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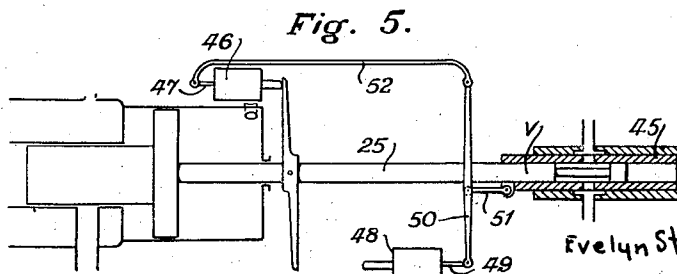
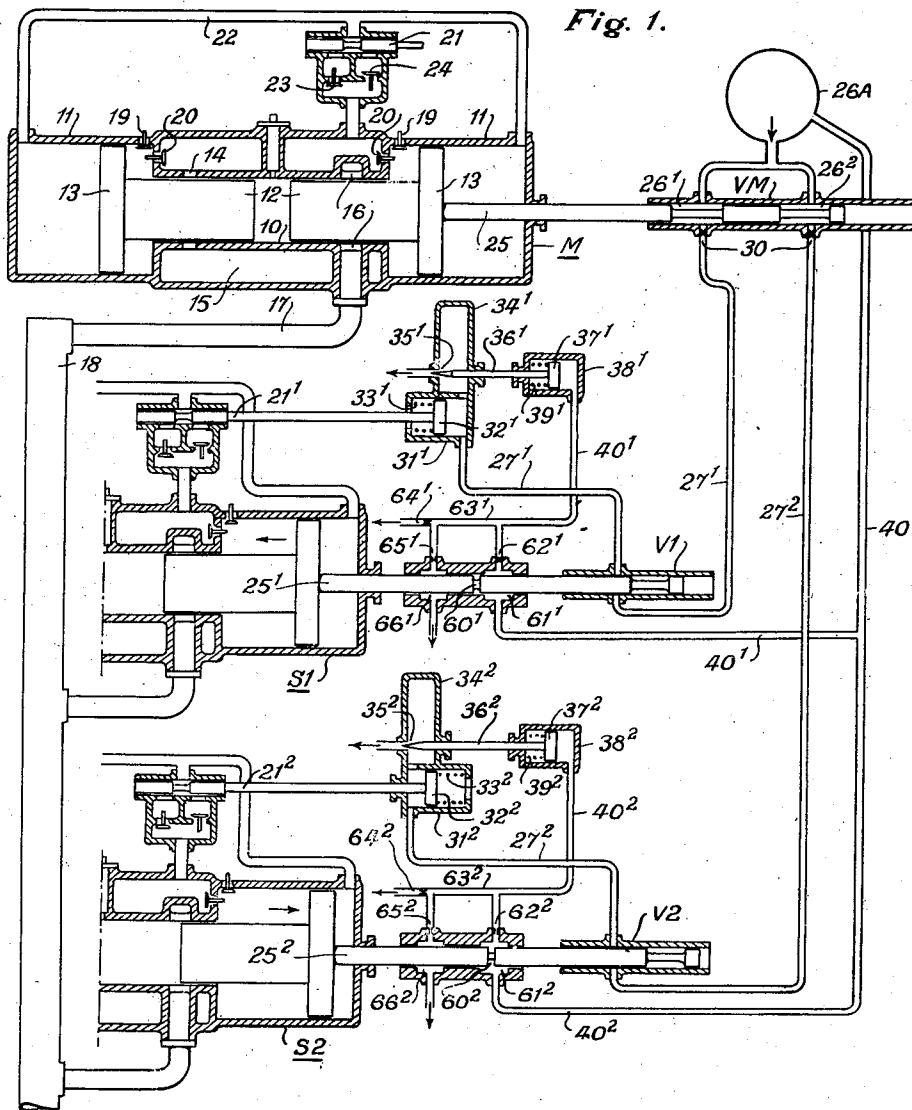
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2,408,362

OSCILLATING FLUID-DISPLACING MACHINES OPERATING IN PARALLEL

Filed Nov. 17, 1943

4 Sheets-Sheet 1



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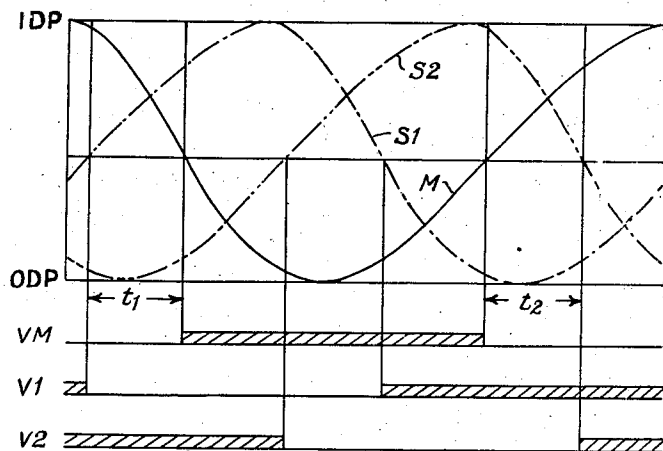


Fig. 2.

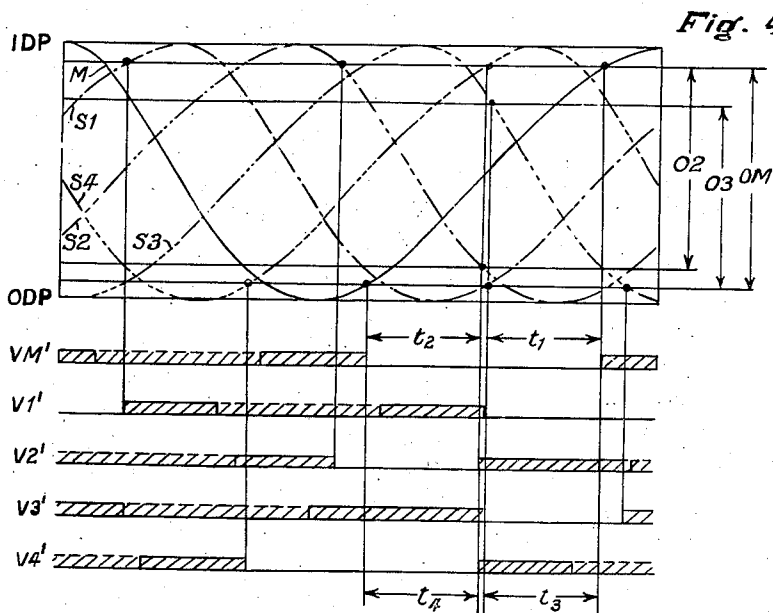


Fig. 4.

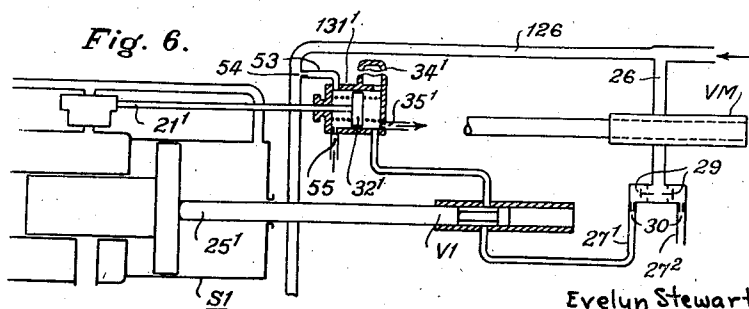


Fig. 6.

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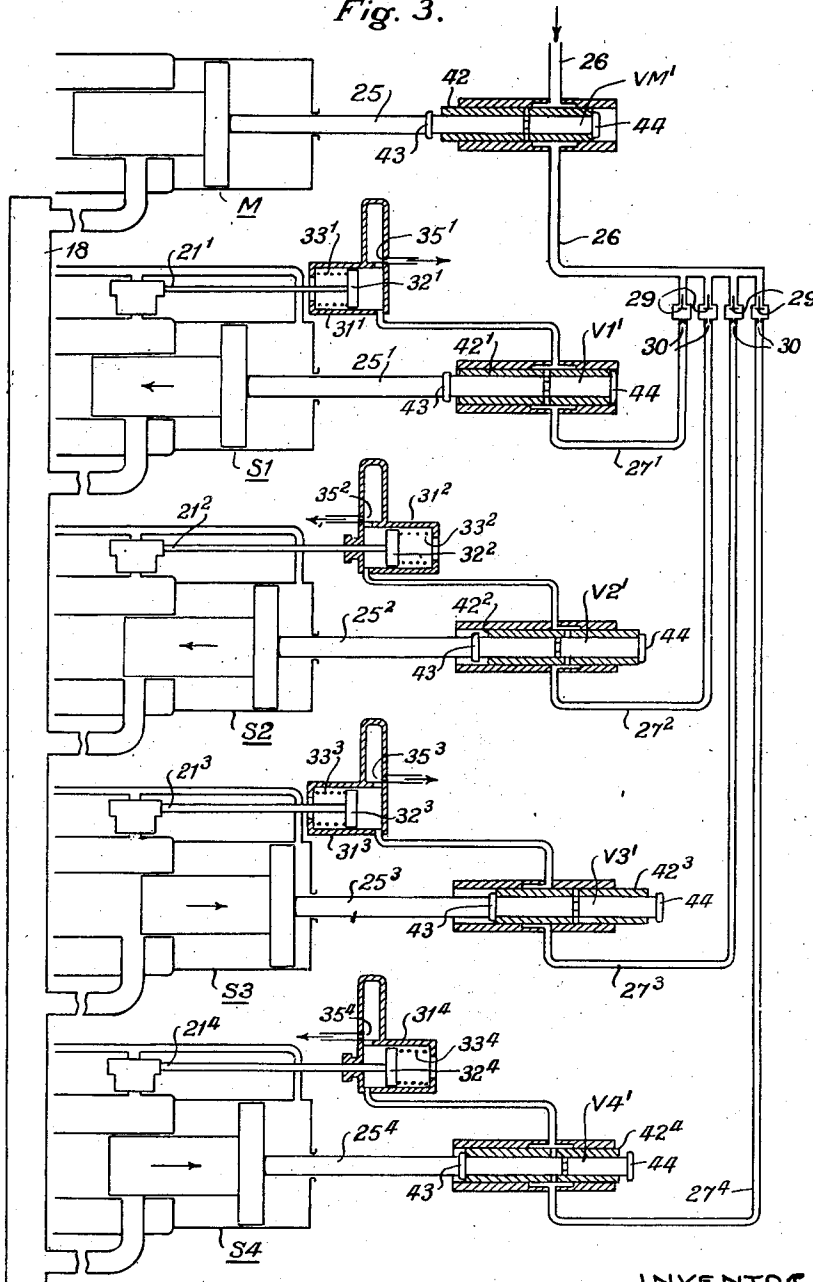
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4 Sheets-Sheet 3

Fig. 3.



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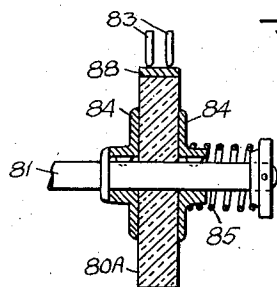
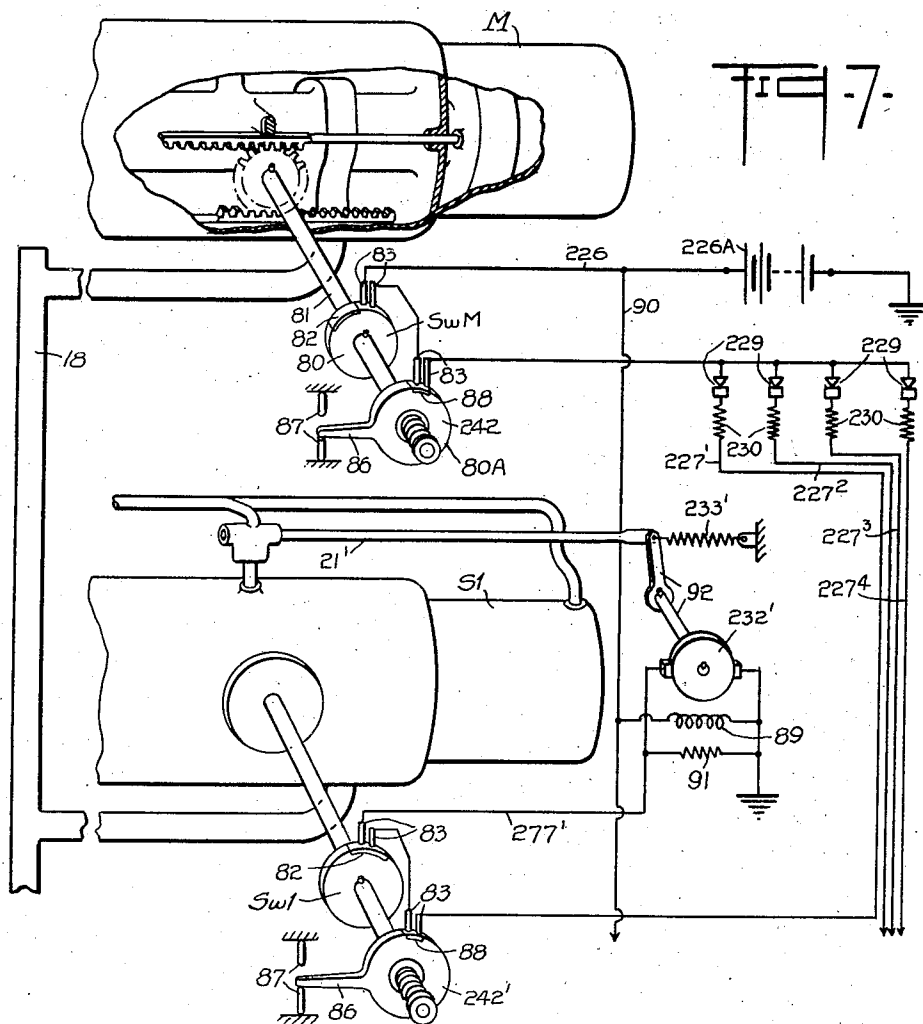
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OSCILLATING FLUID-DISPLACING MACHINES OPERATING IN PARALLEL

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4 Sheets-Sheet 4



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2,408,362

OSCILLATING FLUID-DISPLACING MACHINES OPERATING IN PARALLEL

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Application November 17, 1943, Serial No. 510,638
In Great Britain November 25, 1942

15 Claims. (Cl. 60—97)

1

This invention relates to oscillating fluid-displacing machines arranged to operate in parallel on a common main as either pumps or motors, and liable to variation in the phase-relationship of their respective oscillating fluid-displacing elements.

The invention is concerned especially, but not exclusively, with internal-combustion-operated air-compressors and motive gas generators of the free-piston type, in which the oscillating element includes a power piston and a compressor piston arranged to reciprocate in unison and unconstrained by any continuously-rotatable crankshaft, so that the period of reciprocation depends on the inertia of the free-piston assembly, the gas pressures acting on it, and the restraint due to friction and the driving of accessories.

When oscillating fluid-displacing machines are delivering fluid to or drawing fluid from a common main in parallel, the magnitude of the fluid pulsations in the main depends upon the phase-relationship of the several machines, and it is usually desirable to maintain such a phase-relationship that the fluid-pulsations in the main are minimised. An object of this invention is to provide means for automatically controlling both the magnitude and the sign of the relative phase displacement of two such parallel-operating machines. A further object is to provide improved means for automatically controlling the phase-relationship of three or more such parallel-operating machines.

According to this invention a combination of at least two oscillating fluid-displacing machines arranged to operate in parallel on a common main is provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine, a device actuated by the other of said two machines which acts as a slave, said slave device being connected to receive the interrupted flow of pressure fluid passed by said master device and serving for interrupting the flow of pressure fluid synchronously only once per cycle of said slave machine, the arrangement being such that there is normally an overlap of the non-interrupting periods of said two devices, and a controller for varying the period of oscillation of said slave machine, in response to variation in the mean rate of flow of pressure fluid passed by said two devices in series, in such a sense as to eliminate departure from

2

said intended phase relationship. "Synchronously" herein means during like portions of successive cycles of the oscillating machine concerned.

According to this invention in a further aspect, a combination of at least three oscillating fluid-displacing machines arranged to operate in parallel on a common main is provided with means for maintaining automatically a predetermined phase-relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine, two devices actuated respectively by the other two of said machines which serve as slaves, said two slave devices being connected to receive in parallel the interrupted flow of pressure fluid passed by said master device for interrupting the flow of pressure fluid synchronously only once per cycle of the respective slave machines, the arrangement being such that there is normally an overlap of the non-interrupting period of said master device with the non-interrupting period of each of said slave devices, and two controllers for varying the periods of oscillation of the respective slave machines, said controllers being responsive to the mean rate of flow of pressure fluid passed by said slave devices respectively and being so set that one of them increases, while the other decreases, the period of oscillation of its associated slave machine in response to an increase in the flow of pressure fluid passed by its associated slave device.

Thus, where three oscillating machines are combined to operate in parallel, each of said three devices may be so arranged that its non-interrupting period occurs over one of the dead points of the oscillating elements.

Where it is desired that any of said devices shall be oscillatory and that the non-interrupting period of said oscillatory device shall occur in course of the displacement of the oscillating element between its dead points, the said device may be provided with a disabling element adapted to maintain it in interrupting condition during alternate strokes, i. e. either the instrokes or the outstrokes.

The word "fluid," herein referred to as being "fluid under pressure" or "pressure fluid," means a liquid, electricity or a gas.

Where the pressure fluid is a liquid, for example oil, the interrupting devices are hydraulic. The master valve may have a plurality of separate ports arranged to feed different slave valves respectively; alternatively the master valve may

be arranged to feed a plurality of slave valves through a common valve port, the ducts connecting this common port to the respective slave valves containing non-return valves.

Where the oscillating machines are of the free-piston type, the flow-interrupting devices are conveniently arranged to oscillate with amplitudes dependent on the stroke of the associated free-piston machines, so that these amplitudes vary in dependence on the operating conditions of the machines; and in this case compensating means may be provided for reducing or eliminating the effect of variation of the ratio of the non-interrupting period to the period of oscillation consequent on variation in the operating conditions.

Each of the controllers for varying the period of oscillation of the slave machines may include a differential fluid pressure-responsive device both sides of which are connected to said source of fluid pressure.

Embodiments of the invention as applied to a group of free-piston gas-generators will be described by way of example with reference to the accompanying diagrammatic drawings, in which only those parts of the control mechanism with which this invention is concerned are shown. In the drawings:

Fig. 1 shows in section a group of three gas-generators arranged to operate in parallel,

Fig. 2 is a diagram illustrating the operation of this group,

Fig. 3 shows in section a group of five gas-generators,

Fig. 4 is a diagram illustrating the operation of the group shown in Fig. 3,

Figs. 5 and 6 show modifications of parts of Fig. 1,

Fig. 7 shows part of an arrangement equivalent to that shown in Fig. 3, and

Fig. 8 is a section of a detail of Fig. 7.

In the examples herein to be described with reference to Figs. 1 to 6 the phase control system is hydraulic, the pressure fluid employed being oil. Figs. 7 and 8 show an analogous electrical system wherein switches, resistances and electromagnetic devices take the places respectively of the piston valves, restricted orifices and fluid-pressure-responsive devices of the hydraulic systems.

In Fig. 1 the master gas-generator is denoted by M, and the two slave gas-generators by S1 and S2. The three gas-generators are similar, and each has a two-stroke power cylinder 10 coaxial with a pair of symmetrically opposed compressor cylinders 11. Two like free-piston assemblies have each a power piston 12 rigid with a compressor piston 13. These assemblies are constrained to move equally and oppositely by the usual synchronizing mechanism (not shown). The inner ends of the compressor cylinders serve as air-compressor chambers, air being drawn in through valves such as 19 during the out-strokes of the pistons and delivered through valves such as 20 during the in-strokes to a scavenge air receiver 15 from which inlet ports 14, controlled by one of the power pistons 12, open directly into the power cylinder. Exhaust ports 16, controlled by the other power piston, communicate by an exhaust pipe 17 with a motive gas receiver 18 common to all three gas-generators and supplying for example a gas turbine.

The chambers at the outer ends of the compressor cylinders serve as pneumatic energy accumulators (hereinafter called "cushions") which store energy during the out-strokes of the pistons

and return energy to them during their in-strokes. The proportions are such that, during any one working cycle, the maximum air pressure and the minimum air pressure in the cushions respectively exceeds and is less than the air pressure in the scavenge air receiver 15, which is substantially equal to the delivery pressure of the motive gas in the receiver 18. The air content of the cushions can be varied by a control valve 21, adapted when in the neutral position shown to seal a balance pipe 22 connecting the two cushions. The valve 21, when moved to the left of the neutral position, puts the cushions into communication with the scavenge air receiver 15 through a non-return valve 23 which allows air to pass only from the cushions to the receiver, which will occur during that part of each cycle when the cushion pressure exceeds the receiver pressure. When the valve 21 is moved to the right from its neutral position, it connects the cushions to the receiver 15 through a non-return valve 24 which allows air to pass only from the receiver to the cushions, which will occur during that part of each cycle when the cushion pressure is lower than the receiver pressure. In such a gas-generator the periodic time of a cycle can be reduced by increasing the quantity of air contained in the cushions. Consequently movement of the valve 21 to the left and right respectively will gradually reduce and increase respectively the cyclical speed of the gas-generator. The free-piston assemblies of the master gas-generator M operate synchronously a hydraulic valve VM, shown diagrammatically as a piston valve the piston of which is formed on a tail rod 25 of one of the free-piston assemblies. This valve has two similar sets of ports 26¹ and 26² operating in parallel and arranged to remain open during a part of each cycle when the free-pistons are approaching, passing through and receding from their inner dead point and to remain closed during the rest of the cycle including the outer dead point. The slave gas-generators S1 and S2 are provided with hydraulic valves V1 and V2 similar to the valve VM, except that each has only one set of ports. The two sets of ports 26¹ and 26² of the master valve VM control respectively the flow of oil in two pipes 27¹ and 27² which branch from a source 28A of oil at constant pressure. The two branches 27¹ and 27² are also controlled respectively by the two slave valves V1 and V2. Each branch includes a metering orifice 30.

The branch 27¹ terminates in a cylinder 31¹ containing a piston 32¹ loaded by a spring 33¹. The piston 32¹ is connected to the cushion air control valve 21¹ of the slave gas-generator S1, the arrangement being such that the spring 33¹ biases the valve 21¹ towards the position in which it causes the speed of the gas-generator S1 to increase, while the oil pressure in the cylinder 31¹ urges the valve 21¹ in the opposite direction. The cylinder 31¹ communicates with an air-column chamber 34¹ and with a leakage orifice 35¹.

The branch 27² terminates in a cylinder 31² containing a piston 32² connected to the cushion air control valve 21² of the slave gas-generator S2. The piston 32² is loaded by a spring 33² which biases the valve 21² towards the position in which it causes the speed of the gas-generator S2 to decrease, while the oil pressure in the cylinder 31² urges the valve 21² in the opposite direction. The cylinder 31² communicates with an air-column chamber 34² and with a leakage orifice 35². The frequency-regulating means of the slave gas-generator S2 are thus arranged to operate in the

5

opposite sense to the frequency-regulating means of the slave gas-generator S1.

The operation of this plant will be described with reference to Fig. 2, which shows, on a base of time, in the upper part of the figure the displacements of the free-pistons of the gas-generators, and in the lower part, by the shaded rectangles the period during which the valves VM, V1 and V2 are closed, the length of the time base being exactly the periodic time of the cycle. When the three gas-generators are running at constant cyclical speed, with a phase displacement of one-third of a cycle as shown, which condition may be initially established by manual control, the period during which the master valve VM is open overlaps by the equal intervals t_1 and t_2 the periods during which the slave valves V1 and V2 are open respectively. The flow capacities of the orifices 30, 35¹ and 35² are so selected, in relation to the pressures exerted by the springs 33¹ and 33² and to the ratio of the intervals t_1 and t_2 to the periodic time of the cycle, that the quantity of oil that flows into each of the cylinders 31¹ and 31² during one such interval is sufficient to replace the quantity that escapes through the leakage orifices 35¹ and 35² during one complete cycle. The air columns 34¹ and 34² compensate for the pulsating admission of oil so that the pistons 32¹ and 32² remain substantially stationary, their mean positions being as shown.

Now if the slave gas-generator S2, which is leading the master gas-generator M by one-third of a cycle in phase, tends to run for example slow, the interval of overlap t_2 between the non-interrupting periods of its valve V2 and the master valve VM increases, and the resulting increased admission of pressure oil to the cylinder 31² causes the valve 21² to be moved to the right so that the gas-generator S2 is speeded up. If the slave gas-generator S1, which is lagging the master gas-generator by one third of a cycle in phase, tends to run for example slow, the valve overlap interval t_1 decreases, and the resulting decreased admission of pressure oil to the cylinder 31¹ causes the valve 21¹ to be moved to the right so that the gas-generator S1 is speeded up.

As regulation of the power output or delivery pressure of any of the gas-generators may cause a variation of the outer and inner dead points of its free pistons, if the oil pressure line control valve is operated, as in the example shown in Fig. 1, by a member moving proportionally to the displacement of the free pistons, the ratio of the valve overlap interval to the duration of a cycle will vary with variation of load on the gas-generator. In some circumstances, and with a careful choice of fixed opening positions of the valve ports, the irregularity in phase relationship, due to regulation of the power output or delivery pressure of the gas-generator, can be kept within tolerable limits. Nevertheless, in other circumstances, it may be necessary to provide the phase-controlling mechanism with means adapted to compensate for variation in load on the gas-generator. In Fig. 1 is shown one possible compensating arrangement which serves to vary the ratio of the effective areas of the metering orifice 30 and the leakage orifice 35¹ or 35². The areas of the leakage orifices are controlled by needles 36¹ and 36² rigid with pistons 37¹ and 37² which work in cylinders 38¹ and 38² and are biased by springs 39¹ and 39² in such a direction as to increase the leakage area. Pipes 40¹

6

and 40² branch from a pipe 40 connected to the source 26A of oil under constant pressure and lead to the cylinders 38¹ and 38² so as to admit oil which urges the pistons 37¹ and 37² in such a direction as to decrease the area of the leakage orifices 35¹ and 35². The tail rods 25¹ and 25² are provided with piston valve chambers 60¹ and 60² which, while the free pistons of the associated gas-generator are passing through their outer dead point, open valve ports 61¹ and 61² controlling the pipes 40¹ and 40², the opening period increasing as the outer dead point increases (i. e. recedes from the middle of the gas-generator). Metering orifices 62¹ and 62² are arranged in series with the valve ports 61¹ and 61² respectively. Pipes 63¹ and 63² branch from the pipes 40¹ and 40² downstream of the valve ports and metering orifices just described and lead directly to restricted leakage orifices 64¹ and 64² and also through metering orifices 65¹ and 65² to valve ports 66¹ and 66² forming additional leakage paths and controlled by the piston valve chambers 60¹ and 60² in such a manner that the additional leakage paths are open while the free pistons of the associated gas-generators are passing through their inner dead point, the opening period decreasing as the inner dead point increases (i. e. recedes from the middle of the gas-generator).

The effect on the opening period of the slave valve V1 or V2 of a change in inner dead point is not the same as that of the same change in outer dead point, and furthermore the effect of a change in inner dead point is different according to the nature of the change in the operating conditions of the gas-generator. The leakage orifices 64¹ and 64² are of such a capacity as to provide the best compromise for the inner dead point.

Fig. 3 shows phase-controlling gear for a group of five gas-generators M, S1, S2, S3 and S4 similar to the gas-generators shown in Fig. 1. Like parts in these two figures are denoted by the same reference numerals, the two plants being generally similar in arrangement, except for the following differences.

The master valve VM' has only one set of ports common to all the branches to the slave valves, and each of these branches is provided with a non-return valve 29 permitting oil to flow only in the direction from the master valve towards the slave valve and serving to prevent any flow of oil between the cylinders 31¹, 31² etc. during intervals of overlap of the non-interrupting periods of the slave valves.

Furthermore, the master and slave piston valves VM', V1', V2', V3' and V4' which move in synchronism with the free pistons of the associated gas-generators, are arranged to open while the free pistons are passing through a part of their stroke intermediate between the inner and outer dead points, and in order to obviate the ambiguity in phase that would result if the valves opened and closed twice per cycle, they are provided with ported disabling sleeves 42, 42¹, 42², 42³ and 42⁴ which are fitted between the valve piston and the valve body and which mask the ports during alternate strokes. These sleeves are driven by collars 43 and 44 on the valve pistons arranged to provide the appropriate degree of backlash.

In the present example the duration of the outstroke of the free pistons is about three-quarters of that of their in-stroke, and the four slave gas-generators are arranged to lead the

master gas-generator respectively by phase displacements which increase by equal increments from gas-generator S4 to gas-generator S1, as shown in the upper part of Fig. 4 which shows, on a base of time, the displacements of the free pistons. The valves VM', V1' and V4' are arranged to be masked on the out-strokes, while the valves V2' and V3' are masked on the in-strokes. The lower part of Fig. 4 shows by the shaded rectangles the times during which the valves are closed, the dotted horizontal lines denoting the times during which the valve ports are masked by the disabling sleeves. The non-interrupting periods of the individual valves are shown in the upper part of Fig. 4 where OM denotes this period for each of the valves VM', V1' and V4', O2 the period for the valve V2', and O3 that for the valve V3'.

When the gas-generators are running at a constant speed with their intended phase relationship, the periods of overlap of opening of the master valve VM' and of the slave valves V1', V2', V3' and V4' are those denoted by t_1 , t_2 , t_3 and t_4 in Fig. 4. Lagging of the slave gas-generators S1 and S3 will cause the periods t_1 and t_3 to decrease and consequently the cylinders 31¹ and 31³ are so arranged that a reduction in the quantity of oil supplied to them through the piston valves causes the pistons 32¹ and 32³ to operate the cushion control valves 21¹ and 21³ in such a sense as to speed up the gas-generators S1 and S3. If, however, the gas-generators S2 and S4 lag, the periods t_2 and t_4 increase, and the cylinders 31² and 31⁴ are set to operate oppositely to the cylinders 31¹ and 31³, so that an increase in the quantity of oil supplied to the cylinders 31² and 31⁴ causes the gas-generators S2 and S4 to be speeded up.

It will thus be apparent that such a combination of five gas-generators is constituted by two groups of three gas-generators each of which groups is arranged similarly to that shown in Fig. 1, and which have however a common master gas-generator, the non-interrupting periods of the slave devices of one group differing from the non-interrupting periods of the slave devices of the other group in such a manner that the phase differences of the five machines are substantially uniform.

When it is desired to maintain a substantially constant phase displacement when the power output or the working pressure of a group of units is varied, the opening period of the phasing valve may be varied in accordance with variation in the inner dead point or the outer dead point or both of these points of the free-piston assembly. This result may be attained by providing piston-type phasing valves with ported sleeves controlled by spring-loaded pistons working in cylinders supplied with pressure fluid in the same way as the cylinders 33¹ and 33² in Fig. 1. Alternatively the ported sleeves of the phasing valves may be controlled by dead-point followers, and these sleeves may be actuated by a linkage so arranged that the opening or closing of the phasing ports occurs at a constant percentage of the free-piston stroke. With phasing ports arranged to be open over a dead point, the valve opening or cut-off point may be displaced through the agency of a floating lever in accordance with the weighted mean of the inner and the outer dead points. With phasing ports having an opening period lying between the inner and the outer dead points, the opening or the cut-off points may be similarly displaced in accordance with suitably weighted

means; a simple but approximate compensation for such ports is to displace each cut-off point independently by inner and outer dead-point followers respectively, so as to maintain them at fixed distances from the dead points.

Fig. 5 shows a compensating mechanism applicable to each of the valves of the plant shown in Fig. 1. The phasing valve, here denoted by V, is provided with a ported sleeve 45, the position of which determines the beginning of the non-interrupting period. An inner dead point follower 46, of the kind described in application Serial No. 492,865, filed June 30, 1943, has a connecting member 47 the position of which corresponds to the inner dead point of the free pistons. A similar outer dead point follower 48 has a connecting member 49 the position of which corresponds to the outer dead point of the free pistons. One end of a floating lever 50 is pivotally connected to the connecting member 49 and its other end is coupled by a link 52 to the connecting member 47. An intermediate point on the floating lever is coupled by a link 51 to the valve sleeve 45. The ratio of the arms of the lever 50 above and below the link 51 is so selected that the opening point of the valve is displaced in accordance with the weighted mean of the inner and outer dead points.

The fluid-pressure-responsive devices that operate the cushion air control valves may be of the differential type arranged to balance two hydraulic pressures, instead of being spring controlled as in the examples hereinbefore described. Fig. 6 shows a part of a plant similar to that shown in Fig. 1, except that such a balanced system is used, the means for compensating for variation in load on the gas-generators are omitted, and a master valve VM having one set of ports common to both branches 27¹ and 27² is used, these branches having non-return valves 29. Corresponding parts in Figs. 1 and 6 have the same reference numerals.

In Fig. 6 the fluid-pressure-responsive device that operates the cushion air control valve 21¹ of the slave gas-generator S1 is a cylinder 131¹ containing the piston 32¹, which is spring biased to its central position. The right-hand end of this cylinder is supplied with oil in exactly the same way as the right-hand end of the cylinder 31¹ in Fig. 1, through the valves VM and V1. The left-hand end of the cylinder 131¹ is provided with a restricted leakage orifice 55 and is connected by a branch pipe 53, which contains a metering orifice 54, to a pipe 126 communicating with the source of oil under pressure that supplies the master phasing valve VM. When the master and slave machines are running in the correct phase relationship, the force tending to move the piston 32¹ to the right due to the oil pressure in the left-hand end of the cylinder 131¹ balances the mean force acting on the right hand face of this piston due to the pressure of the oil passed by the phasing valves VM and V1.

This balanced system has the advantage that it is unaffected by accidental variations in the pressure of the oil supplied to the pipe 26.

In order to avoid irregularity in operation of such hydraulic phase-control mechanisms due to variation in viscosity of the pressure liquid, which is conveniently lubricating oil, the said metering orifices and leakage orifices should be so designed that the resistance which they impose to the flow of liquid is substantially proportional to the viscosity of the liquid, that is

to say, they should provide a streamline flow with only small kinetic energy effects. Thus the metering orifices and the leakage orifices will be similarly affected by changes in viscosity.

A large battery of gas-generators may be conveniently and simply phased in two or more groups of two or four slave gas-generators, all the groups having a common master gas-generator. In special cases, it is possible to control, in accordance with this invention, the phase-relationships of the master generators of two or more separate phase-controlled batteries.

As hereinbefore mentioned, an electrical system may be used in place of a hydraulic system, and the analogy between the two will be illustrated by reference to Figs. 7 and 8, which are comparable with Fig. 3. The pipe 26 of Fig. 3 is replaced by a lead 226 to one terminal of a current source, 226A, the other terminal of which is grounded. The hydraulic valves VM' and V1' to V4' are replaced respectively by electrical switches SwM, Sw1, etc. operatively connected with the free pistons of the gas-generators. Where the gas-generators are, as shown, of the usual opposed-piston type, each switch is conveniently formed by a ring 80 of insulating material fast on the oscillatory shaft 81 of the piston synchronising mechanism, each ring having a conducting segment 82 co-operating with a pair of brushes 83. The synchronising mechanism shown in Fig. 7 is of the known rack-and-pinion type, so arranged that the maximum amplitude of oscillation of the shaft 81 is substantially less than 360°.

The sleeves 42 and 42¹ to 42⁴ of Fig. 3 are replaced by switches 242, 242¹ etc., which are generally similar to the rotary switches SwM, etc., but in which the ring 80A is drivably connected to the shaft 81 by friction disks 84 (Fig. 8) loaded by a compression spring 85, and have a range of displacement, which is limited by an arm 86 co-operating with stops 87, between the "on" and "off" positions of the segment 88.

The branch pipes 27¹ to 27⁴ of Fig. 3 are replaced by branch leads 227¹ and 227⁴ respectively, each including a rectifier 229 and a resistor 230, replacing the non-return valves 29 and the orifices 30 of Fig. 3. The cylinder and piston devices of Fig. 3 actuating the air-transfer valves 21¹ to 21⁴ are replaced by spring-biased electromagnetic devices energized from the appropriate branch lead 227¹, 227², etc., through the appropriate pair of switches 242¹ and Sw1, etc. Such a device in its simplest form would be a solenoid having a spring-loaded armature adapted to take up a position dependent on the mean value of the unidirectional current passing through its exciting winding. In practice it is more convenient to use torque motors, one of which appears in Fig. 7. The motor is of the direct-current type and its armature 232¹ is connected between ground and the respective branch lead 277¹. Its field winding 89 is separately energised through a conductor 90 leading directly to the ungrounded side of the current source 226A. A resistor 91 may be shunted across the armature in order to reduce sparking at the contacts of the rotary switches. The armature 232¹ is coupled by a suitable transmission, indicated diagrammatically at 92, to the transfer valve 21¹ and the biasing spring 233¹. In practice the efficiency of the electromagnetic devices will usually be so low that, when they operate as generators, their output will be negligible; thus the rectifiers 229 can be omitted.

I claim:

1. A combination of at least two oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine, a device actuated by the other of said two machines which acts as a slave, said slave device being connected to receive the interrupted flow of pressure fluid passed by said master device and serving for interrupting the flow of pressure fluid synchronously only once per cycle of said slave machine, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two devices, and a controller for varying the period of oscillation of said slave machine, in response to variation in the mean rate of flow of pressure fluid passed by said two devices in series, in such a sense as to eliminate departure from said predetermined phase relationship.

2. A combination of at least three oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine, two devices, actuated respectively by the other two of said machines which act as slaves, said two slave devices being connected to receive in parallel the interrupted flow of pressure fluid passed by said master device for interrupting the flow of pressure fluid synchronously only once per cycle of the respective slave machines, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap of the non-interrupting periods of said master device with the non-interrupting periods of each of said slave devices, and two controllers for varying the periods of oscillation of the respective slave machines, said controllers being responsive to variation in the mean rate of flow of pressure fluid passed by said slave devices respectively and being so set that one of them increases, while the other decreases, the period of oscillation of its associated slave machine in response to an increase in the flow of pressure fluid passed by its associated slave device.

3. A combination of at least two oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously with the operation of said master machine, a device actuated by the other of said two machines which acts as a slave, said slave device being connected to receive the interrupted flow of pressure fluid passed by said master device and serving for interrupting the flow of pressure fluid synchronously with the operation of said slave machine, the non-interrupting period of each of said devices occurring over only one of the dead points of the asso-

ciated oscillatory machine, and the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two devices, and a controller for varying the period of oscillation of said slave machine, in response to variation in the mean rate of flow of pressure fluid passed by said two devices in series, in such a sense as to eliminate departure from said predetermined phase relationship.

4. A combination of at least three oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously with the operation of said master machine, two devices, actuated respectively by the other two of said machines which act as slaves, said two slave devices being connected to receive in parallel the interrupted flow of pressure fluid passed by said master device for interrupting the flow of pressure fluid synchronously with the operation of the respective slave machines; the non-interrupting period of each of said devices occurring over only one of the dead points of the associated oscillatory machine; and the arrangement being such that, when said predetermined phase relationship exists, there is an overlap of the non-interrupting periods of said master device with the non-interrupting periods of each of said slave devices; and two controllers for varying the periods of oscillation of the respective slave machines, said controllers being responsive to variation in the mean rate of flow of pressure fluid passed by said slave devices respectively and being so set that one of them increases, while the other decreases, the period of oscillation of its associated slave machine in response to an increase in the flow of pressure fluid passed by its associated slave device.

5. A combination of at least two oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine; a device actuated by the other of said two machines which acts as a slave, said slave device being connected to receive the interrupted flow of pressure fluid passed by said master device and serving for interrupting the flow of pressure fluid synchronously only once per cycle of said slave machine; at least one of said devices being oscillatory; the non-interrupting period of said oscillatory device occurring in course of the motion of the associated oscillatory machine between its dead points, a disabling element associated with said oscillatory device for maintaining it in interrupting condition during alternate strokes, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two devices, and a controller for varying the period of oscillation of said slave machine, in response to variation in the mean rate of flow of pressure fluid passed by said two devices in series, in such a sense as to elimi-

nate departure from said predetermined phase relationship.

6. A combination of at least five oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of pressure fluid synchronously with the operation of said master machine, four devices, actuated respectively by the other four of said machines which act as slaves, said four devices being connected to receive flows of pressure fluid interrupted by said master device and serving again to interrupt said flows of pressure fluid synchronously with the operation of the respective slave machines, said five devices being oscillatory with their non-interrupting periods occurring in course of the motion of the associated oscillatory machine between its dead points, five disabling elements associated with said five devices respectively for eliminating non-interrupting periods on alternate strokes, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap of the non-interrupting periods of said master device with the non-interrupting periods of each of said slave devices; and four controllers for varying the periods of oscillation of the respective slave machines in response to variation in the mean rate of flow of pressure fluid passed by the respective slave devices, a first pair of said controllers being so set that they increase the periods of oscillation of the associated first pair of said slave machines in response to increase in the flows of pressure fluid passed by the associated first pair of said slave devices, the second pair of said controllers being so set that they decrease the periods of oscillation of the associated second pair of said slave machines in response to increase in the flows of pressure fluid passed by the associated second pair of said slave devices, and the overlap of the non-interrupting period of one device of each of said pairs with that of said master device occurring during like strokes of the master and slave, while the overlap of the non-interrupting period of the other device of each of said pairs with that of said master device occurs during opposite strokes of the master and slave.

7. A combination of at least three oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of liquid under pressure, a hydraulic valve actuated by one of said machines which serves as a master and having two ports for delivering two separate flows of said liquid, each interrupted synchronously once per cycle of said master machine, two hydraulic valves actuated respectively by the other two of said machines, which act as slaves, said two slave valves being connected to receive the interrupted flows of liquid delivered by said two ports respectively of the master valve and serving to interrupt the flow of liquid synchronously only once per cycle of the respective slave machines, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap of the non-interrupting periods of said master valve with the non-interrupting periods of each of said slave valves, and two controllers for varying the periods of oscillation of the respective

13

slave machines, said controllers being responsive to variation in the mean rate of flow of pressure liquid passed by said slave valves respectively, in such a sense as to eliminate departure from said predetermined phase relationship.

8. A combination of at least three oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of liquid under pressure, a hydraulic valve actuated by one of said machines which serves as a master and having a port for delivering a flow of said liquid interrupted synchronously once per cycle of said master machine, two hydraulic valves actuated respectively by the other two of said machines, which act as slaves, said two valves being connected to receive in parallel the flow of liquid delivered from said port and serving to interrupt the flow of liquid synchronously only once per cycle of the respective slave machines, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap of the non-interrupting periods of said master valve with the non-interrupting periods of each of said slave valves, and two controllers for varying the periods of oscillation of the respective slave machines, said controllers being responsive to variation in the mean rate of flow of pressure liquid passed by said slave valves respectively, in such a sense as to eliminate departure from said predetermined phase relationship.

9. A combination of at least two free-piston fluid-displacing machines arranged to operate on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a fluid path connected with said source and including two devices arranged in series in said path and actuated respectively by said machines for interrupting the flow of pressure fluid in said path synchronously with the operation of said machines respectively, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two devices, a controller for varying the period of oscillation of one of said machines, in response to variation in the mean rate of flow of pressure fluid along said path, in such a sense as to eliminate departure from said predetermined phase relationship, said devices having oscillatory elements arranged to oscillate with amplitudes varying with variation in the length of the free-piston strokes of said machines, and means for at least reducing automatically the effect of variation of the ratio of the non-interrupting period of each of said devices to its period of oscillation consequent on variation in the free-piston stroke of the associated machine.

10. A combination of at least two free-piston fluid-displacing machines arranged to operate on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of liquid under pressure, a duct connected with said source and including two hydraulic valves arranged in series in said duct and actuated respectively by said machines for interrupting the flow of liquid in said duct synchronously with the operation of said machines respectively, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting

14

periods of said two valves, a controller for varying the period of oscillation of one of said machines which acts as a slave, said controller including a hydraulic fluid-pressure-responsive device connected to be supplied with liquid by said duct and through a metering port and to discharge liquid through a leakage port, said controller acting to eliminate departure from said predetermined phase relationship, and said valve actuated by said slave machine having an oscillatory element arranged to oscillate with an amplitude varying with variation in the length of the free-piston strokes of said slave machine, and means responsive to variation of the ratio of the non-interrupting period of the said valve actuated by said slave machine to its period of oscillation for varying the ratio of the flow capacities of said ports so as to compensate at least in part for variation in said free-piston stroke.

11. A free-piston fluid-displacing machine intended for operation in predetermined phase relationship in parallel with other like machines on a common main and having a controller for varying the period of oscillation of its free pistons, means for conducting a variable supply of fluid under pressure for actuating said controller, and a device having an oscillatory member connected for movement in synchronism with said free pistons and serving to interrupt synchronously the flow of pressure fluid through said conducting means, and means for adjusting the non-interrupting period of said device automatically in response to variation in at least one of the dead points of said free pistons so as at least to reduce the effect of variation of the length of the free-piston stroke on the ratio of said non-interrupting period to the period of oscillation of said free pistons.

12. A free-piston fluid-displacing machine intended for operation in predetermined phase relationship in parallel with other like machines on a common main and having a controller for varying the period of oscillation of its free pistons, said controller including a hydraulic actuating device responsive to variation in mean rate of flow of liquid thereto, a duct for admitting liquid to said actuating device and including a valve having an oscillatory member connected for movement in synchronism with said free pistons, and means for adjusting the non-interrupting period of said valve automatically in response to variation in at least one of the dead points of said free pistons so as at least to reduce the effect of variation of the length of the free-piston stroke on the ratio of said non-interrupting period to the period of oscillation of said free pistons.

13. A combination of at least two oscillatory fluid-displacing machines arranged to operate in parallel on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of fluid under pressure, a device actuated by one of said machines which serves as a master for interrupting the flow of said pressure fluid synchronously only once per cycle of said master machine, a device actuated by the other of said two machines which acts as a slave, said slave device being connected to receive the interrupted flow of pressure fluid passed by said master device and serving for interrupting the flow of pressure fluid synchronously only once per cycle of said slave machine, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two devices,

15

and a controller for varying the period of oscillation of said slave machine, in response to variation in the mean rate of flow of pressure fluid passed by said two devices in series, in such a sense as to eliminate departure from said predetermined phase relationship, said controller including a differential fluid-pressure-responsive actuating device both sides of which are connected to said source of fluid pressure.

14. A combination of at least two free-piston fluid-displacing machines arranged to operate on a common main and provided with means for maintaining automatically a predetermined phase relationship between them, said means including a source of liquid under pressure, a duct connected with said source and including two hydraulic valves arranged in series in said duct and actuated, respectively, by said machines for interrupting the flow of liquid in said duct synchronously with the operation of said machines respectively, the arrangement being such that, when said predetermined phase relationship exists, there is an overlap between the non-interrupting periods of said two valves, a controller for varying the period of oscillation of one of said machines which acts as a slave, said controller including a differential hydraulic pressure-responsive device one side of which is connected to be supplied with liquid by said duct and through a metering port and to discharge liquid

16

through a leakage port, while the other side of said device is connected to be supplied with liquid from said source through a metering port independently of said duct and to discharge liquid through a leakage port, said controller being set to eliminate departure from said predetermined phase relationship.

15. At least two internal-combustion-operated gas-generators of the free-piston type connected to deliver gas to a common main, in combination with means for maintaining them in predetermined phase relationship, each of said two gas-generators having a speed-controller, a pressure fluid circuit for actuating said controller and a device for interrupting said circuit synchronously once per cycle of the associated gas-generator, and a master device capable of interrupting each of said circuits synchronously at a predetermined frequency, the arrangement being such that, when said gas-generators are maintained in said predetermined phase relationship, there are overlaps between the non-interrupting periods of said master device and of each of said slave devices, variation of said overlaps due to departure of said gas-generators from said predetermined phase relationship causing variation of the mean rates of flow of fluid in said circuits and speed-correcting actuation of said controllers;

30. EVELYN STEWART LANSDOWNE BEALE.