(12) **EUROPEAN PATENT APPLICATION**

(54) **Multifrequency ultrasonic structural actuators**

(57)   The propagation of ultrasonic energy in arbitrary shaped solid structures (D), heavy and very-thick-walls metal containers, pressurized reservoirs, very-thick metal-walls autoclaves, in different mechanical oscillating structures and systems,... is realized using a novel ultrasonic structural, multifrequency actuator (including very particular multifrequency ultrasonic power supply, also the subject of this invention), able to initiate ringing and relaxing, multimode mechanical oscillations (harmonics and sub harmonics) in any heavy-duty, bulky and rigid system, producing pulse-repetitive, phase, frequency and amplitude-modulated bulk-wave-excitation (covering and sweeping extremely large frequency area). Such ultrasonic driving is creating uniform and homogenous distribution of acoustical activity on a surface and inside of the vibrating system, while avoiding creation of stationary and standing waves structure, making that the complete vibrating system is fully agitated. Multifrequency ultrasonic structural actuator is ideal for agitating arbitrary distant and arbitrary shaped liquid and solid masses placed in different open or pressurized vessels, containers, autoclaves, reservoirs and pipes, transferring vibrations via wave-guide solid rod fixed betweem the transducer and a loading mass (where loading mass presents an oscillating body, and/or oscillating vessel, autoclave, container...). This invention presents an extension and continuation of the previous patent, originating from the same Author/Inventor (see 1 060 789 A1), explaining the additional aspects of particular electronics necessary to drive ultrasonic transducers in a multifrequency and multi-mode oscilating regime/s, while keeping high efficiency of electric and ultrasonic energy transfer and/or transformation. Fields o f possible applications related to this invention are: Ultrasonic Cleaning, Welding,Material Processing, Sonochemistry, Liquid Metals treatment, Atomization, Materials Testing, Aging and Stress Release, Homogenization, Process Industry, etc.
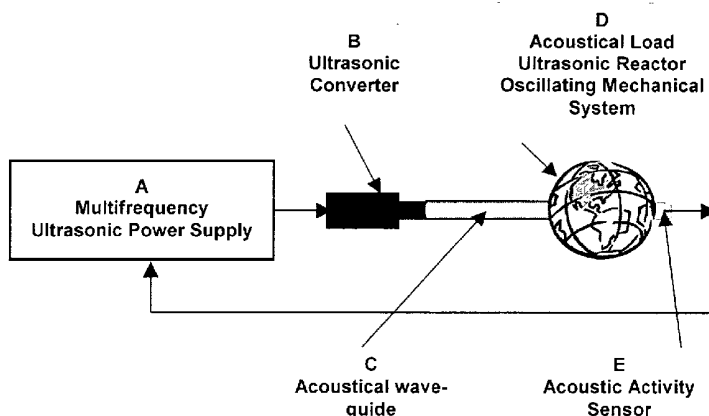
Fig. 1 Block Diagram of a Multifrequency Structural Actuator

Description

Prior Art:

[0001] All double piston, single-element or multi-elements sandwich acoustic transducers, piezoelectric and magnetostrictive stacks, and all types of traditional Bolted Langevin Transducers, as well as Ultrasonic Cleaning and Ultrasonic Welding transducers **operating on a constant resonant frequency (or in a relatively narrow vicinity around certain resonant frequency; -meaning in the frequency interval less than 10% of resonant frequency)**, and their Ultrasonic Power Supplies (or ultrasonic Generators) tuned to operate and track the constant resonant frequency, belong to the Prior Art in the field of acoustic, sonic and ultrasonic sources. Double piston and constant resonant frequency oscillating mode (axial both side contraction-extension mode) is an essential characteristic of all Prior Art transducers.

[0002] **European patents regarding Ultrasonic Transducers:**

[0003] Applicant and Inventor: Miodrag Prokic, 2400 Le Locle EP 1 060 798 A1, Date of filing: 18.06.1999, Date of publication: 20.12.2000
Applicant: Gould Inc. Inventor: Thompson, Stephen Publication number: 0 209 238, A2, int. Cl.: H 04 R 17/10, from 21.01.87

[0004] **U.S. Patent Documents regarding Ultrasonic Transducers:**

4,537,511	8/1985	Frei	310/323
5,200,666	4/1993	Walte et al.	310/323; 310/325
2,990,482	6/1961	Kenny	310/323
3,546,498	12/1970	McMaster et al.	310/323
3,578,993	5/1971	Russell	310/323
3,777,189	12/1973	Skinner et al.	310/328
3,975,698	8/1976	Redman	310/328
4,352,039	9/1982	Hagood et al.	310/328
3,331,589	7/1967	Hammit et al.	366/118 X
3,381,525	5/1968	Kartluke et al.	310/323 X
3,421,939	1/1969	Jacke	134/1
3,542,345	11/1970	Kuris	366/118 X
3,628,071	12/1971	Harris et al.	310/323 X
3,672,823	6/1972	Boucher	134/1 X
3,680,841	8/1972	Yagi et al.	366/118
3,698,408	10/1972	Jacke	366/127 X
3,945,618	3/1976	Shoh	366/118
4,016,436	4/1977	Shoh	310/323

BACKGROUND OF THE INVENTION:

[0005] All today's ultrasonic actuators or transducers (Prior Art) are oscillating in a kind of simple or mixed, constant-frequency contraction-extension vibration mode. This usual mode of oscillations can be described when one or more, axial, lateral or any other space dimension of transducer is/are periodically changing length (following some simple sinusoidal function). Briefly, we can say/simplify that all conventional (industrial, material processing, moderate and high power) ultrasonic sources (performing contraction-extension) have as an input certain (constant frequency) oscillating electrical signal, and producing as an output, (proportional) oscillating (mechanical) amplitude.

[0006] The high power ultrasonic system (the subject of this invention; - see Fig. 1) generates multimode and high power mechanical oscillations in a certain mechanical system, over a wide frequency range. This is in contrast to conventional power ultrasonic systems, which operate at a single frequency. In addition the method of driving these transducers is optimized.

[0007] Every elastic mechanical system has many vibration modes, plus harmonics and sub harmonics, both in low and ultrasonic frequency domains. Many of vibrating modes could be acoustically and/or mechanically coupled, and others would stay relatively independent. Here described multimode ultrasonic source has the potential to synchronously excite many vibrating modes (including harmonics and sub harmonics), producing a uniform and homogenous repetition of high intensity vibrations.

[0008] The oscillations of here-described ultrasonic source are not random - rather they follow a consistent pulse-

repetitive pattern, frequency and amplitude-modulated by the control system. This avoids the creation of stationary or standing waves (typically produced by traditional ultrasonic systems operating at a single frequency) that generate regions of high and low acoustic activity.

[0009] This technique (multimode and wide-band excitation) is beneficial in many other applications, e.g. Liquid processing, fluid atomization, powders production, artificial aging of solids and liquids, accelerated stress relief, advanced ultrasonic cleaning, liquid metal treatment, surface coating, accelerated electrolysis, mixing and homogenizing of any fluid, waste water treatment, water sterilization, accelerated heat exchange...

[0010] A Multifrequency Ultrasonic Structural Actuator (see Fig. 1) consist of:

A) Sweeping-frequency Ultrasonic Power Supply (including all regulations, controls and protections),
B) High Power Ultrasonic Converter (see also Patent EP 1 060 798 A1),
C) Acoustical Wave-guide (metal rod, aluminum, titanium), which connects ultrasonic transducer with an acoustic load, oscillating body, resonator...
D) Acoustical Load (mechanical resonating body, sonoreactor, radiating ultrasonic tool, sonotrode, test specimen, vibrating tube, vibrating sphere, a mold, solid or fluid media, autoclave...),
E) Sensors of acoustical activity fixed on/in/at an Acoustical Load (accelerometers, ultrasonic flux meters, cavitation detectors, laser vibrometer/s...), which are creating regulation-feedback between the Acoustical Load and Ultrasonic Power Supply.

[0011] A strong mechanical coupling of high power ultrasonic converter (B) to the test specimen or acoustical load (D) is realized using acoustic-wave guide metal rod (C). Ultrasonic converter (B) is electrically connected to the ultrasonic power supply (A), or ultrasonic multimode generator. Acoustic activity sensors (E) are realizing feedback (for the purpose of automatic process control) between Acoustical Load (D) and Ultrasonic Power Supply (A).

The important background (Prior Art) about PLL (auto resonant-frequency control) of mechanically and acoustically loaded ultrasonic transducer/s

[0012] In applications such as Ultrasonic Welding, single operating, well-defined, resonant frequency transducers are usually used (operating often on 20, 40 and sometimes around 100 kHz and much higher). In recent time, some new transducer designs can be driven on limited sweeping frequency intervals (applied to a single transducer: see also Patent EP 1 060 798 A1).

[0013] In Sonochemistry and Ultrasonic Cleaning we use single or multiple ultrasonic transducers (operating in parallel), with single resonant frequency, two operating frequencies, multi-frequency regime, and all of the previously mentioned options combined with frequency sweeping. Frequency sweeping is related to the vicinity of the best operating (central) resonant frequency of transducer group. Frequency sweeping can also be applied in a low frequency (PWM, ON-OFF) group modulation (producing pulse-repetitive ultrasonic train, sometimes-called digital modulation).

[0014] Also, multi-frequency concept can be used in Sonochemistry and Ultrasonic Cleaning when we can drive a single transducer on its ground (basic, natural) frequency and on several higher frequency harmonics (jumping from one frequency to another, without changing transducer/s).

[0015] Real time and fast automatic resonant (or optimal operating frequency) control/tuning of ultrasonic transducers is one of the most important tasks in producing (useful) ultrasonic energy for different technological applications, because in every application we should realize/find/control:

1 ° The best operating frequency regime in order to stimulate only desirable vibrating modes.
2° To deliver a maximum of real or active power to the load (in a given/found operating frequency domain/s).
3° To keep ultrasonic transducers in a pulse-by-pulse, real time, safe operating area regarding all critical overload/ overpower situations, or to protect them against: over-voltage. over-current, overheating, etc.

[0016] All of the previously mentioned (control and protecting) aspects are so interconnected, that none of them can be realized independently, without the other two. All of them also have two levels of control and internal structure:

[0017] Up to a certain (first) level, with the design and hardware, we try to insure/incorporate the most important controls and protecting, (automatic) functions.
At the second level we include certain logic and decision-making algorithm (software) that takes care of real-time and dynamic changes and interconnections between them.

[0018] It is necessary to have in mind that in certain applications (such as ultrasonic welding), operating and loading regime of ultrasonic transducer changes drastically in relatively short time intervals, starting from a very regular and no-load situation (which is easy to control), going to a full-load situation, which changes all parameters of ultrasonic system (impedance parameters, resonant frequencies...). In a no-load and/or low power operation, ultrasonic system

behaves as a typically linear system; however, in high power operation the system becomes more and more non-linear (depending on the applied mechanical load). The presence of dynamic and fast changing, transient situations is creating the absolute need to have one frequency auto tuning control block, which will always keep ultrasonic drive (generator) in its best operating regime (tracking the best operating frequency).

The meaning of mechanical loading of ultrasonic transducers:

[0019]   Mechanical loading of the transducer means realizing contact/coupling of the transducer with a fluid, solid or some other media (in order to transfer ultrasonic vibrations into loading media). All mechanical parameters/properties (of the load media) regarding such contact area (during energy transfer) are important, such as: contact surface, pressure, sound velocity, temperature, density, mechanical impedance, ... Mechanical load (similar to electrical load) can have resistive or frictional character (as an active load), can be reactivelimaginary impedance (such as masses and springs are), or it can be presented as a complex mechanical impedance (any combination of masses, springs and frictional elements). In fact, direct mechanical analogue to electric impedance is the value that is called Mobility in mechanics, but this will not influence further explanation. Instead of measuring complex mechanical impedance (or mobility) of an ultrasonic transducer, we can easily find its complex electrical impedance (and later on, make important conclusions regarding mechanical impedance). Mechanical loading of a piezoceramic transducer is transforming its starting impedance characteristic (in a no-load situation in air) into similar new impedance that has lower mechanical quality factor in characteristic resonant area/s. There are many electrical impedance meters and network impedance analyzers to determine/measure full (electrical) impedance-phase-frequency characteristic/s of certain ultrasonic transducers on a low sinus-sweeping signal (up to 5 V rms.). However, the basic problem is in the fact that impedance-phase-frequency characteristics of the same transducer are not the same when transducer is driven on higher voltages (say 200 Volts/mm on piezoceramics). Also, impedance-phase-frequency characteristics of one transducer are dependent on transducer's (body) operating temperature, as well as on its mechanical loading. It is necessary to mention that measuring electrical Impedance-Phase-Frequency characteristic of one ultrasonic transducer immediately gives almost full qualitative picture about its mechanical Impedance-Phase-Frequency characteristic (by applying a certain system of electromechanical analogies). We should not forget that ultrasonic, piezoelectric transducer is almost equally good as a source/emitter of ultrasonic vibrations and as a receiver of such externally present vibrations. While it is emitting vibrations, the transducer is receiving its own reflected (and other) waves/vibrations and different mechanical excitation from its loading environment. It is not easy to organize such impedance measurements (when transducer is driven full power) due to high voltages and high currents during high power driving under variable mechanical loading. Since we know that the transducer driven full power (high voltages) will not considerably change its resonant points (not more than ±5% from previous value), we rely on low signal impedance measurements (because we do not have any better and quicker option). Also, power measurements of input electrical power into transducer, measured directly on its input electrical terminals (in a high-power loading situation) are not a simple task, because we should measure RMS active and reactive power in a very wide frequency band in order to be sure what is really happening. During those measurements we should not forget that we have principal power delivered on a natural resonant frequency (or band) of one transducer, as well as power components on many of its higher and lower frequency harmonics. There are only a few available electrical power meters able to perform such selective and complex measurements (say on voltages up to 5000 Volts, currents up to 100 Amps, and frequencies up to 1 MHz, just for measuring transducers that are operating below 100 kHz).

Optimal driving of ultrasonic transducers:

[0020]   For optimal transducer efficiency, the best situation is if/when transducer is driven in one of its mechanical resonant frequencies, delivering high active power (and very low reactive power) to the loading media. Since usually resonant frequency of loaded transducer is not stable (because of dynamical change of many mechanical, electrical and temperature parameters), a PLL resonant frequency (in real-time) tracking system has to be applied. When we drive transducer on its resonant frequency, we are sure that the transducer presents dominantly resistive load. That means that maximum power is delivered from ultrasonic power supply (or ultrasonic generator) to the transducer and later on to its mechanical load. If we have a reactive power on the transducer, this can present a problem for transducer and ultrasonic generator and cause overheating, or the ultrasonic energy may not be transferred (efficiently) to its mechanical load. Usually, the presence of reactive power means that this part of power is going back to its source. The next condition that is necessary to satisfy (for optimal power transfer) is the impedance matching between ultrasonic generator and ultrasonic transducer, as well as between ultrasonic transducer and loading media. If optimal resonant frequency control is realized, but impedance/s matching is/are not optimal, this will again cause transducer and generator overheating, or ultrasonic energy won't be transferred (efficiently) to its mechanical load. Impedance matching is an extremely important objective for realizing a maximum efficiency of an ultrasonic transducer (for good impedance

matching it is necessary to adjust ferrite transformer ratio and inductive compensation of piezoelectric transducer, operating on a properly controlled resonant frequency). Output (vibration) amplitude adjustments, using boosters or amplitude amplifiers (or attenuators) usually adjust mechanical impedance matching conditions. Recently, some ultrasonic companies (Herman, for instance) used only electrical adjustments of output mechanical amplitude (for mechanical load matching), avoiding any use of static mechanical amplitude transformers such as boosters (this way, ultrasonic configuration becomes much shorter and much more load-adaptable/flexible, but its electric control becomes more complex). By the way, we can say that previously given conditions for optimal power transfer are equally valid for any situation/system where we have energy/power source and its load (To understand this problem easily, the best will be to apply some of the convenient systems of electromechanical analogies).

[0021]   It is important to know that Impedance-Phase-Frequency characteristics of one transducer (measured on a low sinusoidal-sweeping signal) are giving indicative and important information for basic quality parameters of one transducer, but not sufficient information for high power loaded conditions of the same transducer. Every new loading situation should be rigorously tested, measured and optimized to produce optimal ultrasonic effects in a certain mechanical load.

[0022]   It is also very important to know that safe operating limits of heavy-loaded ultrasonic transducers have to be controlled/guaranteed/maintained by hardware and software of ultrasonic generator. The usual limits are maximal operating temperature, maximal-operating voltage, maximal operating current, maximal operating power, operating frequency band, and maximum acceptable stress. All of the previously mentioned parameters should be controlled by means of convenient sensors, and protected/limited in real time by means of special protecting components and special software/logical instructions in the control circuits of ultrasonic generator. A mechanism of very fast overpower/overload protection should be intrinsically incorporated/included in every ultrasonic generator for technologically complex tasks. Operating/resonant frequency regulation should work in parallel with overpower/overload protection. Also, power regulation and control (within safe operating limits) is an additional system, which should be synchronized with operating frequency control in order to isolate and select only desirable resonances that are producing desirable mechanical output.

[0023]   Electronically, we can organize extremely fast signal processing and controls (several orders of magnitude faster than the mechanical system, such as ultrasonic transducer, is able to handle/accept). The problem appears when we drive ultrasonic configuration that has high mechanical quality factor and therefore long response time, which is when mechanical inertia of ultrasonic configuration becomes a limiting factor. Also, complex mechanical shapes of the elements of ultrasonic configuration are creating many frequency harmonics, and low frequency (amplitude) modulation of ultrasonic system influencing system instability that should be permanently monitored and controlled. We cannot go against physic and mechanical limitations of a complex mechanical system (such as ultrasonic transducer and its surrounding elements are), but in order to keep ultrasonic transducer in a stable (and most preferable) regime we should have absolute control over all transducer loading factors and its vital functions (current, voltage, frequency...). This is very important in case of applications like ultrasonic welding, where ultrasonic system is permanently commuting between no-load and full load situation. In a traditional concept of ultrasonic welding control we can often find that no-load situation is followed by the absence of frequency and power control (because system is not operational), and when start (switch-on) signal is produced, ultrasonic generator initiates all frequency and power controls. Some more modern ultrasonic generators memorize the last (and the best found) operating frequency (from the previous operating stage), and if control system is unable to find the proper operating frequency, the previously memorized frequency is taken as the new operating frequency. Usually this is sufficiently good for periodically repetitive technological operations of ultrasonic welding, but this situation is still far from the optimal power and frequency control. In fact, the best operating regime tuning/tracking/control should mean a 100% system control during the totality of ON and OFF regime, or during full-load and no-load conditions. Previously described situation can be guaranteed when Power-Off (=) no-load situation is programmed to be (also) one transducer-operating regime which consumes very low power compared to Power-ON (=) full-load situation. This way, transducer is always operational and we can always have the necessary information for controlling all transducer parameters. Response time of permanently controlled/driven ultrasonic transducers can be significantly faster than in the case when we start tracking and control from the beginning of new Power-ON period.

[0024]   When transducers are driven full power, it happens in the process of harmonic oscillation, so input electrical energy is permanently transformed to mechanical oscillations. What happens when we stop or break the electrical input to the transducer? - The generator no longer drives the transducer, and/or they effectively separate. The transducer still continues to oscillate certain time, because of its elastomechanical properties, relatively high electro-mechanical Q-factor, and residual potential (mechanical) energy. Of course, the simplest analogy for an ultrasonic transducer is a certain combination of Spring-Mass oscillating system. Any piezoelectric or magnetostrictive transducer is a very good energy transformer. It means that if the input is electrical, the transducer will react by giving mechanical output; but, if the active, electrical input is absent (generator is not giving any driving signal to the transducer) and the transducer is still mechanically oscillating (for a certain time), residual electrical back-output will be (simultaneously) generated. It will go back to the ultrasonic generator through the transducer's electrical terminals (which are perma-

nently connected to the US generator output). Usually, this residual transducer response is a kind of reactive electrical power, sometimes dangerous to ultrasonic generator and to the power and frequency control. It will not be synchronized with the next generator driving train, or it could damage generator's output switching components.

[0025] Most existing ultrasonic generator designs do not take into account this residual (accumulated) and reversed power. In practice, we find different protection circuits (on the output transistors) to suppress self-generated transients. Obviously, this is not a satisfactory solution. The best would be never to leave the transducers in free-running oscillations (without the input electrical drive, or with "open" input-electrical terminals on the primary transformer side). Also, it is necessary to give certain time to the transducers for the electrical discharging of their accumulated elasto-mechanic energy.

Resonant frequency control under load:

[0026] Frequency control of high power ultrasonic converters (piezoelectric transducers) under mechanical loading conditions is a very complex situation. The problem is in the following: when the transducer is operating in air, its resonant frequency control is easily realizable because the transducer has equivalent circuit (in the vicinity of this frequency) which is similar to some (resonant) configuration of oscillating R-L-C circuits. When the transducer is under heavy mechanical load (in contact with some other mass, liquid, plastic under welding...), its equivalent electrical circuit loses (the previous) typical oscillating configuration of R-L-C circuit and becomes much more closer to some (parallel or series) combination of R and C. Using the impedance-phase-network analyzer (for transducer characterization), we can still recognize the typical impedance phase characteristic of piezo transducer. However, it is considerably modified, degraded, deformed, shifted to a lower frequency range, and its phase characteristic goes below zero-phase line (meaning the transducer becomes dominantly capacitive under very heavy mechanical loading). If we do not have the transducer phase characteristic that is crossing zero line (between negative and positive values, or from capacitive to inductive character of impedance) we cannot find its resonant frequency (there is no resonance), because electrically we do not see which one is the best mechanical resonant frequency.

Active and Reactive Power and Optimal Operating Frequency:

[0027] The most important thing is to understand that ultrasonic transducers that are used for ultrasonic equipment (piezoelectric or sometimes magnetostrictive) have complex electrical impedance and strong coupling between their electrical inputs and relevant mechanical structure (to understand this we have to discuss all relevant electromechanical, equivalent models of transducers, but not at this time). This is the reason why parallel or serial (inductive for piezoelectric, or capacitive for magnetostrictive transducers) compensation has to be applied on the transducer, to make the transducer closer to resistive (active-real) electrical impedance in the operating frequency range. The reactive compensation is often combined with electrical filtering of the output, transducers driving signals. Universal reactive compensation of transducers is not possible, meaning that the transducers can be tuned as resistive impedance only within certain frequencies (or at maximum in band-limited frequency intervals). Most designers think that this is enough (good electrical compensation of the transducers), but, in fact, this is only the necessary first step.

[0028] This time we are coming to the necessity of making the difference between electrical resonant frequency and mechanical resonant frequency of an ultrasonic converter. In air (non-loaded) conditions, both electrical and mechanical resonant frequencies of one transducer are in the same frequency point/s and are well and precisely defined. However, under mechanical loading this is not always correct (sometimes it is approximately correct, or it can be the question of appearance of some different frequencies, or of something else like very complicated impedance characteristic). From the mechanical point of view, there is still (under heavy mechanical load) one optimal mechanical resonant frequency, but somehow it is covered (screened, shielded, mixed) by other dominant electrical parameters, and by surrounding electrical impedances belonging to ultrasonic generator. To better understand this phenomenon, we can imagine that we start driving one ultrasonic transducer (under heavy loading conditions), using forced (variable frequency), high power sinus generator, without taking into account any PLL, or automatic resonant frequency tuning. Manually (and visually) we can find an operating frequency producing high power ultrasonic (mechanical) vibrations on the transducer. As we know, heavy loaded transducer presents kind of dominantly capacitive electrical impedance (R-C), but it is still able to produce visible ultrasonic/mechanical output (and we know that we cannot find any electrical pure resonant frequency in it, because there is no such frequency). In fact, what we see, and what we can measure is how much of active and reactive power circulates from ultrasonic generator to piezoelectric transducer (and back from transducer to generator). When we say that we can see/detect a kind of strong ultrasonic activity, it means most probably that we are transferring significant amount of active/real electrical power to the transducer, and that much smaller amount of reactive/imaginary power is present, but we cannot be absolutely sure that such loaded transducer has proper resonant frequency (it could still be dominantly capacitive type of impedance, or some other complex impedance). In fact, in any situation, the best we can achieve is to maximize active/real power transfer, and to minimize

reactive/imaginary power circulation (between ultrasonic generator and piezoelectric ultrasonic transducer). If/when our (manually controlled) sinus generator produces/supplies low electrical power, the efficiency of loaded ultrasonic conversion is also very low, because there is a lot of reactive power circulating inside of loaded transducer (and back to the generator).

[0029] Here is the most interesting part of this situation: if we intentionally increase the electrical power that drives the loaded transducer (keeping manually its best operating frequency, or maximizing real/active power transfer), the transducer becomes more and more electro-acoustically efficient, producing more and more mechanical output, and less and less reactive power. Also, thermal dissipation (on the transducer) percentage-wise (compared to the total input energy) becomes lower. What is really happening: under heavy mechanical loading and high power electrical driving (on the manually/visually found, best operating frequency, when real power reaches its maximum) the transducer is again recreating/regaining (or reconstructing) its typical piezoelectric impedance-phase characteristic which, now, has new phase characteristic passing zero line, again (like in real, oscillatory R-L-C circuits). Somehow, high mechanical strain and elasto-mechanical properties of total mechanical system (under high power driving) are accumulating enough (electrical and mechanical) potential energy, and the system is again coming back, mechanically decoupling itself from its load (for instance from liquid) and/or starting to present typical R-L-C structure that is easy for any PLL resonant frequency control (having, again, real/recognizable resonant frequency).

[0030] Of course, loaded ultrasonic transducer (optimally) driven by high power will have some other resonant frequency, different than the frequency when it was driven by low power, and also different than its resonant frequency (or frequencies) in non-loaded conditions (in air), because resonant frequency is moving/changing according to time-dependant loading situation (in the range of ±5% around previously found resonant frequency).

[0031] To better understand the importance of active power maximization, we know that when we have optimal power transfer (from the energy source to its load), the current and the voltage time-dependant shapes/functions (on the load) have to be in phase. This means that in this situation electrical load is behaving as pure resistive, or active load. (Electrically reactive loads are capacitive and inductive impedances). The next condition (for optimal power transfer) is that load impedance has to be equal to the internal impedance of its energy source (meaning the generator). In mechanical systems, this situation is analogous or equivalent to the previously explained electrical situation, but this time force and velocity time-dependant shapes/functions (on the mechanical load) have to be in phase, which means that in such situations mechanical load is behaving as pure (mechanically) resistive, or active load. Active mechanical loads are basically frictional loads (and mechanically reactive loads/impedances are masses and springs in any combination). We usually do not know/see exactly (and clearly) if we are producing active mechanical power, but by following/monitoring/controlling electrical power, we know that when we succeed in producing/transferring certain amount of active electrical power to one ultrasonic transducer, that corresponds, at the same time, to one directly proportional amount of active mechanical power (dissipated in mechanical load). Delivering active power to some load usually means producing heat on active/resistive elements of this load. We also know that productivity, efficiency and quality of ultrasonic action (in Sonochemistry, plastic welding, ultrasonic cleaning...) strongly and directly depends on how much active mechanical power we are able to transfer to a certain mechanical load (say to a liquid or plastic, or something else). When we have visually strong ultrasonic activity, but without transferring significant amount of active power to the load, we can only be confused in thinking (feeling) that our ultrasonic system is operating well, but in reality, we do not have big efficiency of such system. Users and engineers working in/with ultrasonic cleaning know this situation well. Sometimes, we can see very strong ultrasonic waving in one ultrasonic cleaner (on its liquid surface), but there is no ultrasonic activity and cleaning effects are missing.

[0032] In conclusion, it is correct to say that: active _electrical power_ $\cong$ _active mechanical power,_ for an electromechanical system where we transfer electrical energy to the mechanical load. Another conclusion is that we also need to install convenient mechanical/acoustical/ultrasonic sensors which are able to detect, follow, monitor and/or measure resulting ultrasonic/acoustical/mechanical activity (in real-time) on the mechanical load, in order to be 100% sure that we are transferring active mechanical power to certain mechanical load, and to be able to have a closed feedback loop for automatic (mechanical, ultrasonic) power regulation. For instance, in liquids (Sonochemistry and ultrasonic cleaning applications), the appearance of cavitation is the principal sign of producing active ultrasonic power. To control this we need sensors of ultrasonic cavitation. Also, we know that the last step in any energy chain (during electromechanical energy transfer) is heat energy. By supplying electrical resistive load with electrical energy we produce heat. The same is valid for supplying mechanical resistive/frictional load with ultrasonic energy, when the last step in this process is again heat energy (but, again, force and velocity wave shapes of delivered ultrasonic waves have to be in phase, measured on its load). From the previous commentary we can conclude that the best sensors for measuring active/resistive ultrasonic energy transfer in liquids are real-time, very fast responding temperature sensors (or some extremely sensitive thermocouples, and/or thermopiles).

[0033] There can be a practical problem (for resonant frequency tracking) if we start driving certain transducer full power, under load, if we are not sure that we know its best operating mechanical resonant frequency (because we can destroy the transducer and output transistors if we start with a wrong frequency). In real life, every well designed PLL

starts with a kind of low power sweep frequency test (say giving 10% of total power to the transducer), around its known best operating frequency taking/accepting one frequency interval that is given in advance. When the best operating resonant frequency is confirmed/found, PLL system tracks this frequency, and at the same time the power regulation (PWM) increases output power (of ultrasonic generator) to the desired maximum. Of course, when the transducer is in air (mechanically non-loaded), previous explanation is readily applicable because we can easily find its best resonant frequency, and later on we can start gradually increasing the power on the transducer. If starting and operating situation is with already heavy loaded transducer (which can be represented by dominantly R-C impedance), the problem is much more serious, because we should know how to recognize (automatically) the optimal mechanical resonant frequency (without the possibility of using phase characteristic that is crossing zero line). There are some tricks that may help us realize such control. Of course, before driving one transducer in automatic PLL regime, we should know its impedance-phase VS frequency properties (and limits) in non-loaded and fully loaded situations. In order to master previous complexity of driving ultrasonic transducers (and to explain this situation) we should know all possible and necessary equivalent (electrical) circuits of non loaded and loaded ultrasonic transducers, where we can see/discuss/adjust different methods of possible PLL control/s. Since ultrasonic transducer is always driven by using ultrasonic generator which has output ferrite transformer, inductive compensation and other filtering elements, it is necessary to know the relevant (and equivalent) impedance-phase characteristics in all of such situations in order to take the most convenient and proper current and voltage signals for PLL.

[0034]   All previous comments are relevant when driving (input) signal is either sinusoidal or square shaped, but always with a (symmetrical, internal) duty cycle of 1:1 (T_{on}: T_{off} = 1:1), meaning being a regular sinusoidal or square shaped wave train. There is a special interest in finding a way/method/circuit capable of driving ultrasonic transducers directly using high power (and high ultrasonic frequency), PWM electrical (input) signals, because of the enormous advantages of PWM regulating philosophy. Applying special filtering networks in front of an ultrasonic transducer can be very useful when we want to drive ultrasonic transducer with PWM signals.

Influence of External Mechanical Excitation:

[0035]   One of the biggest problems for PLL frequency tracking is when ultrasonic (piezoelectric) transducer under mechanical load, driven by ultrasonic generator, produces mechanical oscillations, but also receives mechanical response from its environment (receiving reflected waves). Sometimes, received mechanical signals are so strong, irregular and strangely shaped that equivalent impedance characteristic of loaded transducer becomes very variable, losing any controllable (typical impedance) shape. It looks like all the parameters of equivalent electrical circuit of loaded transducer are becoming non-linear, variable and like transient signals. There is no PLL good enough to track the resonant frequency of such transducer, but luckily, we can introduce certain filtering configuration in the (electrical) front of transducer and make this situation much more convenient and controllable (meaning that external mechanical influences can be attenuated/minimized).

[0036]   Sometimes loaded ultrasonic transducer (in high power operation) behaves as multi-resonant electrical and mechanical impedance, with its entire equivalent-model parameters variable and irregular. Optimal driving of such transducer, either on constant or sweeping frequency, becomes uncontrollable without applying a kind of filtering and attenuation of external vibrations and signals received by the same transducer. In fact, the transducer produces/emits vibrations and at the same time receives its own vibrations, reflected from the load. There is a relatively simple protection against such situation by adding a parallel capacitance to the output piezoelectric transducer. Added capacitance should be of the same order as input capacitance of the transducer. This way, ultrasonic generator (frequency control circuit) will be able to continue controlling such transducer, because parallel added capacitance couldn't be changed by transducer parameters variation. In case of large band frequency sweeping, we can also add to the input transducer terminals certain serial resistive impedance (or some additional L-R-C filtering network). This way we avoid overloading the transducer by smoothly passing trough its critical impedance-frequency points (present along the sweeping interval).

[0037]   In any situation we can combine some successful, useful and convenient PLL procedures with a real/active power maximizing procedure incorporated in an automatic, closed feedback loop regulation (of course, trying in the same time to minimize the reactive/imaginary power).

Objectives in ultrasonic processing:

[0038]   *Traditional ultrasonic equipment exploits mainly single resonant frequency sources, but it becomes increasingly important to introduce/use different levels of frequency and amplitude modulating signals, as well as low frequency (ON - OFF) group, PWM and digital-modulation in low and high frequency domains **(what is the principal subject of this invention)**. Several modulation levels and techniques could be applied to maximize the power and frequency range delivered to heavily loaded ultrasonic transducers (and, this way, many of the above-mentioned loading problems*

could be *avoided or handled in a more efficient way, that will be* described in this invention).

Operating Principles Related to Multifrequency *Structural Actuators* (The subject of this invention)

[0039] Ultrasonic Converter (B), driven by Power Supply (A), is producing a sufficiently strong pulse-repetitive multifrequency train of mechanical oscillations or pulses (see Fig. 1). Acoustical load (D), driven by incoming frequency and amplitude modulated pulse-train starts producing its own vibration and transient response, oscillating in one or more of its vibration modes or harmonics. As the excitation changes, following the programmed pattern of the pulse train, the amplitude in these modes will undergo exponential decay while other modes are excited.

[0040] A simplified analogy is a single pulsed excitation of a metal bell that will continue oscillating (ringing) on several resonant frequencies for a long time after the pulse is over. How long each resonant mode will continue to oscillate after a pulse depends on mechanical quality factor in that mode.

[0041] Every mechanical system (in this case the components B, C and D) has many resonant modes (axial, radial, bending, torsional, ...) and all of them have higher frequency harmonics. Some of resonant modes are well separated and mutually isolated, some of them are separated on a frequency scale but acoustically coupled, and some will overlap each other over a frequency range - these will tend to couple particularly well.

[0042] Since the acoustical load (D) is connected to an ultrasonic converter (B) by an acoustical wave-guide (C), acoustical relaxing and ringing oscillations are traveling back and forth between the load (D) and ultrasonic converter (B), interfering mutually along a path of propagation. The best operating frequency of ultrasonic converter (B) is found by adjustment when maximum traveling-wave amplitude is reached, and when a relatively stable oscillating regime is found. The acoustical load (D) and ultrasonic converter (B) are creating a "Ping-Pong Acoustical-Echo System", like two acoustical mirrors generating and reflecting waves between them. For easier conceptual visualization of this process we can also imagine multiple reflection of a laser beam between two optical mirrors. We should not forget that the ultrasonic converter (B) is initially creating a relatively low pulse frequency mechanical excitation, and that the back-and-forth traveling waves can have a much higher frequency.

[0043] In order to achieve optimal and automatic process control, it is necessary to install an amplitude sensor (E) of any convenient type (e.g. accelerometer, ultrasonic flux sensor) on the Acoustical Load (D). The sensor is connected by a feedback line to the control system of Ultrasonic Power Supply (A).

[0044] There is another important effect related to the ringing resonant system described above. Both the ultrasonic source (B) and its load (D) are presenting active (vibrating) acoustic elements, when the complete system starts resonating. The back-forth traveling-waves are being perpetually reflected between two oscillating acoustical mirrors, (B) and (D). An immanent (self-generated) multifrequency Doppler effect (additional frequency shift, or frequency and phase modulation of traveling waves) is created, since acoustical mirrors, (B) and (D), cannot be considered as stable infinite-mass solid-plates. This self-generated and multifrequency Doppler effect is able to initiate different acoustic effects in the load (D), for instance to excite several vibrating modes in the same time or successively, producing uniform amplitude distribution of acoustic waves in acoustic load (D), etc. For the same reasons, we also have permanent phase modulation of ultrasonic traveling waves (since opposite-ends acoustic mirrors are also vibrating). We should strongly underline that the oscillating system described here is very different from the typical and traditional half-wave, ultrasonic resonating system, where the total axial length of the ultrasonic system consists of integer number of half-wavelengths. Generally speaking, here we do not care too much about the ultrasonic system geometry and its axial (or any other) dimensions. Electronic multimode excitation continuously (and automatically) searches for the most convenient signal shapes in order to excite many vibration modes at the same time, and to make any mechanical system vibrate and resonate uniformly.

[0045] In addition to the effects described above, the ultrasonic power supply (A) is also able to produce variable frequency-sweeping oscillations around its central operating frequency (with a high sweep rate), and has an amplitude-modulated output signal (where the frequency of amplitude modulation follows sub harmonic low frequency vibrating modes). This way, the ultrasonic power supply (A) is also contributing to the multi-mode ringing response (and self-generated multifrequency Doppler effect) of an acoustical load (D). The ultrasonic system described here can drive an acoustic load (D) of almost any irregular shape and size. In operation, when the system oscillates we cannot find stable nodal zones, because they are permanently moving as a result of the specific signal modulations coming from Ultrasonic Power Supply (A)).

[0046] It is important to know that by exciting an acoustical load (D) we could produce relatively stable and stationary oscillations and resonant effects at certain frequency intervals, but also dangerous and self-destructive system response could be generated at other frequencies. Everything depends on the choice of the central operating frequency, sweeping-frequency interval and ultrasonic signal amplitudes from the ultrasonic power supply (A). Because of the complex mechanical nature of different acoustic loads (D), we must test carefully and find the best operating regimes of the ultrasonic system (B, C, D), starting with very low driving signals (i.e. with very low ultrasonic power). Therefore an initial test phase is required to select the best operating conditions, using a resistive attenuating dummy load in

serial connection with the ultrasonic converter (A). This minimizes the acoustic power produced by ultrasonic converter, and can also dissipate accidental resonant power. When the best driving regime is found, we disconnect the dummy load and introduce full electrical power into ultrasonic converter. The best operating ultrasonic regimes are those that produce very strong mechanical oscillations (or high and stable vibrating, mechanical amplitudes) with moderate output (electric) power from the ultrasonic power supply. The second criterion is that thermal power dissipation on the total mechanical system continuously operating in air (with no additional system loading) is minimal. Differently formulated, low thermal dissipation on mechanical system (B, C, D) means that the ultrasonic power supply (A) is driving the ultrasonic converter (B) with limited current and sufficiently high voltage, delivering only the active or real power to a load. The multifrequency ultrasonic concept described here is a kind of "Maximum Active Power Tracking System", which combines several PLL and PWM loops. The actual size and geometry of acoustical load are not directly and linearly proportional to delivered ultrasonic driving-power. It can happen that with very low input-ultrasonic-power, a bulky mechanical system (B, C, D) can be very strongly driven (in air, so there is no additional load), if the proper oscillating regime is found.

[0047]   Traditionally, in high power electronics, when driving complex impedance loads (like ultrasonic transducers) in resonance, PLL (Phase Locked Loop) is related to a power control where load voltage and current have the same frequency, and in order to maximize the Active Load Power we make zero phase difference between current and voltage signals (controlling the driving voltage frequency). In modern Power Electronics we use Switch-Mode operating regimes (for driving Half or Full Bridge, or some other output transistors configuration/s). The voltage shape on the output of the Power Bridge is square shaped (50% Duty Cycle), and current (in case of R/L/C resonant circuits as electrical loads) always has a sinusoidal shape. Here we are dealing with a time domain current and voltage signals.

[0048]   This invention describes the Best Frequency Fitting in the Power domain (=) **Power-BFF** concept (the name Power-BFF is given here for the purpose of abbreviating long names), as the most general case of transducers driving (valid for here introduced, Multifrequency Structural Actuators, for wide-frequency-band driving of complex R/L/C res-onant circuits, such as ultrasonic transducers).

[0049]   The special ultrasonic power supply, (A), Fig. 1, (applicable for Multifrequency Structural Actuators) is deliv-ering square shaped, PWM and modulated-frequency output (driving voltage signal), causing that the load (output) current presents multifrequency and multicomponent (basically periodical, sinusoidal) signal (of course, the load current can also have the same frequency as the driving voltage signal, but this would be the case of traditional PLL). Again we have the same objective: To maximize the Active Load Power, but now we cannot use the simple and traditional PLL concept in order to make the phase difference between the output voltage and current to be equal zero (operating only on its principal resonant frequency), since complex R/L/C oscillating circuits usually have coupled and mutually dependant sub-harmonics and higher frequency harmonics (which are also present at the load side; -visible as the load-current and load-voltage modulation/s). Here we deal with the time and frequency domains of the real time output-power-signal (as well as with time domains of corresponding load current and voltage signals and their harmonics). This method **(Power-BFF)** looks like creating the multiple PLL-s between the envelope of the output active power signal and certain frequency-modulating signal (PLL with sub-harmonic/s in a low frequency domain), combined with the second PLL ("in-average-PLL") between the high (resonant) frequency output load current and voltage (this way practically realizing a double PLL frequency control). The second very important objective for BFF is that complete power inverter/converter or any other type of AC-power supply should look to the principal Main AC power input like 100% resistive load (PF=1 = Power Factor).

[0050]   **We can summarize the traditional PLL concept as:**

Input values, Source CAUSE ⇒ (driving voltage)	Produced Response CONSEQUENCE/s (output current)	Regulation method in order to get maximal Active Output Power
Square (or sine) shaped driving-voltage on the output Power Bridge	Sinusoidal output current	To control the driving-voltage frequency in order to get minimal phase difference between output Load Voltage and Current signals.
Relatively Stable driving frequency (or resonant frequency)	Load Voltage and Current have the same frequency	To control the current and/or voltage amplitude's in order to get necessary Active Power Output (and to realize correct impedance matching)

[0051]   All over-power, over-voltage, over-current and over-temperature regulations, limitations and protections (pulse-by-pulse and in average) should be implemented.

[0052] The new Power-BFF, Multifrequency Actuator concept can be summarized as:

Input values, Source CAUSE ⇒ (driving voltage)	Produced Response CONSEQUENCE/s (output current)	Regulation method in order to get maximal Active Output Power: The average phase differences between the output HF current and voltage and their subharmonies (on the output ferrite transformer) should be minimal (in average)
Square shaped voltage on the output Power Bridge: PWM + Band Limited, Frequency Modulation (+ limited phase modulation in some applications)	Multi-mode or single sinusoidal output current (or ringing decay current) with Variable operating frequency + Harmonics	First PLL at resonant frequency: To control the central operating frequency (of a driving-voltage signal) in order to produce the Active Load Power to be much higher than its Reactive Power. To realize the maximal input (LF) power factor (PF = cos(theta) = 1).
Stable central operating, driving frequency + band limited frequency modulation (+ limited phase modulation in some applications)	Stable mean operating (Load) frequency coupled with the driving-voltage central operating frequency, as well as with harmonics	To make that complete power inverter/converter looks like resistive load to the principal Main Supply AC power input. To realize the maximal input (LF) power factor (PF = cos (theta) = 1).
Output transformer is "receiving" reflected harmonics (current and voltage components) from its load.	Particular frequency spectrum/s of a Load Voltage and Current could sometimes cover different frequency ranges.	Second PLL at modulating (subharmonic) frequency: To control the modulating frequency in order to produce limited RMS output current, and maximal Active Power (on the load). To realize maximal input (LF) power factor (PF = cos(theta) = 1).

[0053] All over-power, over-voltage, over-current and over-temperature regulations, limitations and protections (pulse-by-pulse and in average) should be implemented. Safe operating components margins should be chosen sufficiently higher than in the cases of traditional, single frequency PLL systems.

[0054] *The New BFF (multiple "In Average-PLL") concept is the most general case of Maximum Active Power Tracking and it covers the Traditional PLL concept. A number of variations of Power-BFF are imaginable depending on resonant-load applications (like suppressing or stimulating certain operating frequencies or harmonics, implementing frequency sweeping, or randomized frequency and phase modulation/s etc.). Traditionally the PLL concept is applied to immediate load current and voltage signals, and in Power-BFF we apply the similar concept to the immediate active load-power signal. In any case the principal objectives are to realize optimal and maximal active power transfer to the load, and that complete power system (in-average, time-vise) looks like resistive load to the main supply input, and this is exactly how Multifrequency Structural Actuators operate.*

Applications of Multifrequency Structural Actuators

[0055] The spectrum of various imaginable applications related to above described multifrequency structural ultrasonic actuators could be illustrated by the following list:

1. Ultrasonic liquid processing

- mixing and homogenization
- atomization, fine spray production
- surface spray coating
- metal powders production and surface coating with powders

2. Sonochemical reactors

3. **Water sterilization**

4. **Heavy duty ultrasonic cleaning in open-air or pressurized vessels**

5. **Pulped paper activation (paper production technology)**

6. **Liquid degassing, or liquid gasifying (depending of how sonotrode is introduced in liquid)**

7. **De-polymerization (recycling in a very high intensity ultrasound)**

8. **Accelerated polymerization or solidification (adhesives, plastics...)**

9. **High intensity atomizers (cold spay and vapor sources). Metal atomizers.**

10. **Profound surface hardening, impregnation and coating**

- surface hardening (implementation of hard particles)
- capillary surface sealing
- impregnation of aluminum oxide after aluminum anodizing
- surface transformation, activation, protection

11. **Material aging and stress release on cold**

- Shock testing. 3-D random excitation

12. **Complex vibration testing (NDT, Structural defects detection, Acoustic noise...)**

- accelerated 3-dimensional vibration test in liquids
- leakage and sealing test
- structural stability testing of Solids
- unscrewing bolts testing

13. **Post-thermal treatment of hardened steels (cold ultrasonic treatment)**

- elimination of oxides and ceramic composites from a surface
- profound surface cleaning
- residual stress release, artificial aging, mechanical stabilization

14. **Ultrasonic replacement for thermal treatment.** Accelerated thermal treatment of metal and ceramic parts in extremely high intensity ultrasonic field in liquids.

15. **Surface etching**

- abrasive and liquid treatment
- active liquids (slightly aggressive)
- combination of active liquids and abrasives

16. **Surface transformation and polishing**

- combination of abrasives and active liquid solutions
- electro-polishing and ultrasonic treatment

17. **Extrusion (of plastics and metals) assisted by ultrasonic vibrations**

- special ultrasonic transducers in a direct contact with extruder

18. **Founding and casting (of metals and plastics) assisted by ultrasound**

- vacuum casting, homogenization, degassing
- micro-crystallization, alloying, mixing of different liquid masses

19. Adhesive testing

- aging test
- accelerated mechanical resistance testing
- accelerated moisture and humidity testing

20. Corrosion testing

- in different liquids
- in corrosive liquid, vapor phase

21. Ultrasonic and vibrations, plastic and metal welding...

SUMMARY OF THE INVENTION:

[0056]   It is an object of the present invention to provide Multifrequency and Multimode oscillating Actuator tracking and exciting a selected group of natural resonant modes of its acoustic load.

[0057]   It is another object of the present invention to produce device capable of efficient Multifrequency driving of external medium masses of arbitrary shapes and sizes without necessity of realizing precise resonant tuning and impedance matching between the transducer and external oscillating mass (on a stable and single resonant frequency), all of that is impossible using traditional ultrasonic systems.

[0058]   It is another object of the present invention to produce device capable to be separated with long solid rod from external medium mass and to introduce strong wide-band structural vibrations into heavy duty operating conditions without necessity of resonant tuning and impedance matching (on a stable and single resonant frequency) between the transducer and external oscillating mass.

[0059]   It is another object of the present invention to produce device capable to penetrate arbitrary thick and arbitrary shaped solid masses and to introduce strong wide-band vibrations into heavy duty operating conditions without necessity of resonant tuning and impedance matching between the transducer and external mass (on a stable and single resonant frequency).

[0060]   It is still a further object of this invention to achieve the preceding objects in a relatively compact, lightweight and inexpensive device.

[0061]   The present invention achieves the above objects by realizing wide-band, "Maximum Active Power (multifrequency) tracking" delivering complex vibrations to an ultrasonic transducer and to its mechanical load, all of that already described in this invention, or realizing the specific Ultrasonic Power Supply able to perform multifrequency and multimode transducer-driving.

[0062]   These, together with other objects and advantages, which will be subsequently apparent, reside in the details of construction and operation as more fully hereinafter described and claimed, reference being had to the accompanying drawings forming a part hereof, wherein like numerals refer to like parts throughout.

BRIEF DESCRIPTION OF THE DRAWINGS:

[0063]   Fig. 1 depicts the Block Diagram of a Multifrequency Structural Actuator System, containing 5 different functional blocks, marked with A, B, C, D and E;

[0064]   The blocks (A, B, C, D and E) belonging to Fig. 1 are:

A) Sweeping-frequency, multifrequency and multimode Ultrasonic Power Supply (including all regulations, controls, modulations and protections), connected to (B) and receiving feedback signal from (E)

B) High Power Ultrasonic Converter, or multifrequency Structural Actuator (see also Patent EP 1 060 798 A1), driven by (A)

C) Acoustical Wave-guide (metal rod; -aluminum, titanium), which connects ultrasonic transducer (B) with an acoustic load, oscillating body, resonator, autoclave, reservoir, pressurized tank, ultrasonic cleaning tank...(D)

D) Acoustical Load (mechanical resonating body, sonoreactor, radiating ultrasonic tool, sonotrode, test specimen,

vibrating tube, vibrating sphere, a mold, solid or fluid media, autoclave, pressurized tank, ultrasonic cleaning tank...),

E) Sensor of acoustical activity fixed on/in/at an Acoustical Load. As sensors here we understand accelerometers, ultrasonic flux meters, cavitation detectors, laser vibrometer/s..., and/or any other applicable sensor/s able to create regulation-feedback between the Acoustical Load (D) and Ultrasonic Power Supply (A).

DESCRIPTION OF THE PREFERED EMBODIMENTS:

[0065] The present invention (Fig.1) achieves multifrequency and multimode response in an acoustic load by driving an ultrasonic transducer, connected to its load, with mixed PWM, pulse-repetitive, amplitude, frequency and phase modulated signal, while tracking the selected group of characteristic resonant and modal frequencies belonging to the same acoustic load (taking the feedback signal that is the spectral signature of the load pulse response), and applying the power regulation principle that only Maximal Active Power should be delivered to the load. This way, the load is driven only on its most sensitive and natural resonant areas, receiving mixed, low frequency and ultrasonic frequency driving signals, where for every particular oscillating mode a separate PLL tracking (and PWM regulation) is implemented, and all of them are mutually synchronized, having common ultrasonic frequency carrier. The ultrasonic carrier-frequency is also frequency and phase modulated by the same feedback signal.

[0066] An additional alternative embodiment of the present invention can achieve further performance enhancement in some applications by providing somewhat different loading and fixation arrangements between ultrasonic transducer and its load. Modifications of this type could allow the single-sided, unidirectional and/or omni-directional load-radiation to be optimized for somewhat different operating frequency bands, and thus increase the total operating bandwidth and uniformity of acoustical activity of the transmitting system and Acoustic Load. Especially convenient ways for realizing effective and omni-directional multifrequency excitation on different acoustical loads is to install (to fix rigidly or to weld) appropriate mounting interfaces, metal shells, rings, tight and pre-stressed metal envelopes... around the acoustical load, and to fix the wave guide rod and ultrasonic transducer to such mounting interfaces.

[0067] Another additional alternative embodiment of the present invention can achieve further performance enhancement in some applications by connecting several ultrasonic transducers (in parallel) to drive the same load, and/or by connecting several ultrasonic power supplies to different ultrasonic transducers (each of them driving the same load), and to use, or not to use, acoustic wave-guide rods between ultrasonic transducer/s and acoustic load/s.

[0068] The many features and advantages of the present invention are apparent from the detailed specification and thus it is intended by the appended claims to cover all such features and advantages of the device that fall within the true spirit and scope of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact description and operation illustrated and described, and accordingly, all suitable modifications and equivalents may be resorted to falling within the scope of the invention.

Claims

1. A Multifrequency Structural Actuator System, comprising:

    Ultrasonic Power Supply in contact with an
    Electro-acoustic or Ultrasonic transducer; Connected to
    Wave-guide metal rod and an
    Acoustic Load placed at the opposite side of that wave-guide metal rod; and

    an
    Acoustic Activity Sensor, fixed to Acoustic Load, for transferring vibration feedback-signal between Acoustic Load and Ultrasonic Power Supply, and allowing Acoustic Load vibration to be alternatively enhanced by the frequency, phase and amplitude modulation produced in Ultrasonic Power Supply, by spectral, PLL, tracking of the group of modal and resonant frequencies of the Acoustical Load, found in the Acoustic Activity Sensor signal, and maximizing only the Active (and wide-band frequency) Power delivered to an Acoustic Load.

2. A Multifrequency Structural Actuator System, as recited in claim 1, comprising:

    Ultrasonic Power Supply in contact with an
    Electro-acoustic or Ultrasonic transducer; Connected to
    Wave-guide metal rod and an

Acoustic Load placed at the opposite side of that wave-guide metal rod; and allowing Acoustic Load vibration to be alternatively enhanced by the frequency, phase and amplitude modulation produced in Ultrasonic Power Supply, by spectral, PLL, tracking of the group of modal and resonant frequencies of Acoustical Load, found in current, voltage and power signals circulating between Ultrasonic Power Supply and Ultrasonic transducer, and maximizing only the Active (and wide-band frequency) Power delivered to an Acoustic Load.

3. A ultrasonic transducer as recited in claims 1 and 2, directly fixed to its Acoustic Load, without using acoustic wave-guide, and with or without using Acoustic Activity Sensor.

4. A group of Ultrasonic transducers (instead of using only one ultrasonic transducer), as recited in claims 1, 2 and 3, connected electrically and mechanically in parallel to the same Acoustic Load, with or without using acoustic Wave-guide and Acoustic Activity Sensor.

5. A transducer/s as recited in claims 1,2, 3 and 4, rigidly fixed to some appropriate
   Mounting interface, such as metal shell, ring, tight and pre-stressed metal envelope, placed around the Acoustic Load, with or without using the wave-guide rod and Acoustic Activity Sensor (in order to create omni-directional or unidirectional acoustic excitation of an Acoustic Load).

6. A transducer/s as recited in claims 1, 2, 3, 4, and 5, each of them fixed to a single and separate, rigidly coupled Wave-guide rod, each of them in contact with an Acoustic Load.

7. A transducer/s as recited in claims 1, 2, 3, 4, 5 and 6, each of them fixed to a single and separate, rigidly coupled Wave-guide rod, each of them in contact with the same Acoustic Load, and each, or some of them driven by separate Ultrasonic Power Supply/ies.

B
Ultrasonic
Converter

D
Acoustical Load
Ultrasonic Reactor
Oscillating Mechanical
System

A
Multifrequency
Ultrasonic Power Supply

C
Acoustical wave-
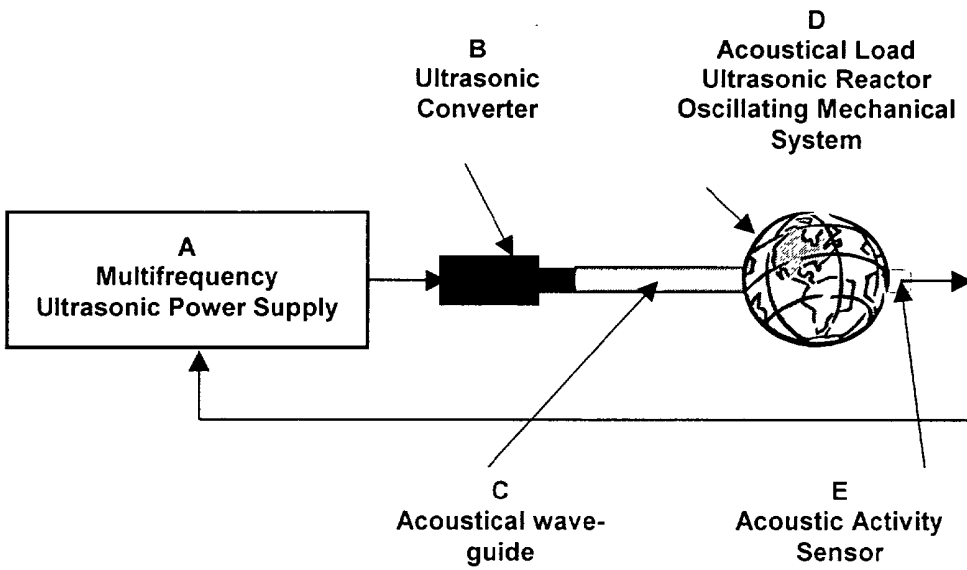guide

E
Acoustic Activity
Sensor

Fig. 1 Block Diagram of a Multifrequency Structural Actuator

European Patent
Office

PARTIAL EUROPEAN SEARCH REPORT   Application Number

which under Rule 45 of the European Patent Convention EP 01 81 0227
shall be considered, for the purposes of subsequent
proceedings, as the European search report

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
Y	US 5 421 829 A (BROADWIN ALAN ET AL) 6 June 1995 (1995-06-06) * abstract * * figures 1,6 * * column 2, line 15 - line 21 * * column 2, line 42 - line 64 * * column 3, line 44 - line 46 * ---	1-4	B06B1/02
Y	US 5 880 580 A (JOHANSEN DAVID K) 9 March 1999 (1999-03-09) * abstract * * figure 2 * * claims 1,4 * ---	1-4	
Y	US 5 834 871 A (PUSKAS) 10 November 1998 (1998-11-10) * abstract * ---	4	
A	US 5 276 376 A (PUSKAS PETER J) 4 January 1994 (1994-01-04) * abstract * * figure 1 * --- -/--	1	TECHNICAL FIELDS SEARCHED (Int.Cl.7) B06B

INCOMPLETE SEARCH

The Search Division considers that the present application, or one or more of its claims, does/do
not comply with the EPC to such an extent that a meaningful search into the state of the art cannot
be carried out, or can only be carried out partially, for these claims.

Claims searched completely :

Claims searched incompletely :

Claims not searched :

Reason for the limitation of the search:

see sheet C

Place of search	Date of completion of the search	Examiner
THE HAGUE	15 August 2001	Ph. de Heering

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another
document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or
after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding
document

EPO FORM 1503 03.82 (P04C07)

European Patent Office	**INCOMPLETE SEARCH SHEET C**	Application Number EP 01 81 0227

Claim(s) searched completely:
   1,2

Claim(s) searched incompletely:
   5-7

Claim(s) not searched:
   3,4

Reason for the limitation of the search:

Cl. 3 has the technical feature "without wave-guide", in direct contradiction with Cl. 1 and 2 on which it depends, which have the technical feature "connected to wave-guide".

The remaining claims (4-7), as far as they depend on Cl. 3 have not been searched.

Cl. 4 recites "a group of transducers", but depends on Cl. 1-3, which relate to "only one transducer" as stated in Claim 4.

The remaining claims (5-7) as far as they depend on Cl. 4 have not been searched.

In all these cases, the objectionable drafting of the claims results in a lack of clarity (see Art. 84 EPC) regarding the definition and extent of the protection sought by teh applicant.

European Patent Office

PARTIAL EUROPEAN SEARCH REPORT

Application Number

EP 01 81 0227

	DOCUMENTS CONSIDERED TO BE RELEVANT		CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	
A	US 5 754 016 A (CORBELLINI ALFRED E ET AL) 19 May 1998 (1998-05-19) * abstract * * figures 1A,1C *	1,2	
A	US 5 917 266 A (MURAI KATSUMI ET AL) 29 June 1999 (1999-06-29) * figure 5 *		
A	US 5 900 690 A (JAMESON LEE KIRBY ET AL) 4 May 1999 (1999-05-04) * abstract * * figures 5,6 *		
A	US 6 016 821 A (PUSKAS) 25 January 2000 (2000-01-25) * figure 38 *	1	TECHNICAL FIELDS SEARCHED (Int.Cl.7)

EPO FORM 1503 03.82 (P04C10)

ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.

EP 01 81 0227

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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15-08-2001

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
US 5421829	A	06-06-1995	AU	672227 B	26-09-1996
			AU	4858893 A	22-06-1994
			AU	691118 B	07-05-1998
			AU	6078896 A	24-10-1996
			CA	2150487 A	09-06-1994
			DE	9321021 U	07-09-1995
			EP	0768840 A	23-04-1997
			JP	7508910 T	05-10-1995
			JP	2554851 B	20-11-1996
			WO	9412108 A	09-06-1994
US 5880580	A	09-03-1999	NONE		
US 5834871	A	10-11-1998	AU	3962197 A	25-02-1998
			CA	2262540 A	12-02-1998
			TW	407066 B	01-10-2000
			US	6181051 B	30-01-2001
			US	6002195 A	14-12-1999
			WO	9806143 A	12-02-1998
			US	6016821 A	25-01-2000
			US	6242847 B	05-06-2001
			US	6172444 B	09-01-2001
			US	6181052 B	30-01-2001
US 5276376	A	04-01-1994	AU	4407293 A	04-01-1994
			EP	0645057 A	29-03-1995
			WO	9326054 A	23-12-1993
US 5754016	A	19-05-1998	CA	2247382 A	26-03-1998
			CN	1216455 A	12-05-1999
			EP	0927005 A	07-07-1999
			JP	2001500760 T	23-01-2001
			WO	9811844 A	26-03-1998
US 5917266	A	29-06-1999	JP	10116121 A	06-05-1998
			DE	19742661 A	16-04-1998
US 5900690	A	04-05-1999	AU	3576997 A	14-01-1998
			CA	2257811 A	31-12-1997
			WO	9749500 A	31-12-1997
			US	5892315 A	06-04-1999
US 6016821	A	25-01-2000	US	5834871 A	10-11-1998
			US	6242847 B	05-06-2001
			US	6172444 B	09-01-2001
			AU	3962197 A	25-02-1998

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.

EP 01 81 0227

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

15-08-2001

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
US 6016821 A		CA	2262540 A	12-02-1998
		TW	407066 B	01-10-2000
		US	6181051 B	30-01-2001
		US	6002195 A	14-12-1999
		WO	9806143 A	12-02-1998
		US	6181052 B	30-01-2001
		AU	7967198 A	04-01-1999
		WO	9858417 A	23-12-1998