero.

A further object of the present invention is to provide a rack and pinion arrangement for connecting the power assembly, with the novel balancing and synchronizing assembly, which arrangement includes double racks connected with and carried by the power assembly and racks mounted on the balancing and synchronizing assembly so

that each rack of the balancing and synchronizing assembly faces one of the racks connected with the power assembly. A pair of pinions, mounted for rotation about fixed axes, are positioned between the facing racks so that the teeth of the pinions engage the teeth of the facing racks whereby the balancing and synchronizing assembly is caused to move in the opposite direction to the direction of movement of the power assembly with minimal losses, due to friction.

A still further object of the present invention is to provide an improved, balanced, free piston engine of the type described wherein the balancing and synchronizing assembly includes means for balancing the normal components of the forces created by the transmission of forces between the teeth of the pinions and the teeth of the racks so as to minimize the losses, due to friction, resulting from the utilization of the balancing and synchronizing assembly.

These and other objects and advantages of the present invention will become apparent from the following description of the preferred embodiments of this invention described in connection with the drawings.

Description of the drawings

FIGURE 1 is a vertical cross-sectional view of an embodiment of the improved, balanced free piston engine of the present invention shown connected with an energy absorbing device.

FIGURE 2 is a vertical cross-sectional view taken along the section line **2**—**2** in FIGURE 1.

FIGURE 3 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with an energy absorbing device.

FIGURE 4 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with a double-acting compressor.

FIGURE 5 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with an outwardly compressing compressor.

FIGURE 6 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with an outwardly compressing compressor.

FIGURE 7 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with an inwardly compressing compressor.

FIGURE 8 is a schematic, vertical cross-sectional view of another embodiment of the improved, balanced free piston engine of the present invention shown connected with an outwardly compressing compressor.

Throughout the various figures of the drawings, the same reference numerals have been used to designate the same or identical parts or elements in the various embodiments of the engines 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

FIGURE 1 embodiment.—An improved, balanced free piston engine **11** of the present invention is shown in FIGURES 1 and 2, and includes a power section **12** and a balancer-synchronizer section **13**. An energy absorbing device, shown diagrammatically at **14**, is spaced from the right end of the balancer-synchronizer section **13**. The energy absorbing device **14** may be a compressor, such as shown in FIGURES 4–8, a pump, a generator, a power saw or any other device which utilizes or absorbs reciprocatory power.

The power section 12 includes a cylinder housing 15 which has a power cylinder 16 formed therein. A power piston 17 is positioned within the cylinder 16 for reciprocal movement therein. The piston includes an outer face 18, a recessed inner face 19 and a skirted side wall 21. Piston rings 22 are carried in grooves formed in the piston 17 for minimizing the leakage of gases between the cylinder 16 and the piston 17.

The left end 23 of the housing 15 is closed by cylinder head 24 which is bolted to the end 23 of the housing 15 by a plurality of bolts 25. The cylinder head 24, together with the outer face 18 of the piston 17, define a combustion chamber 26 in the cylinder 16.

In the engine 11, a conventional fuel injector unit 27 is positioned in a central aperture 28 formed in the head 24 so that its inner end communicates with the chamber 26. By proper selection of the return energy, as explained below, air is compressed in combustion chamber 26 by the leftward movement of piston 17 until the air pressure and temperature in chamber 26 have been raised beyond the auto-ignition point, at which time the fuel introduced into chamber 26 through fuel injector unit 27 will effectively burn in accordance with the principles of operation of conventional diesel engines. Of course, by varying the return energy accordingly and by introducing a conventional spark plug and associated conventional ignition system and a conventional carburetor or fuel injector system, combustion may also operate in accordance with the principles of conventional spark ignition or stratified charge engine.

The housing 15 also includes an integral, radially outwardly extending portion 29, which has a generally annular chamber 31 formed about the right end 32 of the cylinder 16. The chamber 31 communicates with the end portion 33 of the cylinder 16 to the right of the inner face 19 of the piston 17. The right end of the housing portion 29, and thus the housing 15, are fastened to a wall 34 by a plurality of bolts, two of which being shown at 35, so that the wall closes both the right end of the chamber 31 and the left end of the synchronizer section 13.

The wall 34 has a central aperture 36 formed therein so that the central longitudinal axes of the aperture and the cylinder 16 are coaxial. Conventional shaft seals 37 are positioned in the aperture 36, for reasons hereinafter explained. The wall 34 also has a conventional one-way valve 38 positioned therein which permits air or gas in the interior of the synchronizer section 13 to pass or be drawn into chamber 31.

Conventional one-way valves, one of which being shown schematically at 39, are positioned in the housing 15 and control the ingress of air or fuel-air mixture into the chamber 31. A plurality of inlet ports, one of which is shown at 41, are formed in the housing 15 and permit the air or mixture in chamber 31 to flow into the chamber 26 of cylinder 16. A plurality of exhaust ports or openings, one of which being shown at 42, are also formed in the housing 15 and permit the combustion gases in the combustion chamber 26 to be exhausted from the cylinder 16. To insure proper "blow-down," the ports 42 are positioned closer to the left end 23 of the housing 15 than the ports 41. The ports 41 and 42 are arranged, relative to the combustion chamber 26, so that the chamber 26 will be properly scavenged during normal operation of the engine.

The piston 17 controls the flow of air or gas through the ports 41 and 42. In addition, the communication between the end portion 33 of the cylinder 16 and the chamber 31 permits the piston 17 to provide a scavenging pump action for the engine section 12. In other words, as the piston 17 moves to the left, from the position shown in FIGURE 1, air or mixture is drawn through the valve 39 into the chamber 31 and into the end portion 33 of the cylinder 16. After combustion in chamber 26 drives or forces the piston 17 to move

to the right, as shown in FIGURE 1, the piston compresses the air or mixture in the end portion 33 of the cylinder 16 and thus in the chamber 31 so that when the ports 41 and 42 are uncovered by the piston, the chamber 31 is a source of pressurized air or mixture to scavenge the chamber 26.

As noted above, the piston 17 is a part of a power assembly 43 that includes, in addition, all other main pistons (power pistons, scavenge compressor pistons, or bouncer compressor pistons) and all the other parts of the engine and the energy absorbing device which move with and are connected with the power piston 17. 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 the shaft 44 is connected with the left end of a double rack member 46. A control piston 47 is connected to the right end of the double rack member 46. A second shaft 48 is connected to the right face of the piston 47 and interconnects the piston 47 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 control piston 47, the shaft 48, and the reciprocal 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 carried by the pistons. 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 wall 34 and is sealed by the conventional shaft seals 37 positioned in the aperture 36 so as to minimize leakage of gas or lubricant between the shaft and aperture.

The synchronizer section 13 includes a housing 49 which, as noted above, has its left end closed by the wall 34. The same bolts 35 used to fasten the housing 15 to the wall 34 are also used to secure the housing 49 to the wall 34. An end wall 51 closes the right end of the housing 49 and is formed integrally with the side wall 52 of the housing, as shown in FIGURE 1. Of course, if desired, the 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, stepped aperture 53 formed therein designed to receive the flanged right end 54 of a control cylinder 55. The flanged end 54 of the control cylinder 55 is arranged in the stepped aperture 53 so that the control cylinder 55 cannot be moved axially to the left, relative to the end wall 51, and so that the central longitudinal axes of the cylinders 16 and 55 are coaxial.

A closure wall 56 is attached to the right side of the end wall 51 by a plurality of bolts, two of which being shown at 57, so that the wall 56 covers the right end of control cylinder 55. The wall 56 includes an opening 58 positioned so that its central axis is coaxial to the central axis of the aperture 53. The second shaft 48 extends through the opening 58 formed in the wall 56, and a conventional shaft seal 59 is mounted in the opening 58 so as to minimize leakage of gas or lubricant between the shaft 48 and the opening 58. The shaft 48 is arranged in axial alignment with the shaft 44.

The control piston 47 is mounted within the control cylinder 55. The length of the control cylinder 55 is slightly greater than the maximum possible length of the stroke of the piston 17, and thus the stroke of the control piston 47, so that the piston 47 will, at all times, remain in control cylinder 55. Conventional piston seals 61 are positioned about the periphery of the piston 47 so as to minimize leakage between the piston 47 and control cylinder 55.

As noted above, the right end 54 of the cylinder 55

is closed by the wall **56** so that the control piston **47** functions as a positive bouncer piston within the cylinder **55**. The left end of the cylinder **55** is open to the interior of the housing **49**. The control piston **47** works in the cylinder **55** with a preselected compression ratio so that sufficient return energy is obtained by supplying the bouncer chamber, i.e., the space in cylinder **55** between control piston **47** and wall **56**, with gas or air of appropriate pressure, and thus to return the piston **17** to its firing position in cylinder **16** whereby combustion in chamber **26** can effectively initiate another cycle of operation of the engine. In other words, the control piston **47** and control cylinder **55** are designed to provide the requisite return energy required for the piston **17** so that the engine **11** does not have to depend on obtaining return energy from the energy absorbing device **14**. The diameter of the control piston **47** and control cylinder **55** may be relatively small, as compared to the diameter of the piston **17**, although the actual diameters will be a function of the actual operating conditions of the engine, the compression ratio of the bouncer chamber, its charging pressure and other design parameters.

As will be appreciated from the foregoing, since all the parts of the power assembly **43** move in the same direction, the engine **11**, would be dynamically unbalanced and thus would be subject to serious vibrational problems. To achieve a dynamically balanced engine, the engine **11** includes a balancing and synchronizing assembly **62** mounted within the housing **49**.

The balancing and synchronizing assembly **62** is connected with the power assembly **43** through the double rack member **46**. 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 side plates **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 wall member **34** and the other ends **69** thereof project to the right from the wall **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 central axis of the power assembly **43**.

The shafts **65** and **66** are supported by the plates **67** and **68** approximately midway between the wall **34** and the ends **69** of the plates 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 longitudinal central axes of the shafts **65** and **66** being arranged at 90° to the longitudinal central axes 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 balancing and synchronizing assembly **62** includes a pair of movable wall members **73** and **74** which are positioned adjacent to and parallel with the fixed side plates **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 FIGURE 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, 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 FIGURE 2, the balancing and synchronizing assembly **62**, including racks **75** and **76**, can reciprocate freely 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 losses, due to friction, resulting from the transfer of forces between the balancing and synchronizing 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 the racks **71** and **72** tend to "float" between, and the racks **75** and **76** tend to "float" on 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 counter-balancing movable weight of the balancing and synchronizing assembly **62**, i.e., the weight of the movable members **73** and **74** and the pins **77**, plus the weight of the racks **75** and **76** times the distance the counter-balancing weight of assembly **62** moves during a stroke of the engine must be equal to the product of the sum of the weights 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 counter-balancing weight of the assembly **62**.

As noted above, the engine **11** is suitable for use with various different energy absorbing devices, which, of course, means that the weight of the element of the energy absorbing device **14** which is attached to and carried by the 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 counter-balancing weight of the balancing and synchronizing assembly **62** may be easily varied without affecting the structure or operation of the engine.

Moreover, as noted above, 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-dead-center position **17**, i.e., when the piston **17** has moved to its left-most operating position, and such combustion, together

with any other energy in the engine **11** and/or the device **14** available to support the rightward movement of the power assembly **43**, causes the piston **17**, and thus the rest of the power assembly **43** including the connecting part of the balancing and synchronizing assembly **62**, rack member **46**, to be moved translationally to the right with respect to the housing. 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 counter-balancing weight of the balancing and synchronizing assembly **62**, including the racks **75** and **76**, to move to the left with respect to the housing **49**, also in a translational manner. Thereafter, as the presure in the closed end of the control cylinder **55** increases, due to the rightward movement of the control piston **47**, the rightward movement of the power assembly **43** stops and the "return energy" thus stored in the compressed air or gas in the control cylinder **55**, together with any other "return energy" developed in the engine **11** and/or device **14**, forces the piston **47**, and thus the rest of the power assembly **43**, again to move to the left.

During the movement of the piston **17** to the right in cylinder **16**, first the exhaust port **42** is uncovered to allow the "blow-down" of the combustion gases and then the intake port **41** is uncovered by the piston **17** so that the chamber **26** can be properly scavenged and a new charge of air or fuel-air mixture introduced into chamber **26**. As the piston **17** moves to the left, first the port **41** and then the port **42** are again blocked by the piston **17**. Thereafter the air or fuel-air mixture in the chamber **26** is compressed until combustion again occurs in the chamber **26**, and the cycle of operation is repeated.

As noted above, during the rightward translational movement of the power assembly **43** with respect to the housing, the counter-balancing weight of the balancing and synchronizing assembly **62**, including the racks **75** and **76**, are translationally moved to the left in housing **49**. Conversely, when the power assembly **43** translationally moves to the left, the counter-balancing weight of the balancing and synchronizing assembly **62**, including the racks **75** and **76**, translationally moves to the right. Moreover, as explained hereinabove, if the weights of the movable wall members **73** and **74** are selected so that the product of the sum of the weights of the power assembly **43** times the length of the stroke of the assembly **43**, is equal to the product of the sum of the counter-balancing weights of the balancing and synchronizing assembly **62**, including the racks **75** and **76**, times the corresponding distance through which the counter-balancing weight of the balancing and synchronizing assembly **62** moves in the opposite direction of the piston, then dynamically balanced operation of the engine **11** can be achieved. Furthermore, because of the incorporation of the control piston **47** into the engine **11**, the engine can operate through a wide range of operating parameters. In other words, and for example, thermodynamic balance of the engine can be maintained through a wide range of changes in the load on the engine, and/or the fuel supplied thereto.

FIGURE 3 embodiment.—The engine **78**, shown schematically in FIGURE 3, has a power section **79** and synchronizer section **81** which are substantially identical, in structure and mode of operation, to sections **12** and **13**, respectively, of engine **11**, except that the synchronizer section **81** does not include a control piston and cylinder, such as the piston **47** and cylinder **55** utilized in section **13** of engine **11**. In engine **78**, the second shaft **48** directly interconnects the right end of double rack member **46** with the reciprocally movable portion of the energy absorbing device **14**.

The principal structural difference between engines **78** and **11** is that in engine **78**, a control cylinder **82** is positioned between the right end wall **83** of the power section **79** and the left end wall **84** of the synchronized section **81**. As shown in FIGURE 3, the control cylinder **82** may be an integral part of the housing **49**.

A control piston **85** is positioned for reciprocal movement in the control cylinder **82**. The left face **86** of the control piston **85** is connected with the face **19** of the piston **17** by a shaft **87** which extends through a sealed aperture in the wall **83**. The right face **88** of the control piston **85** is connected with the left end of the double rack member **46** by a shaft **89** which extends through a sealed aperture in the wall **84**.

A first chamber **91** is defined in the cylinder **82** between the wall **83** and the face **86** of the piston **85**, and a second chamber **92** is defined in cylinder **82** between wall **84** and face **88** of the piston **85**. The chambers **91** and **92** may function as bouncer chambers or one of the chambers may be utilized as a scavenge pump which may be used to supplement or instead of the scavenge pump action provided by piston **17**.

One of the advantages of engine **78** is that it permits a larger diameter control piston to be utilized which, in turn, permits lower pressure levels to be used in the chambers **91** and **92**. In addition, the provision of two bounced chambers permits relative flexibility in controlling the operation of the engine whereby thermodynamic balance of the engine can be achieved through a wide range of design and operating parameters. Moreover, the arrangement of engine **78** minimizes the chances that the lubricant used in the power section **79** will contaminate or be mixed with the lubricant in the synchronizer section **81**, and vice versa, since the pressure in the chambers **91** and/or **92** can be kept higher than the pressures in the power and synchronizer sections **79** and **81**.

FIGURE 4 embodiment.—The engine **93** shown schematically in FIGURE 4, includes power section **94** and a synchronized section **95** substantially identical in structure to the power section and synchronizer sections **12** and **13**, respectively, of the engine **11**. The engine **93** differs from engine **11** in that in engine **93**, the energy absorbing device driven by the engine is a double acting compressor **96** positioned adjacent to the right end wall **51** of the synchronizer section **95**.

The compressor **96** includes a compressor piston **97** which is attached to the end of the shaft **48** for reciprocal movement therewith within a compressor cylinder **98**, which, in FIGURE 3, is formed as an integral part of the housing **49**.

Conventional compressor inlet and outlet valves, two of which being shown schematically at **99** and **101**, permit the ingress and egress of air or gas into and out of the compressor chamber **102** formed between the left end wall **51** of the section **96** and the inner face **103** of the piston **97**. Similarily, conventional compressor inlet and outlet valves, two of which being shown schematically at **104** and **105**, permit the ingress and egress of air or gas into and out of the compressor chamber **106** formed between the outer face **107** of the piston **97** and the right end wall **108** of the compressor housing **98**.

A passage **109** is formed in the end wall **51** and permits communication between the closed end of the control cylinder **55** and the atmosphere. One-way valve **111** is positioned within the passage **109** so as to permit air or gas to flow only into the closed end of the cylinder **55**. The passage **109** is utilized in engine **93** to insure that there is always sufficient air or gas within the closed end of cylinder **55** so that the control piston **47** can perform its intended function. The passage **109** could be connected with a source of air or gas under pressure, rather than the atmosphere, if desired.

In engine **93**, the clearance volume of the chamber **106** assists in providing return energy for the continuous operation of the engine, and the clearance volume in the chamber **102** assists the rightward movement of the power assembly **43**, including the compressor piston **97**. Otherwise the operation of the engine **93** is identical to that of engine **11**.

FIGURE 5 embodiment.—Engine **112** is substantially identical, in structure, to engine **93** in that the power and synchronizer sections **113** and **114** are identical in structure to sections **94** and **95** and the energy absorbing device is a compressor **115**. However, compressor **115** differs from compressor **96** in that compressor **115** is a single acting, outwardly compressing compressor. A chamber **116** formed between the end wall **51** of the section **114** and the inner face **103** of the piston **97** functions as a negative bouncer chamber.

One-way valves **117** and **118** are positioned in passages in the end wall **51** and permit the pressurized air or gas in chamber **116** to flow into the interior of the synchronizer section **114** and into the closed end of cylinder **55**, respectively, when the pressure of the air or gas in chamber **116** exceeds a preselected value as a result of the movement of the piston **97** to the left, within compressor cylinder **98**. Alternatively, if desired for control purposes, a passage and valve arrangement, such as passage **109** and valve **111** used in engine **93**, could be used in engine **112** in place of valves **117** and/or **118**. Otherwise, the operation of engine **112** is substantially identical to that of engine **93**.

FIGURE 6 embodiment.—Engine **119** is substantially identical, in structure and mode of operation, to engine **112** with the only significant structural difference being that the control piston **121** and control cylinder **122** of engine **119** are not positioned within the synchronizer section **123** of engine **119**, as are piston **47** and cylinder **55** in engine **112**, but rather are positioned to the right of the end wall **108** of the outwardly compressing compressor **124**.

More specifically, the control cylinder **122**, consisting of an annular side wall **125** and a closed end wall **126**, is secured to the end wall **108** of the compressor **124**. A shaft **127** extends through a sealed aperture **128** in the wall **108** and connects the control piston **121** to the compressor piston **97** so that the piston **121** moves with piston **97**, and thus with the power assembly **43** in the engine **119**. The control piston **121** and the control cylinder **122** are arranged so that the longitudinal central axes of the piston **121**, cylinder **122**, and the power assembly **43** of the engine **119** are coaxial.

A positive bouncer chamber **129** is defined in cylinder **122** between the outer face **131** of the piston **121** and the end wall **126**. A negative bouncer chamber **132** is defined in the cylinder **122** between the inner face **133** of the piston **121** and the wall **108**.

One-way valve **134** is positioned in the side wall **125** of the cylinder **122** to permit the air or gas in chamber **132** to escape to the atmosphere upon the air or gas reaching a predetermined pressure. One-way valve **135** is positioned in the end wall **126** of the cylinder **122** to permit air or gas to be drawn into the chamber **129**, either from the atmosphere or from a source of pressurized air or gas, not shown. If desired, a groove in the side wall **125** of cylinder **122** could be utilized instead of the valves **134** and/or **135**. The groove would permit communication, around the periphery of the piston **121**, between the chambers **129** and **132** during a portion of the stroke of the piston.

One of the advantages of positioning the control piston and the cylinder, as described in engine **119**, is that it facilitates the maintenance and repair thereof.

FIGURE 7 embodiment.—Engine **136** is generally similar, in structure and mode of operation, to engines **93**, **112** and **119** except that the engine **136** does not utilize a separate control piston and control cylinder and that the energy absorbing device is an inwardly compressing compressor **137**. More specifically, power section **138** and synchronizer section **139** of engine **136** are identical, in structure and mode of operation, to sections **94** and **95**, respectively, of engine **93** with, of course, the exception that section **139** does not include a separate control piston and cylinder, such as piston **47** and cylinder **55** in engine **93**.

The compressor **137** includes a positive bouncer chamber **141** formed between the outer face **142** of piston **143** and the end wall **108**. The piston **143** performs both as the compressor piston and the separate control piston, such as pistons **47** and **121**, were utilized in the engines **93**, **112** and **119**, i.e., to provide necessary return energy for the power assembly and to provide a means for controlling the operation of the engine.

One of the advantages of engine **136** is the great simplicity of its structure. Engines of this type are particularly suitable for constant load applications.

FIGURE 8 embodiment.—Engine **144** is generally similar, in structure, to engine **136** in that it does not utilize a separate control piston and control cylinder arrangement. However, engine **144** is connected with the drives and outwardly compressing compressor **145**, as contrasted with the inwardly compressing compressor **137** of engine **136**.

The power section **146** and synchronizer section **147** of engine **144** are identical, in structure and mode of operation, to the sections **138** and **139**, respectively, of engine **136**.

The compressor **145** includes a negative bouncer chamber **148** formed between the end wall **51** of the synchronizer section **147** and the inner face **149** of the piston **151**. Like piston **143**, the piston **151**, alone, performs the functions of compressor piston and the separate control piston utilized in engines **93**, **112** and **119**. A one-way valve **152** is positioned in the cylinder **98** to permit air or gas to be drawn into the chamber **148**. Of course, valve **152** may be reversed so as to discharge air or gas from chamber **148** if that is the desired control effect.

One of the advantages of engine **144** is that the controls necessary for satisfactory operation of the engine can be relatively simple.

From the foregoing, it is apparent that relatively lightweight, balanced free piston engines 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 same basic engine may be utilized to operate a variety of energy absorbing devices, and that because of its light weight and compactness it can be utilized in applications where prior conventional engines are not practical.

Also, it should again be noted that the term "main piston" as used herein is meant to include only those pistons (power pistons, scavenge compressor pistons, or bouncer compressor pistons) which perform the main or principal operating functions of the free piston engines of the present invention. Thus, with respect to the engines described herein: the main pistons are pistons **17** and **47** in engines **11**, **93** and **112**; the main pistons are pistons **17** and **85** in engine **78**; the main pistons are pistons **17** and **121** in engine **19**; and the main piston is piston **117** in engines **136** and **144**. These 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 synchronizing and balancing assembly **62**, in the opposite direction to the main pistons, or an auxiliary oil pump piston could be attached to and moved with power assembly **43**, in the same direction as the main pistons. Of course, in such situations, the weight of any auxiliary piston could be considered as being a part of the movable weight of the balancing and synchronizing assembly or the power assembly, as the case may be, for the purpose of balancing 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.

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, more than one power piston **17** or power section **12** could be utilized with one engine. Also, it would be possible to modify the rack and pinion arrangement described herein so that the power assembly **43** includes two double rack members and a second pair of pinions to cooperate with the second double rack member. Further, other types of gears and/or linkages could be utilized to interconnect the power assembly **43** and the balancing and synchronizing assembly **62**. Also, by an appropriate connection, the length of the stroke of assembly **62** could be different than the length of the stroke of the assembly **43**. Further, the engine shown in FIGURE 3 could be modified by positioning the control cylinder **82** and the control piston **85** between the synchronizer section **81** and the energy absorbing device **14**.

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 by 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.

I claim:

1. An improved, balanced free piston engine adapted to drive a variety of energy absorbing devices that include reciprocally movable input means, the improved engine comprising: housing means including a power cylinder; a power piston mounted in said power cylinder for reciprocal movement therein a direction substantially parallel to the longitudinal central axis of said power cylinder and defining an internal combustion chamber with said power cylinder; power assembly means including the power piston and means connected with the power piston and adapted to be connected with the movable means of an energy absorbing device to be driven by the engine, the components of the power assembly means, and the movable means of an energy absorbing device, being reciprocally movable together as a unit; means, associated with the power assembly means, for returning the power piston to its top-dead-center position in the power cylinder; and balancing and synchronizing means including a counter-balancing means mounted for translational movement with respect to the housing adjacent the power assembly means and between the power cylinder and the movable means of an energy absorbing device, the counter-balancing means having a preselected weight, and including means for interconnecting the power assembly means and the counter-balancing means of the balancing and synchronizing means and for reciprocally moving said counter-balancing means of the balancing and synchronizing means in a direction opposite to that of the power assembly means and through a stroke of such length that the absolute product of the weight of said counter-balancing means of the balancing and synchronizing means times the length of its stroke is substantially equal to the absolute product of the sum of the weights of the components of the power assembly means, including the movable means of an energy absorbing device, times the length of the corresponding stroke of the power assembly means.

2. The improved free piston engine described in claim **1** wherein the counter-balancing means of the balancing and synchronizing means comprises a counter-balancing movable weight.

3. The improved balanced free piston engine described in claim **2** wherein the components of the power assembly means and the balancing and synchronizing means are positioned so that their central longitudinal axes are coaxial and their paths of motion are parallel to their central longitudinal axes.

4. The improved balanced free piston engine described in claim **3** wherein the connecting means of the power assembly means includes means having first and second racks formed thereon, in back-to-back relationship, intermediate its ends; wherein said counter-balancing means of the balancing and synchronizing means includes third and fourth racks mounted thereon with the first and third racks being positioned so that the teeth of the third rack are facing the teeth of the first rack and the second and fourth racks being positioned so that the teeth of the fourth rack are facing the teeth of the second rack; wherein said interconnecting means includes first and second gears mounted for rotation on the housing between the first and third racks and the second and fourth racks, respectively, so that the teeth of the gears engage the teeth of the adjacent racks; wherein said balancing and synchronizing means is mounted so that there is no substantial sliding contact between the housing means and said balancing and synchronizing means; and wherein frame means interconnects the third and fourth racks so that there is no relative movement therebetween and so that the normal components of the forces created by the transmission of forces between the teeth of the racks and the gears are balanced.

5. The improved balanced free piston engine described in claim **4** wherein the frame means includes a pair of removable side plates which may be easily removed from the frame means so that the weight of the balancing and synchronizing means may be easily varied by replacement of these plates.

6. The improved balanced free piston engine described in claim **2** wherein the return means includes a housing having a control cylinder formed therein with the central longitudinal axis of said control cylinder being coaxial with the central longitudinal axis of the connecting means, and a control piston connected with the connecting means for reciprocation with the connecting means within said control cylinder.

7. The improved balanced free piston engine described in claim **6** wherein the connecting means of the power assembly means includes a shaft means; wherein the control piston is connected with and carried by the shaft means, intermediate the ends of the shaft means, and is separate from the movable means of an energy absorbing device; and wherein a wall closes the end of said control cylinder remote from the power piston, with the other end of said control cylinder being open.

8. The improved balanced free piston engine described in claim **7** wherein one end of the shaft means is connected with the power piston; wherein the wall closing the end of said control cylinder forms a part of the end wall of the housing means and has a central aperture formed therein through which the one end of the shaft means projects; and wherein the control means is positioned within the housing means.

9. The improved balanced free piston engine described in claim **2** wherein the connecting means of the power assembly means includes a shaft means; wherein one end of the shaft means is connected with the power piston; wherein the energy absorbing device includes a compressor which comprises: a compressor housing including a compressor cylinder; a compressor piston connected with the other end of the shaft means and mounted for reciprocal movement in said compressor cylinder, the compressor piston and compressor cylinder defining at least one compressor chamber in said compressor cylinder; and compressor inlet and outlet valve means mounted in the compressor housing for permitting the ingress and egress of gas into and from said compressor chamber.

10. The improved balanced free piston engine described in claim 9 wherein the compressor piston and the compressor cylinder define a bouncer chamber in the compressor cylinder; and wherein the compressor piston also functions as the bouncer piston in said bouncer chamber.

11. The improved balanced free piston engine described in claim 9 wherein the compressor is a double acting compressor.

12. The improved balanced free piston engine described in claim 9 wherein said shaft means has first and second racks mounted thereon, in back-to-back relationship, intermediate its ends; and wherein said counter-balancing means of the balancing and synchronizing means includes third and fourth rack means mounted thereon with the first and third racks being positioned so that the teeth of the third rack are facing the teeth of the first rack with the second and fourth racks being positioned so that the teeth of the fourth rack are facing the teeth of the second rack; wherein said interconnecting means includes first and second gears mounted for rotation on the housing between the first and third racks and the second and fourth racks, respectively, so that the teeth of the gears engage the teeth of the adjacent racks; wherein said balancing and synchronizing means is mounted so that there is no substantial sliding contact between the housing means and said balancing and sychronizing means; and wherein frame means interconnects the third and fourth racks so that there is no relative movement therebetween and so that the normal components of the forces created by the transmission of forces between the teeth of the racks and the gears are balanced.

13. The improved balanced free piston engine described in claim 12 wherein the frame means includes a pair of removable side plates which may be easily removed from the frame means so that the weight of the balancing and synchronizing means may be easily varied by replacement of these plates.

14. The improved balanced free piston engine described in claim 9 wherein the components of the power assembly means and the balancing and synchronizing means are positioned so that their central longitudinal axes are coaxial and their paths of motion are parallel to their central longitudinal axes.

15. The improved balanced free piston engine described in claim 9 wherein the return means includes a control cylinder arranged so that the central longitudinal axis of said control cylinder is coaxial with the central longitudinal axis of the shaft means and a control piston connected with the shaft means for reciprocation with the shaft means within said control cylinder.

16. The improved balanced free piston engine described in claim 15 wherein the control piston is connected with and carried by the shaft means, intermediate the ends of the shaft means, and is separate from the movable means of an energy absorbing device; and wherein a wall closes the end of said control cylinder remote from the power piston, with the other end of said control cylinder being open.

17. The improved balanced free piston engine described in claim 15 wherein one end wall of the compressor housing is adjacent to one end of the engine housing; wherein the control means is positioned adjacent the other end of the compressor housing; and wherein the shaft means includes an extension extending between the compressor piston and the control piston, the extension projecting through the other end wall of the compressor housing.

18. The improved balanced free piston engine described in claim 15 wherein the compressor piston also functions as the control piston.

19. The improved free piston engine described in claim 15 wherein the control means is positioned between the balancing and synchronizing means and the compressor and is arranged whereby the pressure therein prevents oil from the balancing and synchronizing means from leaking into the compressor.

References Cited

UNITED STATES PATENTS

2,027,877	1/1936	Pescara	230—56
2,925,072	2/1960	Schmidt	123—46

ROBERT M. WALKER, Primary Examiner