May 6, 1969 A. SHOH 3,443,130

APPARATUS FOR LIMITING THE MOTIONAL AMPLITUDE OF AN ULTRASONIC TRANSDUCER

Filed Dec. 8, 1964

Sheet 1 of 6

Fig. 1.

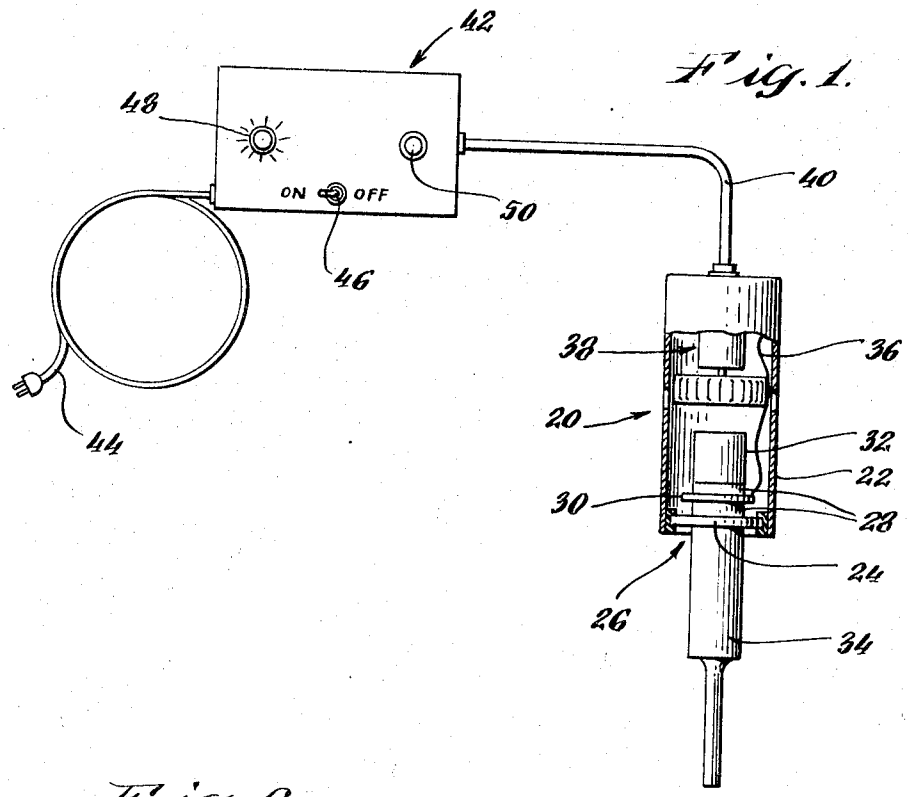
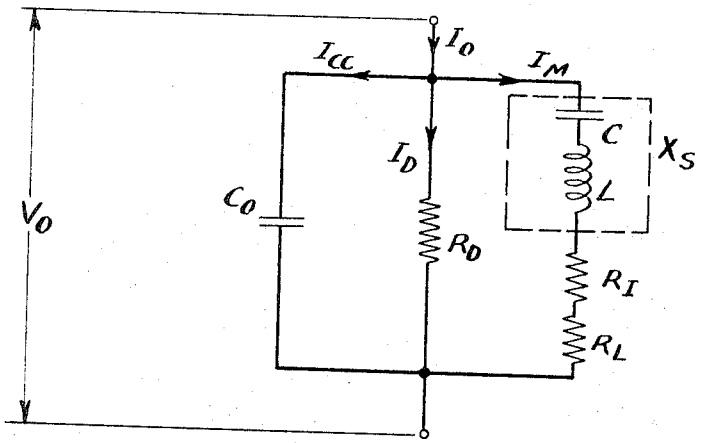


Fig. 2.



INVENTOR.
Andrew Shoh
BY
Blair & Buckles
ATTORNEYS.

Fig. 4.

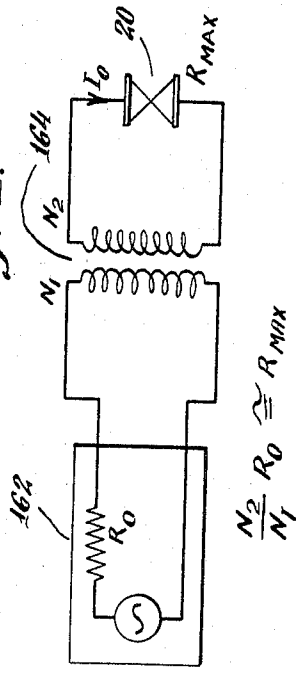


Fig. 3.

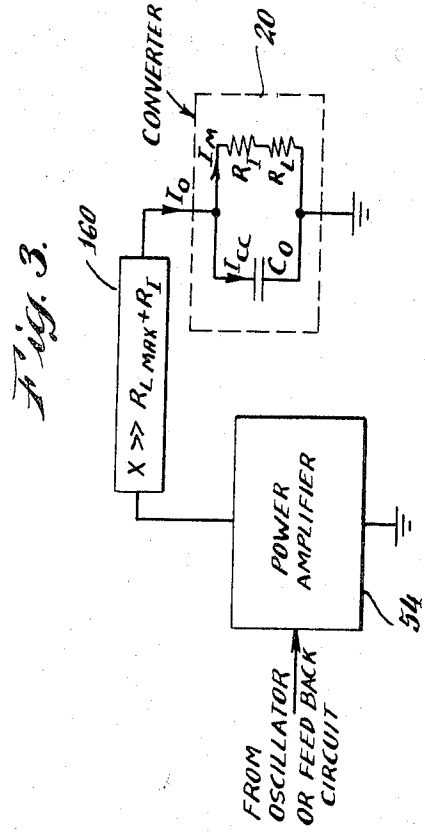


Fig. 5.

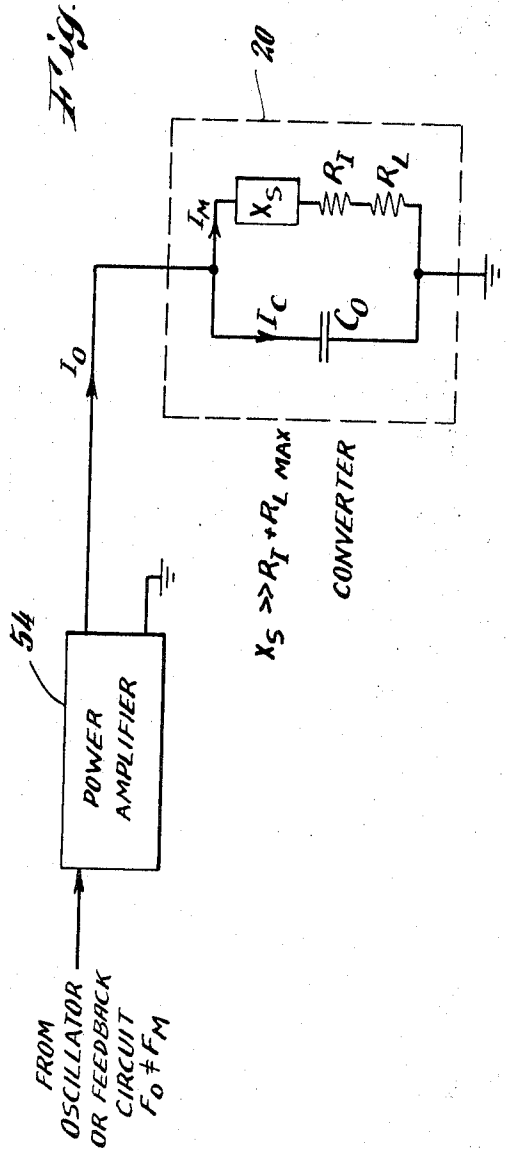
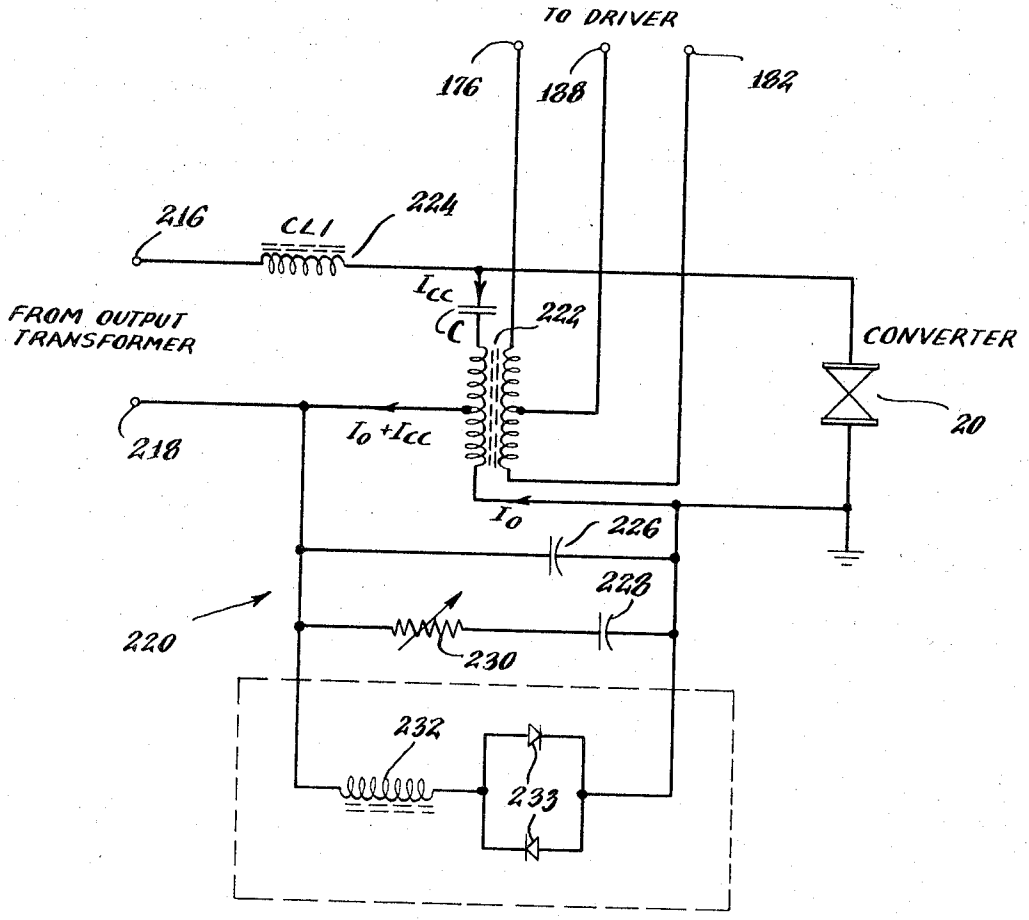


Fig. 6.


TO DRIVER
176
188
182
216
CL1
224
I_{CC}
C
222
FROM OUTPUT TRANSFORMER
CONVERTER
20
218
$I_o + I_{CC}$
I_o
226
228
220
230
232
233

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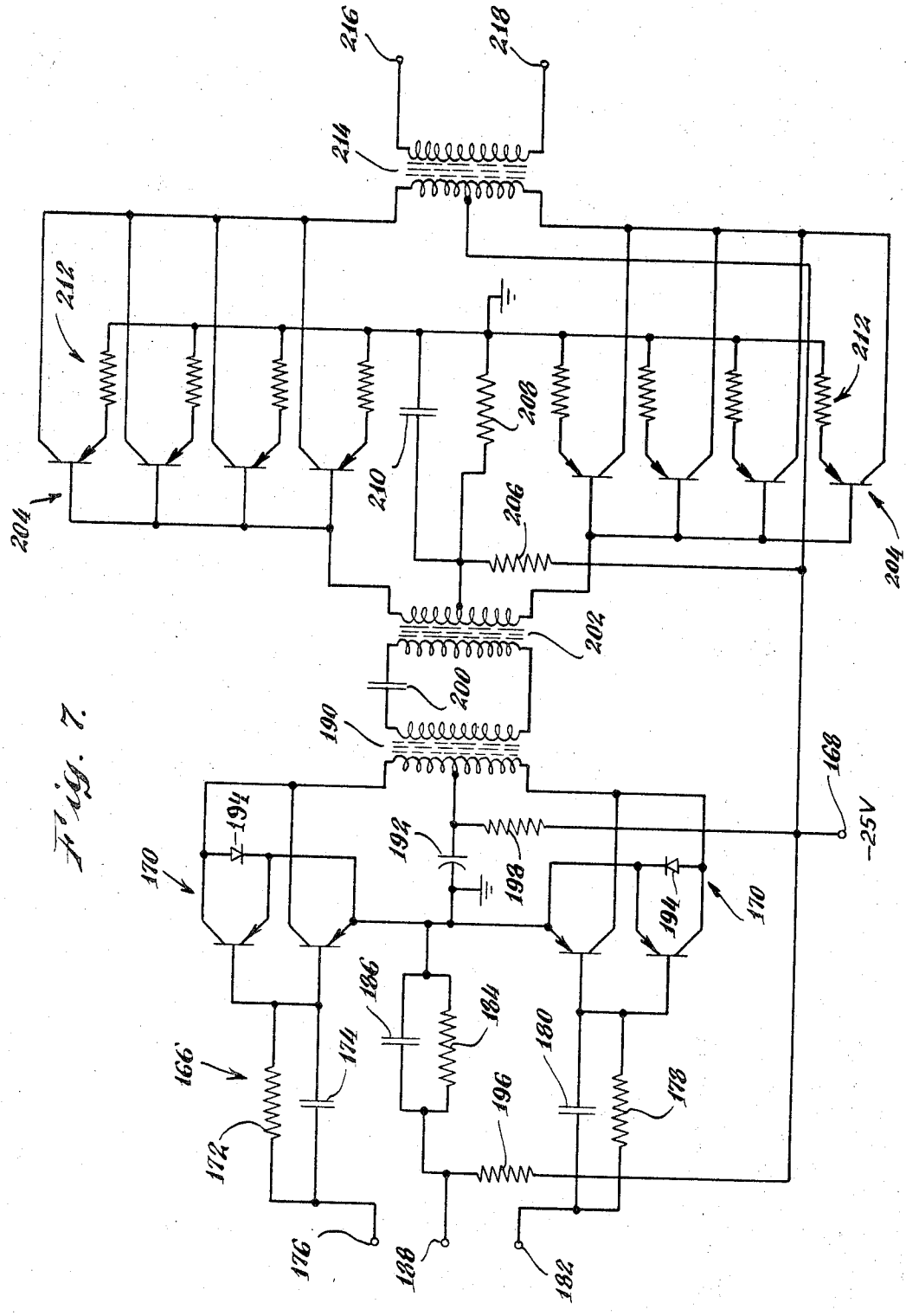


Fig. 7.

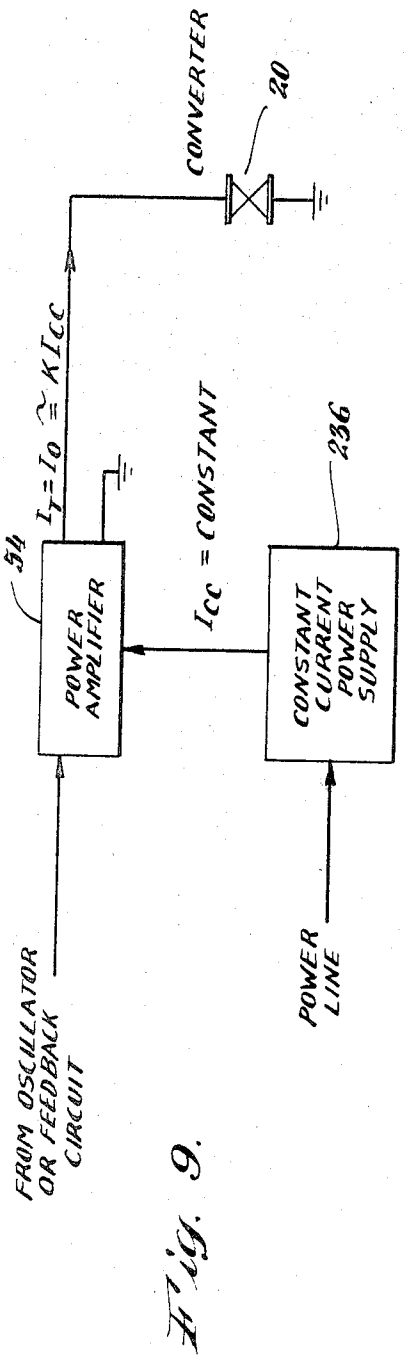

CONVERTER
20
$I_T = I_O \cong KI_{CC}$
54
POWER AMPLIFIER
I_{CC} = CONSTANT
236
CONSTANT CURRENT POWER SUPPLY
FROM OSCILLATOR OR FEEDBACK CIRCUIT
POWER LINE

Fig. 9.

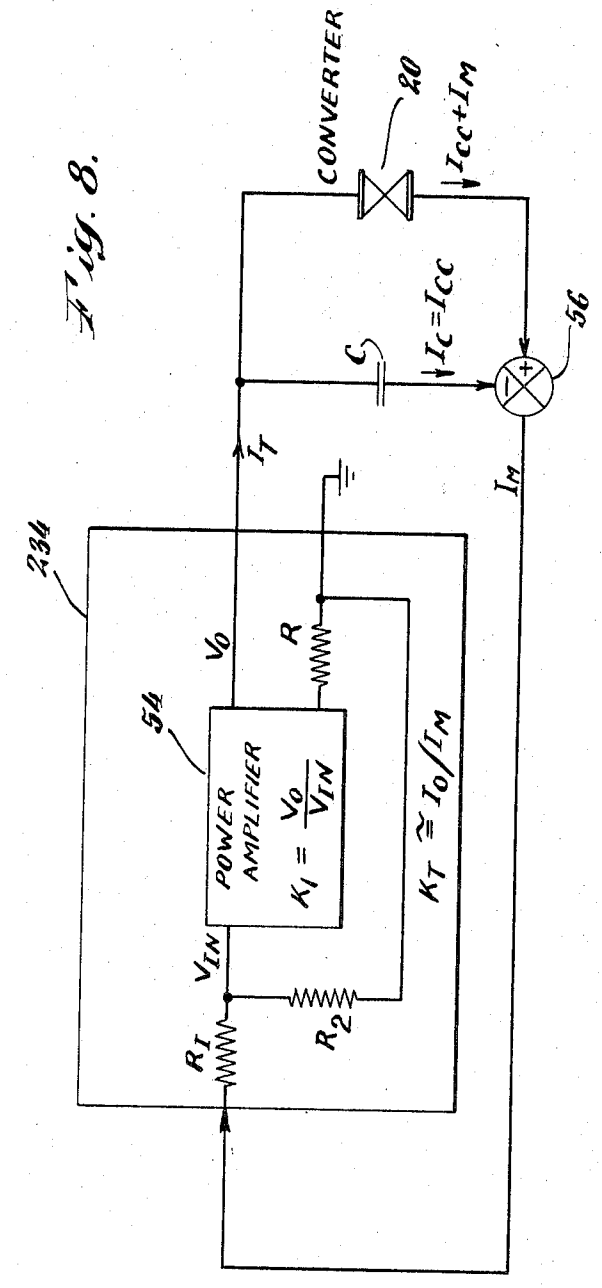

CONVERTER
20
$I_{CC}+I_M$
$I_C=I_{CC}$
C
56
I_T
I_M
234
V_O
R
54
POWER AMPLIFIER
$K_I = \frac{V_O}{V_{IN}}$
$K_T \cong I_O/I_M$
V_{IN}
R_1
R_2

Fig. 8.

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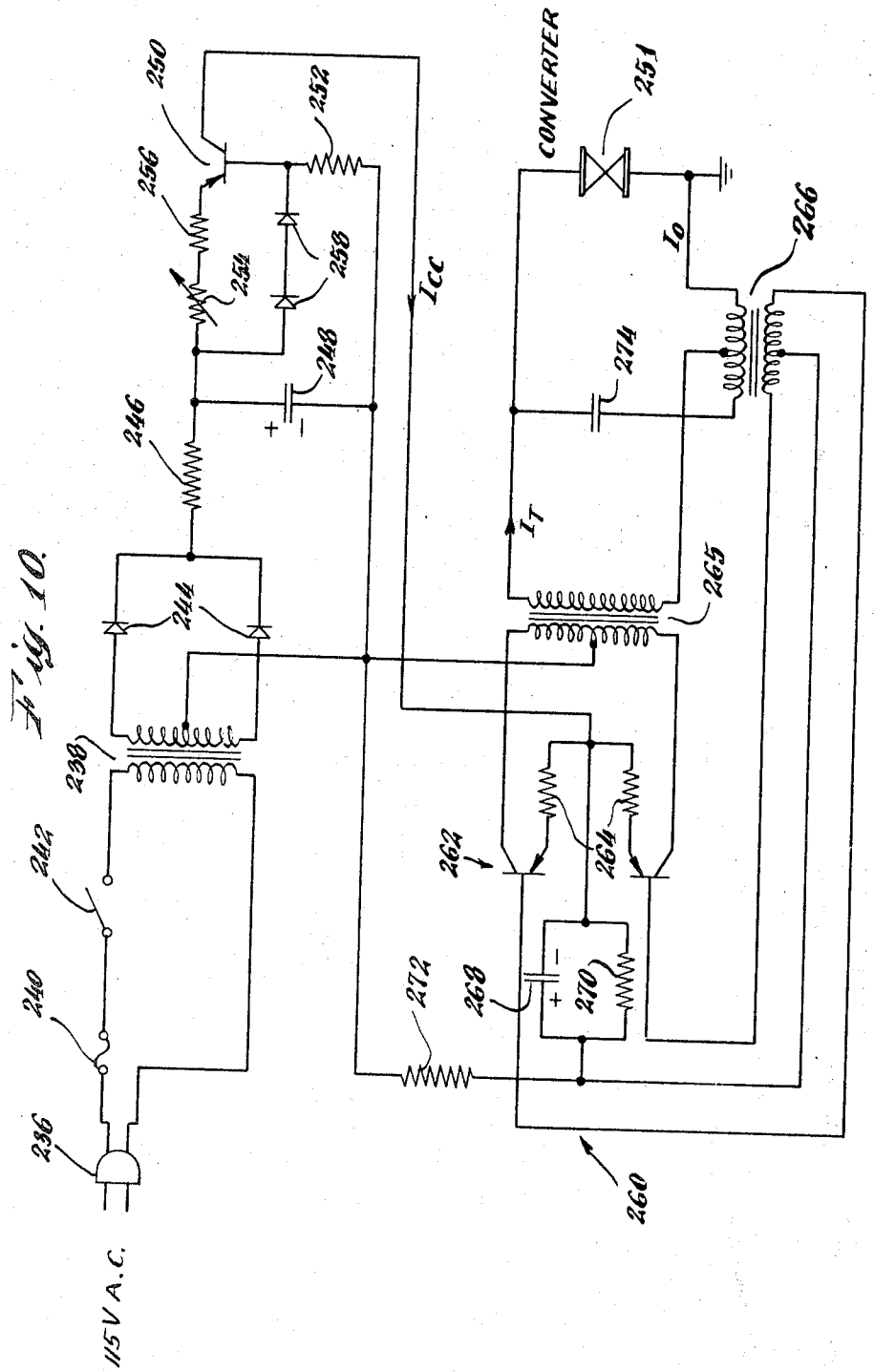


Fig. 10.

United States Patent Office 3,443,130
Patented May 6, 1969

3,443,130

APPARATUS FOR LIMITING THE MOTIONAL AMPLITUDE OF AN ULTRASONIC TRANSDUCER

Andrew Shoh, Stamford, Conn., assignor, by mesne assignments, to Branson Instruments, Incorporated, Stamford, Conn., a corporation of Delaware

Continuation-in-part of application Ser. No. 265,751, Mar. 18, 1963. This application Dec. 8, 1964, Ser. No. 416,816

Int. Cl. H01v 7/00

U.S. Cl. 310—8.1

10 Claims

ABSTRACT OF THE DISCLOSURE

The disclosed embodiments relate to electrical circuit apparatus for driving a electrostrictive transducer in a manner to maintain its amplitude of vibration substantially constant or at least below a predetermined safe maximum despite variations in acoustical load. This is achieved by supplying the transducer with substantially constant current so as to maintain the transducer motional current and thus its motional amplitude substantially constant despite variations in the acoustical load to which it is coupled.

This application is a continuation-in-part of the application of Andrew Shoh, Ser. No. 265,751 filed Mar. 18, 1963, entitled, Ultrasonic Cleaning Apparatus, now Patent No. 3,293,456.

This invention relates to sonics, more particularly it relates to systems for controlling the power supplied to a sonic transducer system subjected to loads of greatly varying acoustic impedance. The invention comprises automatic self-regulating systems and apparatus for continuously delivering varying amounts of acoustic power that are the maximum that can be safely delivered to a transducer system operating into any acoustic impedance. Thus the invention provides systems that make the most efficient use of acoustical transducing means by insuring that they deliver the greatest acoustic power of which they are capable.

In recent years sonic energy has found wide use in science and industry for cleaning, soldering, welding, material treatment, homogenizing, dispersing, microbiological cell disruption and the like. For many years both magnetostrictive and electrostrictive (piezoelectric) transducers have been used in sonic cleaning systems. Magnetostrictive transducers utilize metal laminated core structures that change in length when subjected to a magnetic field provided by a coil. Electrostrictive or piezoelectric transducers utilize crystalline or ceramic elements that change their length under the influence of an applied electric field. Except for the above-mentioned use in cleaning tanks, up until a few years ago, the vast majority of sonic transducer systems for providing high sonic power levels were of the magnetostrictive type. However, the development of piezoelectric ceramics, such as lead titanite lead zirconate, capable of withstanding the high temperatures developed in high powered transducer systems have lead to their use in high power general purpose systems. Such a general purpose transducer system or sonic converter is disclosed in the copending application of Stanley E. Jacke and Henry Biagini, Ser. No. 384,025 filed July 13, 1964 for Sonic Wave Generator, Patent No. 3,328,610.

In the above-identified application the sonic vibrations developed electrostrictively in a pair of ceramic wafers are concentrated and increased in amplitude by a concentrating horn or acoustic impedance transformers to provide at the end thereof extremely high power densities per unit area. This sonic converter is being used in many of the ultrasonic process applications listed above, for

example, for homogenizing, dispersing and disrupting biological cells, in ultrasonic welding, soldering and treatment of materials and the like.

As discussed in the above-identified copending application, one of the problems encountered in operating such a high power sonic converter is that when the device is energized and the tip of the concentrating horn is not coupled to any medium other than air the tip vibrates violently at very large amplitudes. Very little power is transferred to the air and substantially all of the power supplied to the converter must be dissipated therein. In contrast therewith, when the tip of the concentrating horn is coupled to a less compliant medium, such as a liquid, energy transfer occurs from the horn to such a medium, thus leaving a smaller amount of energy to be dissipated in the converter. Depending upon the efficiency of the converter, the medium which receives the acoustic power and the degree of coupling achieved, the power to be dissipated in the converter may vary over a ratio of 10 to 1 from the condition of no power transfer to the load, to the other condition when good power transfer from the horn to the load is achieved.

In order to protect the transducers from the possibility of destruction by excessive power dissipation, the prior art employed principally two approaches. One method is to limit the power supplied to the converter to the amount of power which the converter safely can dissipate under the condition of no power transfer. As is readily apparent, this approach seriously limits the power which is available to the converter when good power transfer between the horn and the load is achieved. The other approach concerns the provision of manually adjustable power control means, for instance, selectable voltage levels in order to vary the power supplied to the converter. This latter method, as is readily apparent, is not satisfactory as the operator must judge the degree of power transfer and, in the event that too much power is applied to the converter, or if the converter is uncoupled from the load and inadvertently left to operate into air without power reduction, the converter may destroy itself.

As a consequence of these problems, converters of this type have been generally limited to low power levels. For example, the converter disclosed in the above-identified copending application has been limited to a maximum of approximately 100 watts. This being the greatest power the converter can internally dissipate when operating in air. Generally speaking the greater the impedance of the acoustic load presented to the converter the smaller the power supplied to the medium.

I have discovered methods, apparatus and systems for controlling the power supplied to a converter, specifically as disclosed in the above-identified copending application. In order to better understand my invention I have made the following observation utilizing an S–75 converter manufactured by Branson Sonic Power Division of Branson Instruments, Inc., in Danbury, Conn., in accordance to the above-identified copending application.

The Branson S–75 converter was connected to a power amplifier to form an oscillator in the manner described in the above-identified copending application, Ser. No. 265,751, now Patent No. 3,293,456. As explained therein, it thus operated at the frequency of maximum conversion efficiency. The converter using a solid step horn acoustic transformer was operated first in air. Various voltages were supplied to the converter. The amplitude of the motion of the tip of the concentrating horn and the motional current supplied to the converter were measured. The motional current was derived in the manner described in the above-identified copending application. That is, a current equal to the clamped capacitance current of the converter was subtracted from the total

current supplied to the converter. This produces a current equal to the motional current in the series branch equivalent circuit of the converter.

It was found that the motional current supplied to the converter and the amplitude of the motion of the tip of the concentrating horn were directly proportional throughout the useful operating range of the converter. It was further found that this proportionality was independent of the acoustic load presented to the transducer when the transducer was operated in air, water or heavy oil.

It was further found by driving the converter with a variable frequency oscillator that this proportionality was substantially independent of frequency at or near the natural resonance of the transducer.

It was further found that the internal dielectric losses of the converter were small and may be neglected. Furthermore it was found that the internal losses in the converter appear to the driving generator or amplifier as a constant impedance in series with a varying impedance directly proportional to the acoustic load presented to the converter.

It is therefore an object of the present invention to provide systems for keeping the heat dissipation in a sonic converter constant or below a predetermined maximum.

Another object of the invention is to provide systems for keeping the mechanical deformation in a sonic converter constant or below a predetermined maximum.

A further object of the invention is to provide systems for keeping the amplitude of the motion of the transducing elements of a sonic converter constant or below a predetermined maximum.

Still another object of the invention is to provide systems for keeping the power dissipated in a sonic converter constant or below a predetermined maximum.

A still further object of the invention is to provide systems for keeping an electrical quantity supplied to a sonic converter proportional to the quantities of the above objects constant or below a predetermined maximum.

Still another object of the invention is to provide systems for keeping motional current supplied to an electrostrictive sonic converter constant or below a predetermined maximum.

Another object of the invention is to provide systems for increasing the total power supplied to a sonic converter as the acoustic impedance into which the converter is working increases.

Still another object of the invention is to provide systems for keeping the total current supplied to a sonic converter employing electrostrictive elements substantially constant or below a predetermined maximum.

Yet another object of the invention is to provide methods, apparatus and systems for driving a high power sonic converter from an apparently high impedance source.

A further object of the invention is to control the power delivered to an ultrasonic transducer.

Another object of the invention is to compensate for the varying acoustic impedances into which an ultrasonic power transducer operates.

A further object of the invention is to provide systems whereby a conventional ultrasonic power transducer is able to deliver more power into a load than heretofore possible.

Other objects of the invention will in part be obvious and will in part appear hereinafter.

The invention accordingly comprises the features of construction, combinations of elements and arrangements of parts which are all as exemplified in the following detailed disclosure. The scope of the invention will be indicated in the claims.

For a fuller understanding of the nature and objects of the invention reference should be had to the following detailed disclosure taken in connection with the accompanying drawings in which:

FIGURE 1 is a front view, partially cut away, of an ultrasonic power converter and electronic driver in accordance with the present invention.

FIGURE 2 is an equivalent circuit of the ultrasonic power converter shown in FIGURE 1.

FIGURE 3 is a block circuit diagram of another embodiment of the invention.

FIGURE 4 is a block circuit diagram of another embodiment of the invention.

FIGURE 5 is a block circuit diagram of another embodiment of the invention.

FIGURES 6 and 7 are detailed circuit diagrams of a preferred embodiment of the invention combining the embodiments of FIGURES 3, 4 and 5.

FIGURE 8 is a block circuit diagram of another embodiment of the invention.

FIGURE 9 is a block circuit diagram of a preferred embodiment of the invention.

FIGURE 10 is a detailed circuit diagram of the embodiment of the invention of FIGURE 9.

The same reference characters refer to the same elements throughout the several views of the drawings.

GENERAL DESCRIPTION

The ultimate objects of the present invention are to limit the dissipation in a sonic converter to a safe, maximum value for all loading conditions and to obtain a loading characteristic wherein the mechanical power output from the converter increases when the converter operates into a load of increased acoustical impedance.

The invention may be realized in its most perfect form by the use of feedback techniques to hold an electrical quantity proportional to acoustic deformation or motion in the converter constant.

In the case of converters employing electrostrictive elements such an electrical quantity is the motional current I_m. This current may be derived from the electrical power supplied to the converter by compensating for the clamped capacitance of the converter in the manner described in Patent No. 3,293,456.

The ultimate objects of the invention are realized by providing means in the power generator connected to the converter such that the total current supplied to the converter is substantially constant as the converter operates into varying acoustic impedances. Thus, the power generator may be provided, in effect, with a high output impedance by connecting a large impedance in series between the generator and the converter; this impedance being much greater than the effective motional impedance of the converter when operating into a load of the largest acoustical impedance. This is shown in FIGURE 3.

The internal impedance of the generator may also be matched by means of a transformer with the total motional impedance of the converter operating into the highest acoustical impedance to which it is to be subjected as shown in FIGURE 4.

In another embodiment of the invention this object is achieved by operating the converter off resonance so that the effective frequency dependent impedance of the converter becomes a large impedance in series with the load varying impedance of the converter as shown in FIGURE 5.

In FIGURE 6 there is shown in detail a circuit for applying the methods of FIGURES 3, 4 and 5 to a conventional transistorized sonic generator amplifier shown in FIGURE 7. A nonlinear impedance is provided in the positive feedback oscillator circuit of FIGURE 6 that causes the converter to operate below its mechanical resonance and the operating resonance of the circuit when it is initially energized. This prevents oscillation at another undesired fairly strong mechanical resonance in the converter only slightly above the desired operating resonance. The entire oscillator feedback loop of the circuit of FIGURE 7 is characterized by a narrow band characteristic about the desired operating frequency so that operation at other nearby resonances is further inhibited.

In another embodiment of the invention a sonic converter may be connected in loop circuit with a linear amplifier utilizing negative current feedback as shown in FIGURE 8 to provide an effective high output impedance for the generator.

Another method of providing a generator with an effective high output impedance is to drive it from a constant current power supply as shown in FIGURES 9 and 10.

SPECIFIC DESCRIPTION

Now referring to FIGURE 1, a high power density ultrasonic converter is generally indicated at **20**. This is constructed in the manner detailed in the above-identified Patent No. 3,328,610. The converter **20** comprises a metal casing **22** supporting a perforated metal vent plate **24** integral with the transducer system generally indicated at **26**. The transducer system is bolted together and comprises a pair of ceramic discs **28** separated by a metal plate **30**. The ceramic discs **28** are backed by a massive metal back plate **32** and operate into a sonic energy concentrating step horn **34**. Electrical energy is supplied to the transducer system **26** by means of a wire **36** connected to the metal plate **30** and the metal casing **22** connected to the vent plate **24**. The converter also comprises a fan **38** for cooling the transducer system **26**.

Power for the transducer system **26** and the fan **38** is supplied via an insulated cable **40** from a power generator generally indicated at **42**. The power generator **42** is connected via line cable **44** to a supply of 115 volts, 60 cycle power.

The converter **20** may be turned on by means of an on-off switch **46** or by means of a foot switch (not shown) which alternatively may be in series with the on-off switch **46**. A jewel light **48** may be provided to indicate that the power generator **42** is energized. A power level control **50** may also be provided.

The experiments discussed in the introduction above indicate that at a given operating frequency the converter **20** may be represented by the equivalent circuit shown in FIGURE 2. This circuit comprises a clamped capacitance C_O representing the frequency independent capacitance of the converter. The clamp capacitance C_O is in parallel with a resistance R_D representing the dielectric or voltage dependent losses in the converter.

A third parallel arm of the equivalent circuit comprises a frequency dependent reactive impedance X_S which may be represented by the series connected capacitance C and inductance L. The resistance R_I represents the internal motional dependent losses in the converter. The resistance R_L represents the transformed acoustical impedance of the load into which the converter **20** is operated. The resistance R_L has been found to be directly proportional to the acoustical impedance of the load over the useful operating range of the converter **20**. The resistance R_I, that is the motionally dependent internal losses, has been found to be substantially constant over the useful operating range of the converter **20**.

When a Branson Sonifier S–75 converter is operated at 20 kilocycles with a 1½ inch probe terminated by a step horn, R_I is found to be approximately 100 ohms. R_L when the converter operates into air is substantially zero. The total Q of the equivalent circuit is found to be approximately 800. When the converter is loaded, R_L may vary from 200 to several thousand ohms. R_D is so large that it has not been accurately measured but appears to be greater than 100,000 ohms. It can therefore be neglected. C_O is approximately .038 microfarad.

Thus, when operating at resonance, the current I_{CC} through the clamped capacitance C_O is constant. The current I_O through the dielectric resistance R_D is substantially zero. The motional current I_M is substantially dependent on R_L, since at a constant frequency, the reactive impedance of X_S is zero and R_I is constant.

Thus the total current I_O supplied to the converter may be vectorially added to the current passing through a capacitor having a value of .038 microfarad connected across the source of the voltage V_O supplying the converter to derive the motional current I_M. Methods for doing this are disclosed in detail in the above-identified Patent No. 3,293,456.

As disclosed in that application, the derived motional current I_M supplied to the converter may be utilized to provide a *positive feedback signal* for a linear power amplifier in the power generator **42** to cause the entire circuit to oscillate and thus the converter to operate at the natural mechanical resonance of the converter having the highest Q.

In the embodiments of the present invention, it is sought to maintain the motional current I_M through the converter substantially constant despite variations in the acoustical load to which the converter is coupled. When the motional current I_M is kept constant the amount of power delivered by the converter into a load will depend solely on the acoustic impedance of the load. That is, as the asoustic impedance of the load increases, R_L increases and the load dissipated power $I_M^2R_L$ will increase. At the same time the internal motional losses in the converter $I_M^2R_I$ will remain constant.

Constant current through the converter

Now referring to FIGURES 3, 4 and 5, as previously explained, the objects of the invention can be somewhat imperfectly realized by keeping the total current I_O supplied to the converter **20** constant rather than the motional current, at least to the extent that the equivalent circuit of FIGURE 2 is an accurate representation of what is going on in the converter.

External impedance in series with generator and converter

Thus, in FIGURE 3, the power amplifier **54** is connected tot he converter **20** through a reactance **160** of impedance X very much greater than the sum of the internal motional losses R_I and the electrical transformation R_L of the external acoustical impedances into which the converter is to operate. That is:

$$X \gg R_I + R_L$$

In the system shown in FIGURE 3, the total current I_O will remain substantially constant even as R_L varies in accordance with the acoustical load into which the converter operates because the large impedance **160** will essentially determine the current I_O in the circuit. In this way the motional current I_M will also be held substantially constant.

Matching generator to highest acoustical load

Another similar way of attaining the objects of the invention is shown in FIGURE 4. In this system the oscillator **162**, which alternatively could be a power amplifier driven by a positive feedback as in the previously described self-tuning circuit, has an internal impedance R_O. R_O is matched by means of transformer **164** to the maximum impedance of the converter **20** when operated into the maximum acoustic load to which it is subjected.

Thus, in the system of FIGURE 4 when the converter is unloaded, that is operating in air or a vacuum, because of the large disparity between the large internal impedance R_O of the oscillator **162** and the small internal impedance of the converter **20** only a small amount of power will be delivered thereto. However, as the acoustic load on the converter **20** increases, the converter will become increasingly matched to the internal impedance R_O of the oscillator **162** and the power delivered by the converter **20** will be at its maximum.

Operating converter off resonance

Now referring to FIGURE 5, another method of keeping the total current supplied to the converter constant is to operate it off its natural resonant frequency. In the system illustrated in FIGURE 5 the operating frequency

F_O supplied by an oscillator or determined by the total phase shift in a feedback circuit connected to the power amplifier **54** is different from the mechanical resonance frequency F_M of the converter **20**. Since the converter is not operating at resonance, the reactive impedance X_S of the converter is not zero. It may be made as large as desired by operating as far as necessary off resonance. Thus, when the reactive impedance X_S is very much greater than the sum of the internal motional losses R_I and the electrical transformation R_L of the maximum external impedance into which the converter operates, the motional current I_M will be substantially determined by the reactive impedance X_S and will be independent of load.

A preferred embodiment

A detailed circuit of a power generator embodying the invention as illustrated in FIGURES 3, 4 and 5 is shown in FIGURES 6 and 7. FIGURE 7 is a circuit diagram of a conventional two stage transistorized power amplifier **166**.

Now referring to FIGURE 7, amplifier **166** is driven from a minus 25 volt D.C. power supply connected to terminal **168**. The first stage of the amplifier comprises four type 2N1905 transistors generally indicated at **170**. The bases of one pair of transistors **170** are connected together and through parallel connected resistor **172** and capacitor **174** to terminal **176**. The bases of another pair of transistors **170** are connected through resistor **178** and capacitor **180** to terminal **182**. The emitters of all transistors are connected together and through parallel connected resistor **184** and capacitor **186** to terminal **188**. The collectors of the upper pair of transistors **170** are connected together through the upper half of the center tapped primary winding of transformer **190** and through capacitor **192** to ground. The emitters of all transistors are grounded. Diodes **194** are connected between the collectors and emitters of each pair of transistors **174**.

Resistors **172** and **178** are each 47 ohms, 1 watt resistors. Capacitors **174** and **180** are each .22 microfarad, 50 volt capacitors. Resistor **184** is a 68 ohm, ½ watt resistor. Capacitor **186** is a 10 microfarad, 150 volt capacitor. Capacitor **192** is a 50 microfarad, 150 volt capacitor. Diodes **194** are each type 1N2071. The first stage of amplifier **166** is connected to the power supply terminal **168** through resistors **196** and **198**. Resistor **196** is a 390 ohm, 1 watt resistor. Resistor **198** is a 2 ohm, 10 watt resistor.

The secondary of transformer **190** is connected through a 2 microfarad, 200 volt capacitor **200** to the primary of a second transformer **192** to form an interstage transformer from the first stage to the second stage of amplifier **166**. Transformers **190** and **192** are wound on Allen Bradley type RO34 cores, catalog number E–1102–142A. The primary of transformer **190** comprises 40 turns and is center tapped. The secondary comprises 30 turns. The primary of transformer **192** comprises 6 turns and its center tapped secondary comprises 6 turns. No. 24 wire is used in the primary of transformer **190**. No. 22 wire is used in the secondary thereof. Both coils of transformer **202** are wound with No. 20 wire.

The second stage of amplifier **166** comprises eight type 2N2076 transistors, generally indicated at **204**. Transistors **204** are connected in parallel groups of four to provide a push-pull output stage. The bases of four of the transistors **204** are connected to the upper half of the secondary of transformer **202** and through the center tap thereof and resistor **206** to power supply terminal **168**.

Resistor **206** is a 470 ohm, 1 watt resistor. The center tap of the secondary of transformer **202** is connected through the parallel combination of resistor **208** and capacitor **210** to ground. Resistor **208** is a 1 ohm, 10 watt resistor. Capacitor **210** is a 50 microfarad, 50 volt capacitor. The emitters of each of the transistors **204** are connected through eight parallel connected resistors, generally indicated at **212**, to ground. Each of resistors **212** are .2 ohm, rated at 10 watts. The collectors of the four upper transistors **204** are connected together and through the upper half of the primary of an output transformer **214** and through the center tap thereof to terminal **168**. Similarly, the collectors of the lower four transistors **204** are connected together and through the lower primary of transformer **204** to terminal **168**. The secondary of transformer **214** is connected to terminals **216** and **218**.

Transformer **214** is wound on an Allen Bradley type WO4 core, catalog number U3000 D 137A. The primary comprises 12 center tapped turns of No. 12L wire. The secondary comprises 130 turns of No. 22 wire and the primary and secondary are bifilarly wound.

As previously stated, amplifier **166** is conventional.

Now referring to FIGURE 6, the power control elements of the invention, generally indicated at **220** and the converter **20** are shown connected in circuit with the amplifier **166** of FIGURE 7 to attain the objects of the invention. Current transformer **222** is the input transformer to the first stage of amplifier **166** in FIGURE 7. Transformer **222** comprises a 22 turn, center tapped, primary and a 14 turn, center tapped, secondary wound on one U and one bar shaped Allen Bradley type WO4 cores, catalog numbers U2375 D 129C and B2375 D 307A, and is wound with No. 20 wire. The cores are spaced apart by an air gap of approximately .022 inch. The secondary of transformer **222** is connected, as shown, to the input terminals **176**, **182** and **188** of the first or driver stage of amplifier **166** of FIGURE 7.

The output terminals **216** and **218** of the output transformer **214** of the amplifier **166** of FIGURE 7 are connected in circuit with the converter from terminal **216** through a 1.32 millihenry inductor **224** through the converter **20** to ground, from ground through the lower half of the primary of transformer **222** to terminal **218** of the output transformer **214** shown in FIGURE 7. Thus the total current I_O supplied to the converter **20** passes through the lower half of the primary of transformer **222**. The clamped capacitance compensating current I_{cc} passes through capacitor C of .0038 microfarad, 2500 volt rating through the upper half of the primary of transformer **222**. The current in the secondary of transformer **222** is therefore directly proportional to the motional current I_M.

The indicator **224** compensates for the reactive nature of the load in the manner well known in the art. This inductor is wound on an Allen Bradley WO4 core, catalog number U2375 D 129C and comprises 149 turns of No. 22L wire.

The ouptut transformer **214** of FIGURE 7, constructed in the manner described, is not matched to the converter **20** when it is operating in air. In the design illustrated in FIGURES 6 and 7, it is approximately matched to the converter when the converter is operating as a plastic welder. Thus, the overall circuit operates in part in the manner shown in FIGURE 4.

Furthermore, the converter **20** is caused to operate off its natural mechanical resonance. In the case illustrated, this is a few hundred cycles below its natural resonance of approximately 20 kilocycles.

This off resonance operation is in part accomplished by choosing inductor **224** to be too large to precisely compensate for the reactive load of capacitor C and converter **20** and by means of capacitors **226** and **228** and resistor **230** connected across the lower primary of transformer **222**.

Capacitor **226** is 3 microfarads rated at 200 volts and capacitor **228** is 1 microfarad also rated at 200 volts. Variable resistor **230** is 50 ohm maximum and is rated at 4 watts. Capacitor **226** and **228** tune with the lower half primary of transformer **222** to form a narrow band pass filter so that the entire loop circuit comprising the converter **20**, the feedback network **220** and the amplifier **166** of FIGURE 7 can only operate around a narrow band of frequencies near the natural resonance of the converter **20**.

Additionally, this circuit of capacitors **226** and **228**

and the lower half of the primary of transformer **222** is tuned to a slightly higher frequency than the natural frequency of the converter **20**. This additional phase shift is partially responsible for the converter operating at a slightly lower frequency than its natural frequency. The frequency of operation may be adjusted by adjusting variable resistor **230**. The off resonance operation results in the converter having a large internal reactive impedance K_S as shown in FIGURE 5.

Because the converter **20** has a natural resonance at approximately 26 kilocycles which is quite strong, an additional precaution is taken to insure that when the converter is first turned on its begins to oscillate at the desired 20 kilocycle natural frequency. This is accomplished by adjusting variable resistor **230** so that the frequency of operation is several hundred cycles lower than that desired for steady state operation.

An inductor **232** connected in series with back-to-back diodes **233** is also connected across the lower half primary of transformer **222**. When power is initially applied to the converter **20**, the voltage across the lower half primary of transformer **222** will be lower than the forward voltage of diodes **233** and inductor **232** will not be in the circuit. Only after the oscillations build up in the circuit at the frequency well below the desried natural resonance of the converter **20** will the forward voltage of diodes **233** be exceeded. Then, inductor **232** will be in the circuit and will partially compensate for the capacitance of capacitors **226** and **228**. The frequency of operation of the converter then increases to the desired operating frequency. Inductor **232** comprises 32 turns of No. 26 wire on one leg of a C core, Allen Bradley type WO4, catalog number U2375 D 129C. Diodes **232** are each type 1N2071.

The overall circuit of FIGURES 6 and 7 controls converter **20** such that, when operated in air, approximately 80 watts are dissipated therein and as the acoustic impedance of the load increases, up to 250 watts may be dissipated in the transducer load combination. No more than approximately 60 watts of this total is dissipated internally. Thus, the converter **20** can deliver into a load up to as much as approximately 190 watts, whereas the converter operated without the cotnrol circuit illustrated in FIGURE 6, using the same amplifier, can deliver perhaps as little as ten percent of this amount into a load.

Negative current feedback amplifier

Now referring to FIGURE 8, another embodiment of the invention for keeping the total current supplied to the converter substantially constant comprises utilizing negative feedback with a power amplifier **54** so that it forms in effect a constant current amplifier **234**. The input to the constant current amplifier **234** may be I_M as derived from a clamped compensating capacitor C, converter **20** and summing network **56**, in the manner previously described, or may be supplied by an oscillator at the natural resonance frequency of the converter **20**.

Power amplifier **54** is supplied with negative feedback voltage derived across resistor R in a well-known manner. This is combined with the input I_M by the resistor network R_1 and R_2 as will be well understood by those skilled in the art. This negative feedback results in amplifier **234** having an effective large internal impedance so that I_T, the current supplied to the converter and capacitor C is substantially constant. Thus, I_O is also held constant.

Current controlled power supply

The object of obtaining a power amplifier having constant current source characteristic may also be obtained in the manner shown in FIGURE 9. There the power amplifier **54** is supplied from a constant current power supply **236** connected to the power line. Constant current power supply **236** produces a constant power supply current I_{CC} to the power amplifier **54** and, as is well known to those skilled in the art, this will cause the output current I_T and current I_O supplied to the converter **20** to be substantially constant. The power amplifier may be driven from an oscillator or a feedback circuit as has been previously described.

A detailed circuit operating in the manner shown in FIGURE 9 is shown in FIGURE 10. Now referring to FIGURE 10, line plug **236** is connected to a source of 115 volt, 60 cycle A.C. Power is supplied to the power supply transformer **238** through a fuse **240** and a switch **242**. The secondary of transformer **238** is center tapped. The secondary produces 50 volts A.C. across rectifiers **244**, both type 1N2071. They are connected to a filter network comprised of a 5 ohm resistor **246** and a 100 microfarad capacitor **248** in the well known manner.

The constant current characteristic to keep the output current I_{CC} of the power supply constant is obtained by connecting a transistor **250** type 2N350A in the power supply circuit, in the manner shown. By means of resistors **252** connected to the base of transistor **250**, variable resistor **254**, and fixed resistor **256**, the bias between the emitter and the base of transistor **250** is fixed in accordance with the forward voltage drop across diodes **258**. Resistor **252** is 470 ohms, variable resistor **254** has a maximum resistance of 5 ohms and resistor **256** is 1 ohm. Diodes **258** are each type 1N2071.

The emitter base bias of transistor **250** may be adjustably fixed by adjusting resistor **254** at approximately 1 volt and the power supply current I_{CC} may be fixed at 0.6 amps in accordance with the characteristic of transistor **250**. The amplifier **260**, which is driven from the power supply, is a 10 watt self-tuning amplifier for use with a converter **251** used in microbiological cell disruption, and the like, where only low power total power levels are desired. The amplifier comprises a single push-pull stage comprising two transistors generally indicated at **262**, these are type 2N1905. The emitters of transistors **262** are connected through 1 ohm resistors **264** to the collector of transistor **250**. The collectors of transistor **262** are connected across the primary of an output transformer **265**. The bases of transistors **262** are connected across a center tapped secondary of an input current transformer **266**. The center tap of the current transformer **266** is connected through a 10 microfarad capacitor **268** and a 68 ohm resistor **270** to the collector of transistor **250**. The center tap of current transformer **266** is also connected to the other side of the power supply through a 1 kilohm resistor **272**. The center tap of output transformer **265** is also connected to this common terminal of the power supply.

The secondary of output transformer **265** is connected in circuit with the converter **251** and one-half of the primary of current transformer **266**. It is also connected in circuit through a compensating capacitor **274** and the other side of the primary of current transformer **266**. The small converter **251** has a clamped capacitance of .002 microfarad and therefore the compensating capacitor **274** has the same capacitance. The primary of transformer **266** comprises 8 turns, center tapped. The secondary comprises 16 turns, center tapped. The primary of output transformer **265** comprises 30 turns, center tapped and the secondary also comprises 30 turns.

It will be seen that the input signal applied to the transistors **262** from the secondary of transformer **266** is proportional to the motional current I_M in the converter **251** and the circuit therefore operates at the frequency of maximum conversion efficiency of the converter. The output current I_T of transformer **265** will be substantially constant as will the current I_O supplied through the converter. This is due to the constant current operation of the amplifying transistors **262**.

SUMMARY OF THE INVENTION

It will thus be seen that I have provided apparatus and systems for keeping the dissipation in a high power density sonic converter, due to motion therein, substantially constant by keeping an electrical quantity derived

from the power supplied to the converter constant. In the case of sonic converters employing electrostrictive elements, this electrical quantity may conveniently be the motional current in the converter.

The systems that I have provided for obtaining relatively constant motional current utilize means for creating a large impedance effectively in series between the sonic power generator and the motional resistance of the sonic converter.

It will be obvious to those skilled in the art that the systems, circuits, methods and apparatus disclosed herein may be modified in many ways for use in practical sonic converter systems specifically designed for particular working conditions. It will also be obvious to those skilled in the art that the methods, apparatus and systems disclosed herein may be modified for use with sonic converters employing magnetostrictive elements.

It will further be noted that the detailed systems disclosed herein all employ positive feedback derived from the motional current in sonic converters employing electrostrictive elements for controlling the frequency of operation of the converter in the manner disclosed in my above-identified Patent No. 3,293,456.

It will further be seen that in the present application I teach the use of an amplifier system connected in such positive feedback circuits having a narrow band pass characteristic centered about the desired operating frequency of the converter with which it is connected. Furthermore, I provide novel means for causing the converter, when initially turned on, to operate off its normal operating frequency so that as oscillations build up in the converter it approaches its operating frequency from either a lower or a higher initial frequency of operation in order to avoid operation of the converter at an undesired nearby mechanical resonance.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above methods, systems, apparatus and circuits without departing from the scope of the invention it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention, which, as a matter of language, might be said to fall therebetween.

Having described my invention what I claim as new and desire to secure by Letters Patent is:

1. Apparatus of the class described comprising, in combination:

(A) an electroacoustic sonic converter, having at least one electrostrictive element;

(B) a sonic power generator connected in circuit with said electroacoustic converter; and

(C) an impedance in series circuit with the motional dependent resistive impedance of said converter and said generator,

(1) said series impedance being substantially greater than the internal impedance of said converter plus the impedance of the acoustic load on said converter, whereby the total current supplied to said converter when presented with varying acoustic loads is substantially constant,

(2) the current through said series impedance being essentially equal to the current through said concerter resistive impedance.

2. The apparatus defined in claim **1** which further includes

(D) feedback circuit means supplying a signal corresponding to the motional current in said converter to said generator such as to control the operating frequency of said converter.

3. The apparatus defined in claim **1** wherein said series impedance comprises an internal impedance of said sonic power generator.

4. The apparatus defined in claim **1** wherein said series impedance comprises a reactive impedance in said converter created by operation of said converter at a frequency different from its natural mechanical resonant frequency.

5. The apparatus as defined in claim **1** wherein a transformer is connected in circuit between said sonic power generator and said sonic converter such that the power generator is reflected as a high impedance source.

6. The apparatus of the class described comprising, in combination:

(A) a power amplifier having an input and an output transformer;

(B) an electroacoustic sonic converter;

(C) an inductor;

(1) connected in series circuit with the secondary of said output transformer and said converter and a portion of the primary winding of said input transformer,

(2) the secondary of said output transformer also connected in circuit with said inductor, a capacitor, and another portion of the primary of said input transformer, whereby the current in the secondary of said input transformer is proportional to the motional current in said converter; and

(D) a reactive impedance connected in circuit with the primary of said input transformer and tuned therewith to cause said converter to operate at a frequency other than its resonant frequency.

7. The apparatus as claimed in claim **6** wherein said inductor has a value to detune its circuit whereby the converter operates at a frequency differing from its natural mechanical resonance.

8. The apparatus as claimed in claim **7** wherein said output transformer causes the internal impedance of said power amplifier to be mismatched from said converter when unloaded and to be matched with said converter when said converter is loaded with the largestacoustic impedance to which it is subjected.

9. Apparatus as claimed in claim **6** which further includes

(E) an additional reactive impedance connected in circuit with nonlinear responsive means and with the primary of said input transformer whereby said additional impedance means has no effect on the primary of said input transformer until the current therethrough reaches a critical value as determined by said nonlinear responsive means to thus connect said additional impedance means in circuit wtih the primary of said input transformer to cause the frequency of operation of said converter to change.

10. Apparatus as claimed in claim **9** wherein said capacitor is tuned with the primary of said input transformer to produce a narrow bandpass frequency characteristic in said power amplifier.

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