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Gladden

[11] **3,781,140**

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[54] **SYNCHRONOUS RECIPROCATING ELECTRODYNAMIC COMPRESSOR SYSTEM**

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[52] **U.S. Cl.** **417/326,** 417/417, 310/27

[51] **Int. Cl.** **F04b 35/04**

[58] **Field of Search** 417/416, 417, 418, 417/326, 444, 562; 310/27

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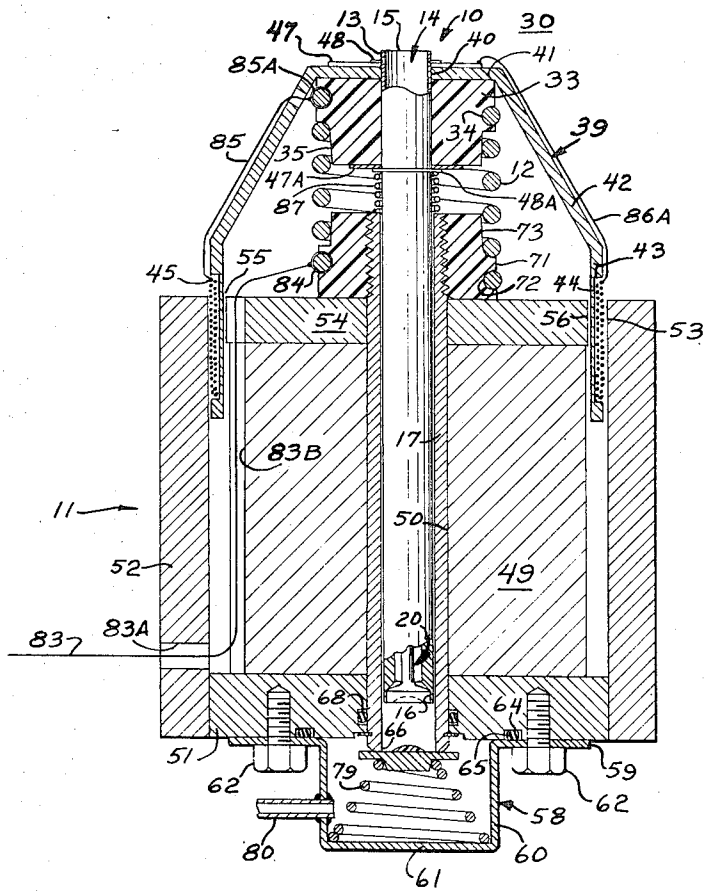
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[57] **ABSTRACT**

An electrodynamic compressor includes an electrical coil mounted for reciprocation in a magnetic field. A piston is connected to the coil for reciprocation with it. A resonance spring resiliently supports the coil and piston in a rest position. An electrical pulse of predetermined duration energizes the coil, and causes a magnetic force to be exerted on it thereby moving the piston to compress fluid and storing energy in the spring. As the piston nears the end of the compression cycle, the pulse is terminated and the piston and coil are returned under action of the spring. When the piston reaches the end of its return cycle, a circuit sensing the self-induced voltage in the coil energizes the coil as it again commences a compression cycle. As the load varies, the period between adjacent electrical signals also varies and remains synchronous with the cycle time of the mechanical reciprocating system so that the period of the electrical signal is always equal to the period of the natural oscillating frequency of the mechanical system.

9 Claims, 5 Drawing Figures



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Fig. 1

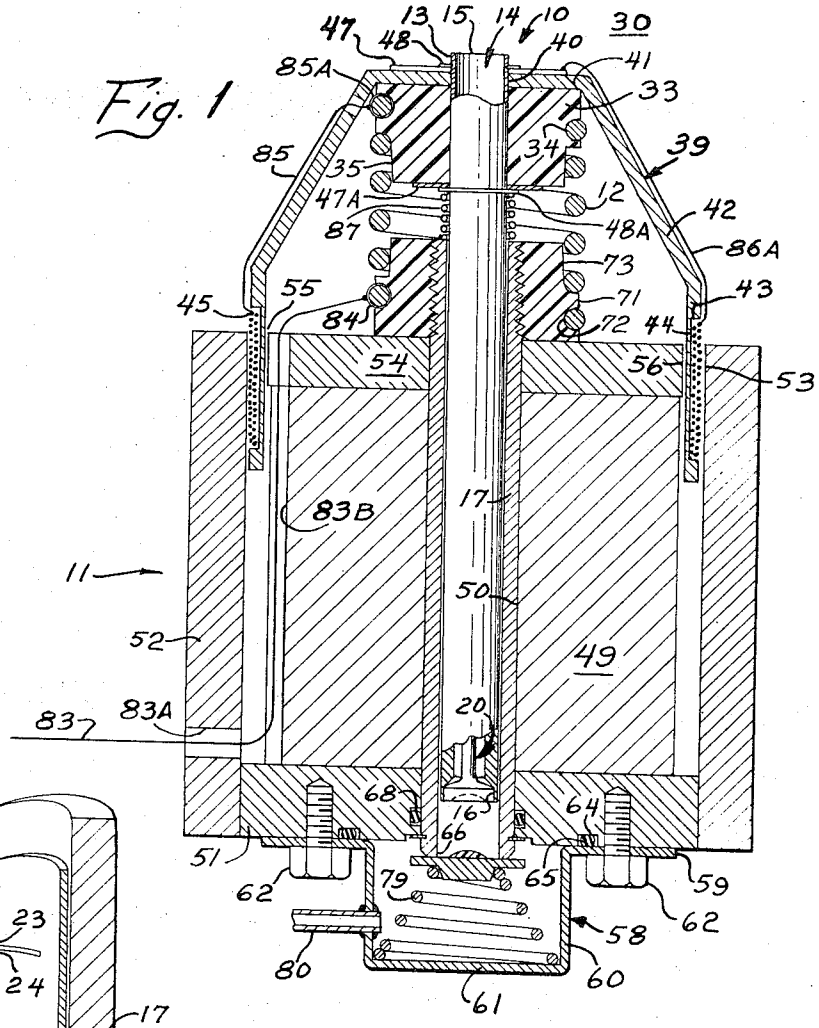
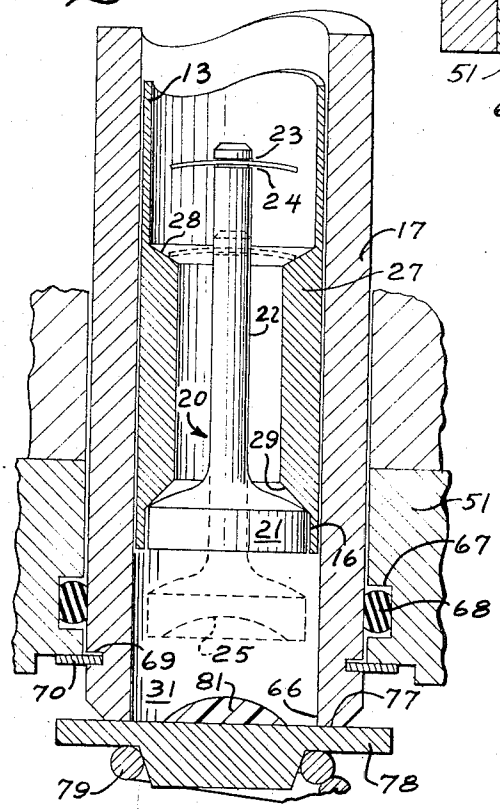


Fig. 2



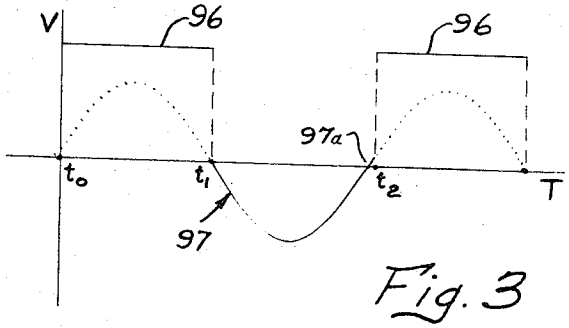


Fig. 3

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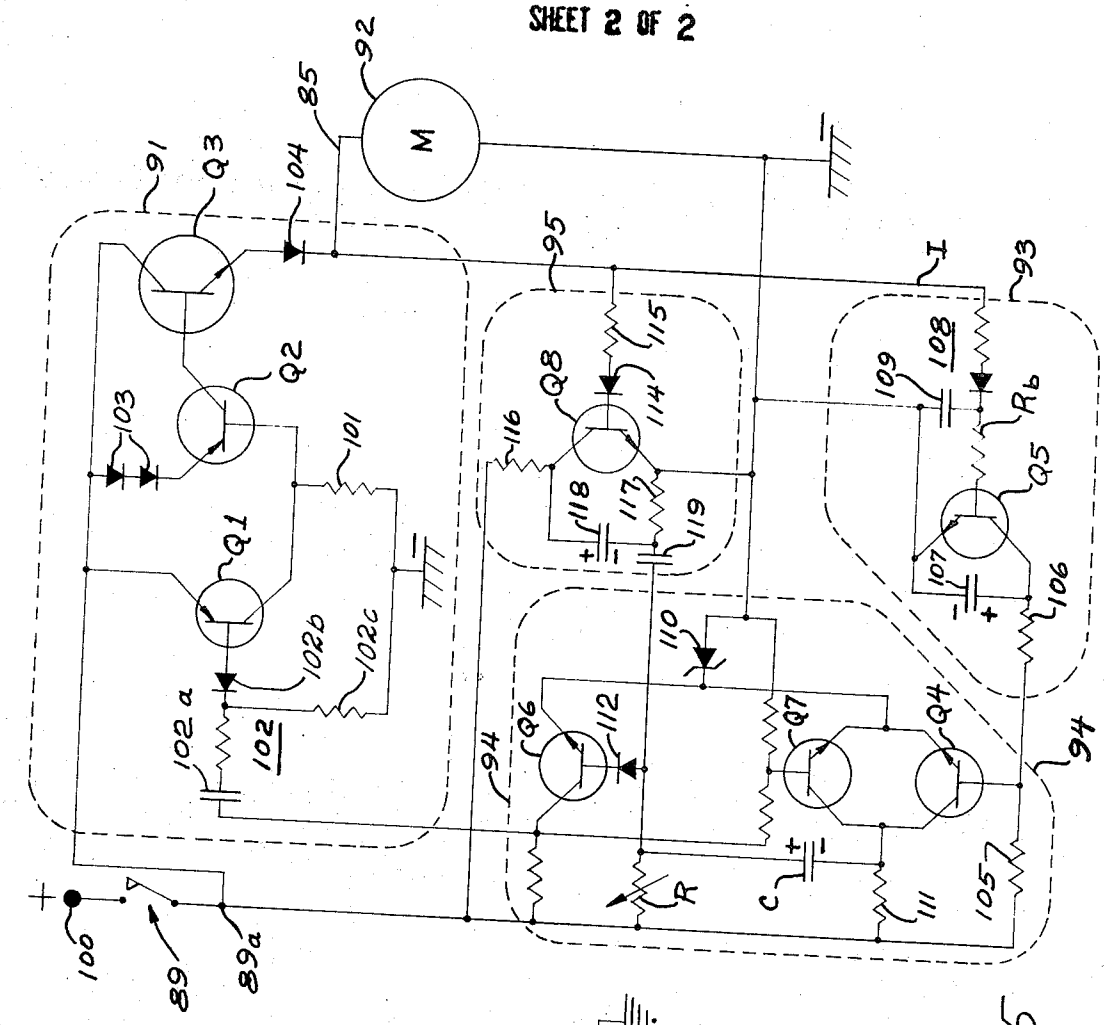


Fig. 5

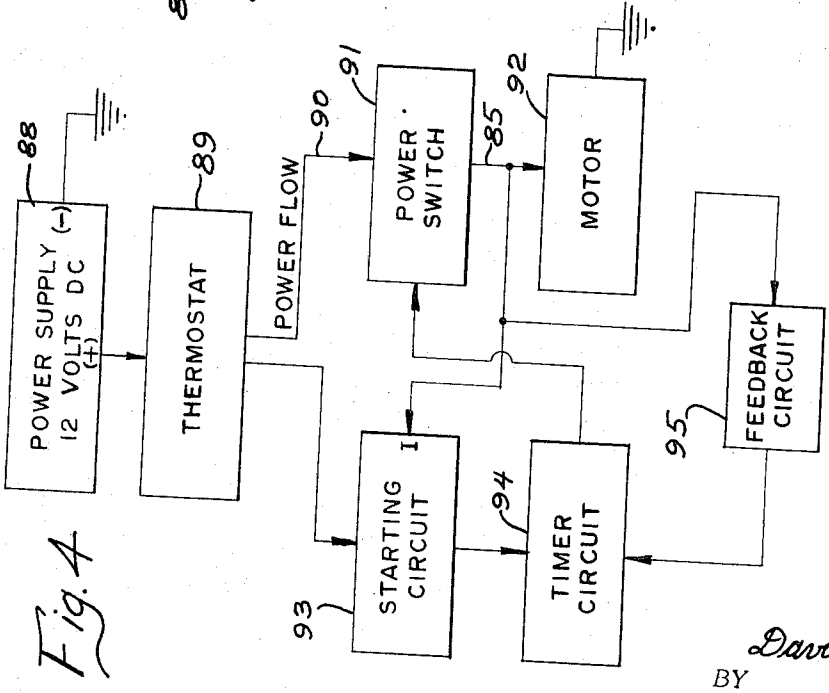


Fig. 4

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SYNCHRONOUS RECIPROCATING ELECTRODYNAMIC COMPRESSOR SYSTEM

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to electrodynamic compressors; and more particularly, it relates to a compressor using a coil-driven piston having particular applicability in small refrigeration systems.

2. Known Systems

Electrodynamic compressors normally have a constant magnetic field provided by a permanent magnet. An electrical coil is wound on a support and located in a gap in the magnetic field. A piston is connected to the coil form, and the coil and piston are usually held in a rest position by one or two main springs, sometimes referred to as "resonance" springs. When the coil is energized with an alternating current, a magnetic force is generated on it to drive the piston. The resonance spring causes the coil and piston to oscillate in reciprocating motion, and it is desirable from the standpoint of efficiency to have the mechanical mechanism oscillate at the same frequency as the frequency of the applied current.

One of the principal problems encountered in attempting to make an electrodynamic compressor system of the type with which the present invention is concerned is that the piston is not connected to a crank so that the length of its stroke is not fixed and may vary. Thus, for varying conditions of load, temperature, etc., the length of the stroke will change. This, in turn, reduces the efficiency of the system because as the length of the stroke increases, the natural oscillatory frequency of the mechanical system decreases correspondingly. As the frequency of oscillation changes, a beating phenomenon develops, and power losses increase.

Although the total change in natural oscillatory frequency is quite small in absolute terms (usually of the order of two or three cycles per second for a nominal frequency of 60 cycles per second), nevertheless, it is enough to have a significant effect on the operating efficiency of the system. The mechanical system may be thought of as a highly tuned, low-loss circuit, so that any deviation between the natural oscillatory frequency of the mechanical system and the energizing electrical energy results in a loss of transfer of electrical energy into work.

In an early electrodynamic compressor system, a solenoid coil is made to reciprocate vertically with respect to the cylindrical magnet, and the frequency of mechanical vibration is determined by the frequency of the operating current supplied from an external power source. The resonance frequency depends on the relationship between the spring constant, the mass of the movable portion of the mechanical system and the compression characteristics of the fluid being compressed. In this early system, the frequency of the excitation external power source was invariable and so there inevitably resulted a mismatch between the frequency of the electrical source and the natural oscillatory frequency of the mechanical system. A further difficulty is presented by mass production of this type of motor because each motor must be precisely balanced to insure mechanical oscillation about a nominal frequency equal to the frequency of the available industrial source.

In U.S. Pat. No. 3,355,676, there is disclosed an electrodynamic compressor in which it is purported that the frequency of the electrical oscillator automatically changes with the actual frequency of the mechanical system. Two symmetrically connected transistors are biased alternately from saturation to cutoff by currents generated from moving two oppositely connected coils of the mechanical oscillator.

SUMMARY OF THE INVENTION

In the present invention, an electrical coil is mounted for reciprocation in a magnetic field which is generated by a permanent magnet. A single resonance spring resiliently supports the coil and its associated piston in a rest position.

During normal operation, a pulse of current in the coil causes a magnetic force to be exerted on the coil thereby moving the piston to compress fluid in the cylinder and, at the same time, compressing the resonance spring to store energy in it. The time of the current pulse is preset to be a little shorter than one-half the time for the known shortest compression cycle for the system—which normally occurs at maximum temperature and load. After the current pulse is terminated, the piston and coil are returned under action of the spring. No electrical current is supplied to the coil during the return cycle.

When the piston reaches the end of its return cycle, a circuit sensing the self-induced voltage in the traveling coil generates a signal that results in supplying another current pulse of predetermined duration to the coil as it again commences a compression cycle. As the load varies, the period of the electrical energizing current also varies, although the duration of the "on" current pulse remains the same. However, the period of the electrical current remains synchronous with the cycle time of the mechanical reciprocating system, so that the period of the source current is always equal to the period of the natural oscillatory frequency of the mechanical system.

The drive circuitry may be started by means of a separate circuit which senses the closing of a thermostat located in the space to be cooled. When the thermostat closes in response to a rise in temperature within the space to be cooled, the starting circuit generates a start signal which causes the first pulse to be supplied to the electrical coil. Thereafter, starting pulses are supplied by the circuit which senses the self-induced coil voltage, as mentioned above.

In the mechanical aspects of the inventive system, the electrical coil is mounted on an annular core, which is mounted in a corresponding annular air gap in a magnetic structure including a permanent magnet. A cylinder sleeve is mounted co-axially with the magnetic structure, and its bore extends in a vertical direction. A helical resonance spring interconnects the top of the coil form with the magnetic structure, and the resonance spring is also co-axial with the piston. Gas is fed through the hollow piston into the cylinder and into an accumulation chamber through a disc valve during compression. Thus, all of the movable parts including the coil, the coil form, and piston and the resonance spring are all located co-axially with the fixed cylinder sleeve. During assembly, the problem of alignment of the movable parts is thereby greatly simplified.

A second spring is located co-axially with the piston and serves as a current return path from the electrical

coil. Current is fed to the coil through the main resonance spring.

Each end of the main resonance spring is attached respectively to the piston and to the cylinder by means of insulating members which provide helical grooves leading from a tapered guide surface. The inner diameter of the grooves receiving the spring have an increasing diameter which serves an an extension of the tapered guide surfaces to provide a self-tightening, interference-free connection.

Other features and advantages of the present system will be apparent to persons skilled in the art from the following detailed description of a preferred embodiment accompanied by the attached drawing wherein identical reference numerals will refer to like parts in the various views.

THE DRAWING

FIG. 1 is a vertical cross-sectional view of an electrodynamic compressor incorporating the present invention;

FIG. 2 is an enlarged vertical cross-section of the discharge end of the cylinder showing the intake valve and the outlet valve;

FIG. 3 is an idealized timing diagram for a control system showing the relationship between the excitation current pulse and the natural oscillatory frequency of the mechanical system;

FIG. 4 is a block schematic diagram of an electrical control system for the compressor of FIG. 1; and

FIG. 5 is an electrical schematic diagram according to the functional block diagram of FIG. 4.

DETAILED DESCRIPTION

Turning first to FIG. 1, an electrodynamic compressor is seen including a movable piston assembly generally designated by reference numeral **10** and a fixed magnetic assembly generally designated by reference numeral **11**. The piston assembly **10** is supported above the magnetic assembly **11** by means of a helical coil spring **12**, sometimes referred to herein as the resonance spring.

The piston assembly includes a piston **13** in the form of a hollow cylinder having a central bore **14** extending through its entire length from an input aperture **15** at its upper end to a release aperture **16** at its lower end. The hollow piston **13** is slidably received within a cylindrical sleeve **17** which is securely mounted within the magnet assembly **11**, and it will be more clearly described below.

Adjacent the discharge aperture **16** of the hollow piston **13**, there is located a check valve generally designated by reference numeral **20**. The check valve **20** includes a disc-shaped closure member **21** connected to the lower end of a valve stem **22** which extends coaxially with the piston **13**. At the upper end of the valve stem **22**, there is formed an annular recess **23** which receives a retainer member **24**. At the lower end of the valve **20**, there is formed a depression **25** in the form of a portion of a sphere for reasons explained below. Adjacent the lower end of the piston **13**, there is a thickened cylindrical wall portion **27** having an upper shoulder **28** and a lower annular seating surface **29**.

The valve **20** reciprocates between an upper or "closed" position (shown in solid line in FIG. **2**) and a lower or "open" position (shown partially in dash line in FIG. **2**). When the piston **13** is moved upwardly, a partial vacuum will be created within the bore of the cylinder **17**, thereby unseating the valve **20** until the retainer member **24** engages the shoulder **28**. In this position, fluid or gas ia admitted through the central hollow **14** of the piston from a suction chamber generally designated **30** in FIG. **1**. The relative movement of the valve **20** and piston **13** is exaggerated in FIG. **2** for purposes of illustration, and it will be realized that only a very small displacement of the valve **20** is required to admit gas into the compression chamber of the cylinder.

When the piston **13** has reached the upper limits of its return or "intake" cycle, it reverses direction, and the inertia of the valve **20** carries it into sealing engagement with the seating surface **29**—that is, the closure member **21** engages the seating surface **29**.

At the upper end of the piston **13** there is secured a retainer member **33** which is formed of electrically insulating material such as neoprene plastic, and it includes an exterior helical groove or thread **34** leading from a lower tapered conical guide surface **35**. The interior of the groove **34** forms a continuation of the expanding diameter of the conical surface **35**—that is, the diameter of the thread **34** increases in accordance with the increasing diameter of the seating surface.

The spring **12** is received within the helical groove **34** of the retainer member **33**, and at least one turn of the spring **12** engages the tapered guide surface **35**. The taper of the guide surface **35** and the expanding interior diameter of the groove **34** facilitates disengagement of the spring from the retainer member **33** during expansion or stretching of the spring. As the spring **12** is stretched, the internal diameter of the helical turns decreases, and the taper of the guide surface **35** as well as the interior of the groove **34** provides for an interference-free disengagement of the spring **12** from the retainer member. Similarly, as the spring is compressed, the interior diameter of the turns increases, and these turns are guided onto the retainer member **33** without interference. Further, when the spring **12** is compressed, there is a torsion induced in it which tends to tighten the spring **12** onto the retainer member **33**, thus providing a self-tightening engagement.

A coil form generally designated **39** having an inverted cup shape includes a central aperture **40** which receives the upper end of the piston **13**. The coil form **39** includes a horizontal planar base **41** in which there is formed the aperture **40**. A frusto-conical connecting portion extends from the base **41**, and a cylindrical side portion **43** depends from the lower end of the frusto-conical section **42**. An annular groove **44** is provided in the cylindrical side portion **43** of the coil form for receiving a coil **45** which is comprised of a number of turns of insulated wire. The base **41** of the coil form is assembled onto the upper flat surface of the retainer member **33**, and it is held there by means of a thrust washer **47** and a snap ring **48** which is received in a circumferential groove formed in the upper end of the hollow piston **13**. A similar thrust washer **47A** and snap ring **48A** are located at the bottom of the retainer member **33**, as viewed in FIG. **1**. These retainer rings and washers hold the elements of the piston assembly in assembled relation, and this construction greatly facilitates assembly of the compressor, as will be explained below.

Turning now to the magnet section **11**, a permanent magnet in the form of an annulus is designated **49**, and

it includes a central bore 50 in which the cylinder sleeve 17 is fitted. An annular plate 51 is secured to the lower surface of the magnet 49, and a cylindrical side wall 52 is attached to and extends upwardly from the outer side surface of the plate 51. The interior surface of the upper end of the cylindrical side wall 52, designated by reference numeral 53 forms a first pole face 53. A second annular plate 54, similar to the plate 51 is attached to the upper surface of the permanent magnet 49, and it has an outer diameter slightly less than the outer diameter of the plate 51 so that, together with the cylindrical side wall 52, there is formed an annular gap 55 in which the cylindrical portion 43 of the coil form 39, together with the coil 45, is received with clearance sufficient to permit reciprocation of the coil and coil form. The outer cylindrical surface 56 of the plate 54 forms a second pole face spaced from but in opposing relation to the previously-described pole face 53. The plates 51 and 54 as well as the cylindrical side wall 52 are formed of magnetic material so that a magnetic circuit is formed from the upper surface of the permanent magnet 49, extending outwardly through the upper plate 54 to the first pole face 56 and thence through the annular gap 55 into the second pole face 53. From there, the magnetic circuit continues downwardly through the cylindrical side wall 52 and radially inward of the lower plate 51 into the lower surface of the permanent magnet 49.

A cup-shaped housing 58 having a peripheral flange 59, a cylindrical side wall 60 and a bottom wall 61 is secured to the annular plate 51 by means of screws 62. A first annular groove 64 is formed in the lower surface of the plate 51, and it receives a sealing O-ring 65 which is compressed within the groove 64 by the flange 59. The O-ring 65 forms a high-pressure liquid seal with the housing 58 which partially defines an accumulator chamber adjacent the bottom or discharge end of the cylindrical sleeve 17, which discharge end is designated by reference numeral 66. Referring again to FIG. 2, a second annular groove 67 is formed in the inner surface of the plate 51 which receives the cylinder sleeve 17, and a sealing O-ring 68 forms a high-pressure liquid seal between the plate 51 and the cylinder sleeve 17.

In the outer surface of the cylindrical sleeve 17, adjacent the discharge end 66, there is formed an annular groove 69 which receives a retainer ring 70. The retainer ring 70 engages a lower surface of the annular plate 51 for holding it in place. The upper end of the cylindrical sleeve 17 is threaded for receiving a spring retainer member 71, similar to the previously-described spring retainer member 33. That is, the spring retainer member 17 includes a helical groove 72 for receiving the lower end of the spring 12 in threaded engagement. The interior diameter of the convolutions of the groove 72 increases from an upper conically tapered guiding side surface 73 for an interference-free seating of the compressed spring onto the retainer member. The retainer member 71 is formed of a hard insulating material, and, together with the retainer clip 70 at the lower end of the cylindrical sleeve 17, it holds the various elements of the magnet section 11 in assembled relation when recieved on a threaded portion of the upper end of the sleeve 17.

Turning again to the discharge end of the cylindrical sleeve 17, and particularly to FIG. 2, the lower surface of the sleeve 17 is designated 77, and it may be ground to form a flat sealing surface for receiving a disc valve 78 which is held against the ground surface 77 of the sleeve 17 by means of a conical coil spring 79. As seen better in FIG. 1, the lower end of the conical spring 79 is held in place by the circular corner formed between the side wall 60 and the bottom wall 61 of the accumulation chamber. Compressed gas within the accumulation chamber is discharged through the side wall 60 by means of a discharge conduit designated 80 in FIG. 1. On the upper surface of the disc valve 78 there is formed a projection 81 in the form of a portion of a cylinder for fitting into the corresponding recess 25 of the valve seat 21. As has been mentioned, the stroke of the piston 13 is variable, depending upon the temperature of the system and the load. For those conditions under which a stroke of the piston 13 is a maximum, it will first unseat the disc valve 78 to admit the compressed fluid from the compression chamber 31 into the accumulation chamber, and it then may engage the disc. When it does, the projection 81 and its corresponding recess 25 in the valve 20 have the function of reducing the clearance volume to a minimum while preventing a metal-to-metal contact (to reduce noise) and, at the same time, retaining the position of the displaced valve 78 co-axial with the moving piston. That is, the lower surface of the valve seat 21 strikes only the resilient projection 81 and not the metal portion of the valve 78. The conical spring 79 has the characteristic of yielding to a small displacement with relatively little force, but resisting additional displacements with an increasingly greater force. That is, in compressing the spring 79, the amount of force per unit of compression increases as the spring is compressed. This has the beneficial result that relatively little force is required to unseat the valve disc, but if the stroke of the piston is at a maximum, more energy will be stored in the compressed spring and returned to the piston in its return cycle.

Referring back to FIG. 1, now, electrical drive current may be coupled to the coil 45 by means of a first wire 83 extending through a hole 83A in the side wall 52 and located in a groove 83B in the magnet 49 and pole piece 54. The end of the wire is then soldered to a contact bushing 84 fitted onto the lower end of the coil spring 12. The current is coupled through the resonance spring 12 to a second wire 85 soldered to an upper contact bushing 86 similarly fitted onto the top of the spring 12. The wire 85 extends along the coil form 39 and is connected to one terminal of the coil 45. The other terminal of the coil 45 is connected by means of a wire 86A to the metallic washer 47 which is in electrical communication with the piston 13. A helical coil spring 87 is located coaxially with the piston 13 and between the spring retainers 33 and 71. The upper end of spring 87 is soldered to the piston 13 or to retainer member 48A; and the lower end of spring 87 is soldered to the cylinder 17. The function of spring 87 is to provide a current return path from the piston to system ground (which includes the cylinder 17 and magnetic structure. In summary, the excitation current flows through lead in wire 83, resonance spring 12, conductor 85, coil 45, conductor 86A, washer 47, piston 13, spring 87, and cylinder 17 to ground. The spring 87 is guided by the piston 13, and it does not require substantial energy to compress or expand, as compared with the main resonance spring 12.

The entire system illustrated in FIG. 1 is housed in a chamber which serves as an accumulator for the expanded gas. It is mounted according to conventional

technique to minimize noise transmisson; and hermetic seals are provided at the locations at which the outlet conduit **80**, wire **83** and suction pipe enter the suction chamber.

Turning now to the electrical portion of the drive system, and particularly to the functional block diagram of FIG. **4**, a power supply is diagrammatically designated by the block **88**, and it may be the 12-volt battery of an automobile, which, of course, is a dc source. One terminal of the power supply, for example, the negative terminal, is grounded, and power is fed through a thermostat **89** along a power lead **90** into a power siwtch **91**. The power switch **91** is normally in a nonconducting or open state, and when it is actuated, it conducts power to the compressor winding (functionally designated by the block **92** labeled "motor") along, among other things, the previously described lead **85**.

A signal is also fed through the thermostat **89** into a starting circuit **93** which has an inhibit lead designated I. The output of the starting circuit is fed to one input of a timer circuit **94**, the output of which energizes the power switch **91**. The other input of the timer circuit **94** is energized via a feedback circuit **95** by the output of the power switch **91**. The details of the circuit diagram of FIG. **5** may be better understood if a description of the functions performed by each of the individual circuits is first described. In operation, then, when the temperature of the space being cooled has risen above a preset value, the thermostat **89** will close, thereby conducting power to one input of the power switch **91** and also signaling the starting circuit **93**. The starting circuit **93**, will, in turn, generate a first pulse and transmit it to the timer circuit **94**. The output of the timer circuit **94** will enable the power switch **91** to conduct for a preset interval of time, which is determined by circuitry in the timer circuit **94**. This preset time interval is slightly less than one-half the minimum oscillation period for the mechanical portion of the compressor system which is determined by the spring constant of the resonance spring **12**, the mass of the movable portion of the piston assembly **10**, the pressure in the accumulator, the operating temperature, etc.

The voltage pulses fed through the power switch **91** to the coil **45** of the compressor is illustrated graphically in FIG. **3** by the waveform **96**. The duration of the first pulse is measured between the times t_0 and t_1. The sinusoidal waveform generally designated **97** represents the oscillatory motion of the piston assembly, and more particularly, it represents the self-induced voltage of the coil **45** as it travels in the magnetic field. Hence, the dotted portion of the curve **97** is masked by the applied voltage **96**, whereas the solid portion of the curve **97** physically exists and may be sensed because during that portion of the cycle (namely from time t_1 to t_2), there is no applied voltage energizing the coil **45**. In a preferred embodiment, the positive portion of the curve **97** represents the compression cycle, and the negative portion of the curve represents the return or intake cycle of the compressor. Thus, the applied voltage **96** generates a current in the coil **45** causing the piston assembly **10** to move downward in FIG. **1**—resulting in compression of gas in the compression chamber **31** and compression of the spring **12**. The force of the compressed spring then causes the piston assembly to return, and the momentum of the piston assembly will then cause an extension of the spring **12** beyond its rest position. During the return cycle, the valve **20** will be open to permit passage of gas from the chamber **30** through the hollow piston **13** into the compression chamber **31**. As the force of the spring **12** due to extension overcomes the inertia of the piston assembly **10**, the compressor will again enter the compression cycle and the self-induced voltage will reverse its polarity. It will be observed from FIG. **3** that there is a slight delay between the time at which the self-induced voltage reverses polarity (i.e., the solid line **97** crosses the abscissa) as represented by the point **97***a* and the time t_2 at which the second voltage pulse **96** is initiated. This is merely an inherent feature of the operation of the illustrated embodiment because the circuitry which senses the self-induced coil voltage is level sensitive. Other circuit arrangements could equally well be used. For example, the start of the energizing could be further delayed or advanced even to a point wherein the power switch is turned on before the self-induced voltage has reversed polarity (indicating that the piston is still in a compression cycle), if desired.

In an alternative construction, it would be possible to apply the electrical energy during the return cycle so as to extend the spring **12** beyond its rest position, in which case energy supplied during the compression cycle would be delivered from the spring. In other words, it is not critical that the electrical energy be applied suring the compression cycle, although by applying the voltage pulse during only either the compression cycle or the return cycle, the present system has been able to operate an electrodynamic compressor with a uni-polar electrical signal.

Returning then to the functional block diagram of FIG. **4**, the timer circuit **94** predetermines the duration of the voltage pulses **96**. During start-up, a first triggering pulse for the timer circuit **94** is generated by the starting circuit **93**, and this first timer pulse is sent to cause the power switch **91** to conduct and power is thence transmitted to the compressor motor **92**. The first output from the power switch **91**, in addition to energizing the motor, also transmits a signal to the inhibit lead I of the starting circuit **93** to inhibit the further transmission of pulses from the starting circuit **93** as long as the compressor is operating normally. A second control signal is generated not by the output of the power switch **91**, but rather by the self-induced voltage in the oscillating coil **45**. That is to say, when the self-induced voltage in the coil **45** returns to the same polarity as the excitation voltage pulse as represented in FIG. **3** by returning to a positive polarity, the feedback circuit **95** senses this change in polarity, and energizes the timer circuit **94** after a short delay, as represented at the time t_2, to generate a second preset pulse which causes the power switch **91** to conduct and transmit a second voltage pulse **96**.

As long as the thermostat **89** remains closed, the train of pulses **96** will be transmitted to energize the motor winding, and these pulses will occur in timed relation with the natural frequency of mechanical oscillation of the plunger assembly because the self-induced voltage of the coil **45** determines when the excitation voltage pulses will be generated. This normal operation will further hold the starting circuit **93** in an inhibit condition so that it will not affect the timer circuit **94**. Thus, the compressor action will continue until the temperature within the space being cooled lowers to a temperature sufficient to open the thermostat **89** and thereby

prevent further power flow to the power switch **91.** After a time, the charge holding the starting circuit **93** in an inhibit condition dissipates, so that when the thermostat **89** subsequently closes to energize the starting circuit **93** a first pulse is transmitted to the timer circuit **94** to resume operation.

Turning now to the detailed circuit schematic of FIG. **5,** reference numeral **100** denotes the positive terminal of the supply battery, the negative of the supply battery being grounded. One terminal of the thermostat **89** is connected to the terminal **100,** and the thermostat **89** is shown in an open condition representative of the temperature's being at or below a preset value. When the temperature rises above the preset value, the thermostat **89** will close. The second terminal of the thermostat **89** is designated by reference numeral **89***a*, and it is connected to the emitter of a first transistor denoted Q1, the collector of which is connected through a load resistor **101** to ground. The transistor Q1 functions as an amplifier at the input stage of the power switch, and it is seen as enclosed within the dashed line **91** corresponding to the power switch **91** of FIG. **4.**

Certain of the circuit details disclosed in FIG. **5** are illustrative of one way of incorporating the invention in a physical embodiment, and they are not to be taken as necessary limitations of the invention. Further, since some of these circuit details are well within the skill of the art, an elaborate description will not be given in the interests of brevity. Thus, the base of the transistor Q1 is connected to a bias network **102**; and it includes a diode **102***b* and a resistor **102***c* connected in series between the base of transistor Q1 and ground. Thus, the transistor Q1 is normally conducting, but a positive level appearing at capacitor **102***a* will reverse-bias the diode **102***b* and cut off the base current. The positive level is received from the output of the timer circuit which is enclosed within the dash line **94.**

The output signal from the collector of transistor Q1 is fed to the base of a second amplifying transistor Q2 having its emitter connected to the terminal **89**a by means of two diodes **103.** The collector of transistor Q2 is directly connected to the base of a power transistor Q3 having its collector directly connected to the terminal **89**a and its emitter connected by means of a diode **104** to one terminal of the motor **92.** That is, referring to FIG. **1,** the emitter of transistor Q3 is connected via line **85** to the winding **45.** The other side of the motor winding is grounded. The transistor Q3 serves as the main power switch, being in series with the motor, the thermostat **89** and the source of power. Normally, transistors Q2 and Q3 are in a non-conducting state and transistor Q1 is conducting. When a positive level is received at the cathode of diode **102**b, it will reverse bias the emitter-base junction of transistor Q1, and the transistor becomes non-conducting. Thus, its collector voltage goes negative which forward biases transistor Q2 and causes it to conduct. This, in turn, causes the base of the transistor Q3 to go positive thereby causing it to conduct. When transistor Q3 conducts, it couples the positive terminal of the battery to the motor **92.** The function of the diode **104** is to prevent negative spikes generated at the input terminal of the motor **92** from affecting the transistor Q3 when the current pulse is shut off. Alternatively, a pair of back-to-back zener diodes could be connected directly across the terminals of the motor **92** to limit the amplitude of the voltage spikes, in which case the diode **104** could be eliminated.

The terminal **89**a is also coupled by means of a resistor **105** to the base of a transistor Q4 and through a second resistor **106** to the collector of a resistor Q5. A capacitor **107** is connected across the collector-emitter junction of resistor Q5, and the base of a transistor Q5 is connected to a bias network generally designated **108** which receives and transmits positive pulses from the ungrounded terminal of the motor **92** and causes a charge to be built up on a capacitor **109.** The input to the bias network **108** forms the inhibit terminal of the starting circuit **93,** and the base terminal of the transistor Q4 forms the inputs of the timer circuit **94.**

Connected to the collector of transistor Q4 is a capacitor C having its other terminal connected through a variable resistor R to the terminal **89**A. A second resistor, acting as a load resistor, designated by reference numeral **111** is connected between the collector of resistor Q4 and the terminal **89**A. The junction between the resistor R and the capacitor C is connected through a diode **112** to the base of a transistor Q6, and the collector of the transistor Q6 is connected to the input of bias network of the transistor Q1. The emitter of the transistor Q6 is connected to the zener diode **110.** A transistor Q7 is connected in parallel with the transistor Q4 and therefore able to actuate the timing mechanism of resistor R and capacitor C when it conducts.

In operation, transistor Q6 is normally in a conducting state because it is forward-biased via resistor R. A negative trigger pulse at its base will cause it to conduct thereby generating a negative pulse at its collector terminal. This ngeative pulse is transmitted to the base of transistor Q6 (which is normally conducting) to drive that transistor to cut off. The resulting negative pulse generated at the common collectors of transistors Q4, Q7 holds transistor Q6 in a cut off state. However, capacitor C begins to charge in the polarity indicated and according to a time constant determined by the product of resistance R and capacitance C. When the junction between capacitor C and resistor R reaches a predetermined positive level after the passage of a preset time, then, transistor Q6 will again conduct and turn transistors Q1 and Q7 back off. Thus, the values of capacitor C and resistor R define the "on" time for the power switch.

In start up, when the thermostat **89** closes, applying a positive potential to terminal **89**a, it causes transistor Q6 to conduct immediately. Transistors Q4 and Q7 are cut off. Since transistor Q5 is cut off, capacitor **107** begins to charge in the polarity shown until transistor Q4 is turned on. When transistor Q4 turns on, capacitor C is coupled to a lower potnetial, and transistor Q6 is cut off, thereby generating the first or "start" pulse to the power switch.

Turning now to the circuitry of the feedback circuit **95,** it includes a transistor Q8 having its base connected by means of a diode **114** and a resistor **115** to the ungrounded terminal of the motor **92** so as to be responsive only to positive pulses. The collector of the transistor Q8 is connected through a resistor **116** to the terminal **89***a* of the thermostat **89,** and the emitter of transistor of Q8 is connected to ground. A resistor **117** and capacitor **118** are connected from the emitter to the collector of transistor Q8, and a capacitor **119** couples the junction between the resistor **117** and the capacitor **118** to the anode of diode **112** in the timer circuit **94.**

Normally, the transistor Q8 is in a non-conducting state so that a charge builds up in the polarity shown across capacitor **118.** When a positive pulse is generated by the power switch **91,** it causes the transistor Q8 to conduct thereby connecting the positively charged terminal of capacitor **118** to ground through the emitter terminal of transistor Q8 and causing a negative voltage spike at the junction between the resistor **117** and the capacitor **118.** This negative spike is transmitted through the capacitor **119** to reverse bias transistor Q7 thereby causing a positive pulse to be generated at the collector of transistor Q6, which as already mentioned, also causes the transistor Q7 to be forward biased and brings the timing network into the circuit to hold the transistor Q6 in its non-conducting state for the preset time. The preset time during which the transistor Q6 is held non-conducting is ideally equal to one-half cycle for a minimum period of the natural period of oscillation of the mechanical system. The reason for this is that as the load decreases and the stroke and period of the mechanical oscillating system increase, the width of the energization pulse need not be increased because less power is required.

Although each of the functions of the various circuits have already been described, a brief summary of the overall operation of the electrical system will now be given. When the thermostat **89** closes in response to a rise in temperature in the area to be cooled, a positive voltage appears across the series network including resistors **105** and **106** and capacitor **107.** At this time, transistor Q5 is non-conducting. Further, transistor Q4 and transistor Q7 are non-conducting; transistor Q1 is conducting; and transistors Q2 and Q3 are non-conducting. Transistor Q6 is conducting at this time and transistor Q8 is non-conducting. Since there had been no charge accumulated on capacitor **107,** it begins to charge positively, and when a sufficient bias is obtained at the base of transistor Q4 by means of this positive charge on capacitor **107,** transistor Q4 will conduct. This, in turn, causes a negative voltage level to be transmitted through capacitor C which, in turn, reverse biases transistor Q6 and causes a positive voltage to be generated at its collector. The positive voltage generated at the collector of transistor Q6 turns off transistor Q1 which, in turn, causes transistor Q2 to conduct. Transistor Q2 causes the power switch Q3 to conduct and a first energizing pulse is transmitted to the coil **45** on the piston assembly **10.**

The current circulating in the coil **45** interacts with the permanent magnetic field established by the magnet **49,** and the piston assembly is caused to move downwardly as viewed in FIG. **1.** The downward movement of the piston assembly **10** compressed the spring **12** and also compresses any gas in the compression chamber **31.**

At the same time, this first positive pulse is transmitted to the input bias network **108** of the starting circuit **93** and causes the capacitor **109** to begin to accumulate charge of a polarity that will hold the transistor Q5 in a state of conduction—thus rendering the system inoperative to subsequent starting pulses for a preset period of time, sometimes referred to as a "refractory" period. The refractory period is determined by the time constant of capacitor **109** and base resistor R_b through which the capacitor discharges. This time constant may be of the order of a few minutes, and it is advantageous to the system under certain operating conditions. For example, in the event that all of the fluid being compressed turns to liquid, and is thus incompressible, it would do harm to the compressor to continue to energize it electrically. The principal harm would be in overheating of the coil **45** because no counter-electromotive force would be generated if the piston assembly were stopped, thereby permitting the flow of large currents through the coil **45.** Also, additional forces would be exerted on the valve.

In the event of total stoppage in the present system, no signal would be sensed by the feedback circuit **95,** and the starting circuit **93** is rendered inhibited for this refractory period—thus enabling sufficient liquid to boil off so that additional compression could take place without harm to the system.

During normal operation, as the coil **45** returns under action of the main resonance spring, the polarity of the self-induced voltage changes, as represented by the negative half cycle shown in solid in FIG. **3.** The spring will stretch until it overcomes the momentum of the piston assembly; and the piston assembly will then reverse and enter a compression cycle. This will cause the transistor Q8 to conduct to generate a negative voltage spike which cuts off transistor Q6 which, in turn, causes transistor Q7 to conduct and start a new timing cycle.

It will be observed that the self-induced positive voltage generated by the free-swinging piston, during the return cycle goes slightly positive sufficient to forward bias the diode **114** and the base-emitter junction of transistor Q8 before again triggering the timer circuit. This accounts for the slight delay between the cross-over point **97***a* in FIG. **3** and the time t_2 at which the voltage pulse **96** begins. The invention, of course, in its broader aspects is not limited to this slight delay.

Having thus described in detail a preferred embodiment of the invention, persons skilled in the art will be able to modify certain of the structure and circuitry shown and to substitute equivalent elements for those which have been disclosed; and it is, therefore, intended that all such modifications and substitutions be covered as they are embraced within the spirit and scope of the appended claims.

I claim:

1. An electrodynamic system for compressing a gas comprising: a cylinder defining a compression chamber for said gas; a piston assembly including a piston slidably received in said cylinder and an electrical coil; resonance spring means connected to said piston assembly to form a mechanical oscillatory system having a natural frequency of oscillation; magnet means for generating a magnetic field for acting on said coil when energized with an electrical current; circuit means responsive to the self-induced voltage of said coil for generating a trigger signal at a predetermined time in the cycle of said self-induced voltage; and timer circuit means responsive to said trigger signal for generating a pulse of predetermined constant time duration less than about one-half the minimum cycle time for a full oscillation of said mechanical system, said timer circuit means transmitting said pulse to said coil to induce a force on said piston assembly; whereby said pulse is applied to said coil synchronously with the movement of said coil.

2. The system of claim **1** wherein said pulse transmitted to said coil occurs during a compression cycle of said piston.

3. An electrical drive system for an electrodynamic compressor including an oscillatory mechanical system with a piston assembly, coil and a spring for oscillating said piston assembly, comprising: a course of dc voltage; power switch means adapted to couple said source of voltage to said coil when actuated; a thermostat in circuit with said source of voltage for closing when the temperature in the space to be cooled rises to a predetermined level; a starting circuit responsive to the closing of said thermostat for generating a start signal; a timer circuit for generating a pulse of predetermined duration less than the time for one-half cycle of the minimum known cycle time for mechanical vibration of said mechanical system, said timer circuit being responsive to said start pulse for actuating said power switch; and feedback circuit means responsive only to the back emf of said coil for periodically energizing said timer circuit in timed relation with the motion of said coil; said starting circuit further including delay circuit means responsive to the voltage at said coil to inhibit said starting circuit as long as said coil is reciprocating and for a predetermined time after said coil has come to rest.

4. In an electrodynamic compressor of the type disclosed, including a mechanical assembly having a piston connected to an electrical coil, the combination comprising: first circuit means for energizing said coil with electrical pulses in timed relation with the motion of said coil in a magnetic field; starter circuit means for generating a first pulse to start said coil in motion, said starter circuit means including a delay circuit responsive to the terminal voltage of said coil for inhibiting said starter circuit means.

5. The system of claim 4 wherein said delay circuit is capable of inhibiting said starter circuit in response to pulses being supplied from said first circuit means to said motor for a predetermined delay time after each such pulse.

6. In an electrodynamic compressor, the combination comprising a magnetic section including a permanent magnet having a generally annular shape with a central bore; means providing a magnetic field path for said magnet and including an annular gap between opposing pole faces; a cylindrical sleeve received in the bore of said magnet; a piston received in said sleeve for reciprocation therein; a resonance spring having one en rigidly connected to said magnetic housing and extending coaxial with said piston; a coil form symmetrical about a central axis; means for mounting said coil form to the other end of said spring and to the intake end of said piston whereby the axis of said coil form extends along the axis of said piston; an electrical coil mounted on said coil form within said air gap for reciprocation with said piston; means for coupling a unipolar pulse to said coil including first lead means interconnecting one terminal of said coil with the main resonance spring; means for electrically isolating said spring from said piston and from said magnetic housing; and second conductive means interconnecting the other terminal of said coil with said piston and cylinder for supplying a ground to said system.

7. The system of claim 6 wherein said means for isolating said coil includes first and second insulating retainer members, each retainer member including a generally conical guiding surface received within its associated end of said spring and a helical groove leading from said guiding center into a radially extending terminal point for attaching said spring; the conical guide surfaces and the interior of said groove forming a gradually expending diameter toward said terminal point for receiving an associated end of said resonance spring in self-tightening relation.

8. An electrodynamic compressor system comprising: magnetic structure providing an air gap; a coil mounted in said air gap; a piston connected to said coil; a cylinder mounted to said magnetic structure and slidably receiving said piston to define a compression chamber; means feeding gas unidirectionally through said piston to said compression chamber; outlet valve means communicating said compression chamber with an accumulation chamber; resonance spring means coaxial with said piston and connected between said magnetic structure and said piston and coil for resiliently holding the same; thermostat means responsive to the temperature within a space to be cooled; first circuit means sensing the self-induced voltage in said coil when the same moves in said magnetic field; second circuit means responsive to said first circuit means and said thermostat for applying a unipolar pulse to said coil during a predetermined time of the reciprocation thereof to urge said coil and piston in one direction to compress said gas and to store energy in said spring, said spring returning said coil after said pulse is terminated; said current pulses being coupled to said coil via said resonance spring; and a second spring located coaxially with said piston and within said resonance spring, said second spring having one end in electrical contact with said piston and the other end in electrical contact with said cylinder to provide a ground path for said coil.

9. In an electrodynamic compressore, the combination of a free piston actuated by a coil in a magnetic field; a cylinder slidably receiving said piston; a check valve including a disc adapted to seal the discharge end of said cylinder; a conical spring urging said disc in a closed position; said piston defining a detent on its working face; and a member of resilient material on said disc conforming to the detent in said piston and adapted to engage said piston to thereby reduce noise as said piston engages said disc, and to act to center said disc on said piston after said compression chamber is cleared.

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