VERY IMPORTANT FACTS ABOUT MMM CONCEPT & MULTIFREQUENCY ULTRASONIC TECHNOLOGIES

1. Typical multifrequency and frequency-wideband, *high power ultrasonic sources*, transducers, sonotrodes, ultrasonic generators and processors do not exist in a literal meaning that somebody could freely (and arbitrarily) select, fix and/or change frequency, amplitude and power from certain low frequency until MHz range. Asking to have something like that is against physics, acoustics and nature of resonant systems. Ultrasonic sources are solid-body, specific-geometry, mechanical structures. Different mechanical structures have different natural resonant frequencies, and different oscillating and resonant modes, but not at all flat, uniform, linear and typically frequency-wideband amplitude, impedance and phase characteristics.

2. Solid, compact, robust, heavy and thick-walls mechanical structures usually have very limited number of discrete resonant frequency modes (including harmonics). Such structures (or ultrasonic resonators and sources) *can never operate high-power*, in a wideband or multi-frequency range (since this is against physics and nature). MMM technology is not applicable or not efficient when driving such mechanical systems.

3. Solid and mechanically flexible structures with complex geometry, relatively thin-walls, internal holes and channels, with number of distinctive compartments... usually have big number of natural resonant frequencies and harmonics. Such mechanical structures are usually convenient to be driven high-power, with signals-modulated MMM ultrasonic generators. Produced acoustic emission and associated frequency, amplitude and phase distributions and spectrum could be considered as being wideband, as much as mechanical and spatial or geometric complexity will allow (but not more). Of course, *different ultrasonic-carrier-signal modulations will (mathematically) tend to produce number of harmonics (like known in Fourier Signal Analysis), but specific mechanical system will really accept and resonate high-power only where resonant properties of mechanical system will accept (or allow to happen) mentioned mathematically created, wideband spectrum*.

4. Really-wideband, linear, flat and stable characteristics ultrasonic sources and resonators *could be realized only when producing very low oscillating amplitudes and power*. Everything else are unreasonable and imaginative expectations.

5. Many producers of ultrasonic cleaning and multifrequency technology are creating ultrasonic sources (fixed to the same tank or ultrasonic reactor) with 2, 3 or several different groups of transducers (each group operating on its single and discrete resonant frequency). Later, they need to apply either 2 or 3 or several ultrasonic generators and operate each group of transducers separately, or to have the same generator with different output (inductive matching) circuits and to operate (sequentially) each group of transducers during certain limited period. Since many ultrasonic transducers could operate on 2 or 3 different frequencies, some producers are creating ultrasonic generators that are able to change operating frequency with certain time intervals sequencing. This is like having 2 or 3 or several ultrasonic generators, each of them operating on its fixed (discrete) frequency, driving its group of transducers. In fact, this is not a real multifrequency and wideband ultrasonic technology. This is just standard, old fashion ultrasonic technology, hardware and software extended to operate on few different, fixed frequencies. Here, under MMM technology, we do not address such false multifrequency sources.

6. Good, industrially and technologically applicable, efficient high power and wideband or *MMM ultrasonic sources can be realized only by applying proper ultrasonic generator to a properly designed mechanical system*. Mechanical system, or ultrasonic load, should naturally have many resonant frequencies (different oscillating modes and harmonics) in order to be efficiently driven by MMM ultrasonic generators. We cannot realize something what is against Physics, acoustics or mechanics. MMM generators are operating on a selectable carrier (or dominant) ultrasonic frequency, which is additionally modulated on different ways (by

amplitude, frequency, phase, PWM, repetition rate, randomly etc.), and within bands-limited, mathematically defined, operating and signals-processing frequency interval (realized by software settings of MMM generators). *Only combination of specific and targeted mechanical design situation and specific MMM ultrasonic generator settings will produce efficient and relatively wideband ultrasonic processing*. MMM and wideband multifrequency effects are consequences and products of carrier signal modulations (but in the same time, MMM ultrasonic generator will still operate on a relatively fixed or band-limited carrier frequency; -only acoustic products of such driving will have extended-frequency spectral complexity, as much mechanical system can accept or follow).

7. In cases when we do not have very rich spectral complexity of certain ultrasonic load, we can still achieve MMM effects by proper carrier-signal modulations-settings, creating periodical trains of spatially, time and/or phase shifted repetitions, reflections and echoes of the same single frequency wave-group. *Such effects are effectively destroying standing-waves structure and significantly contributing to spatially uniform and high efficiency ultrasonic processing. Mentioned effects are creating acoustically equivalent state to very high frequency and wideband-frequency sonic and ultrasonic sources* (while carrier frequency is still in a relatively low frequency domain).

See more here:

Vibrations, oscillations, resonant states and united theory of macro and microcosmic matter-waves phenomenology is here (e-book for download):
http://mastersonics.com/documents/revision_of_the_particle-wave_dualism.pdf

http://bookstore.mpi-ultrasonics.com/index.php?main_page=product_info&cPath=48&products_id=165

European Patent Application (related to MMM technology): EP 1 238 715 A1
Multifrequency ultrasonic structural actuator
Applicant: Prokic Miodrag, MP Interconsulting, 5.03.2001 – 11.09.2002

Miodrag Prokic, Piezoelectric Transducers Modeling and Characterization. 240 pages, January 2004, MPI, Le Locle, Switzerland, www.mpi-ultrasonics.com

H. Feng et al. (eds.), Ultrasound Technologies for Food and Bioprocessing, Food Engineering Series, DOI 10.1007/978-1-4419-7472-3_5. *Chapter 5 Wideband Multi-frequency, Multimode, and Modulated (MMM) Ultrasonic Technology (author M. Prokic).* Springer Science+Business Media, LLC 2011

www.UltrasonicsWorldGroup.com
www.MPI-Ultrasonics.com
www.UltrasonicMetallurgy.com
www.Mastersonics.com

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 238 715 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
11.09.2002 Bulletin 2002/37

(51) Int Cl.7: B06B 1/02

(21) Application number: 01810227.7

(22) Date of filing: 05.03.2001

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

(71) Applicant: Miodrag Prokic
2400 Le Locle (CH)

(72) Inventor: Miodrag Prokic
2400 Le Locle (CH)

(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 oscillating 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.

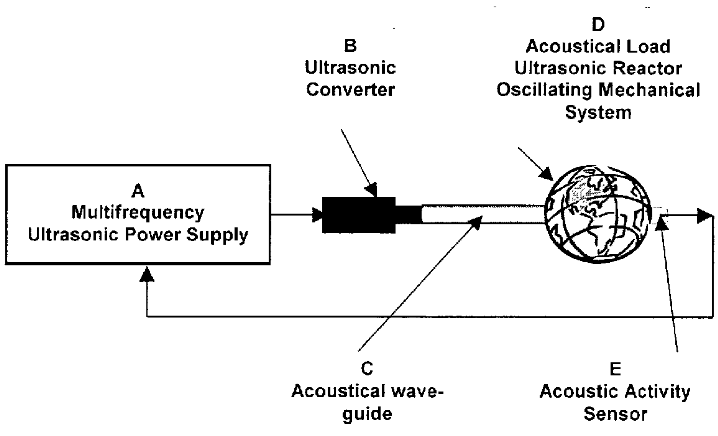


Fig. 1 Block Diagram of a Multifrequency Structural Actuator

EP 1 238 715 A1

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 permanently 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: <u>active *electrical power* ≅ *active mechanical power,*</u> 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 resonant circuits, such as ultrasonic transducers).

[0049] The special ultrasonic power supply, (A), Fig. 1, (applicable for Multifrequency Structural Actuators) is delivering 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.

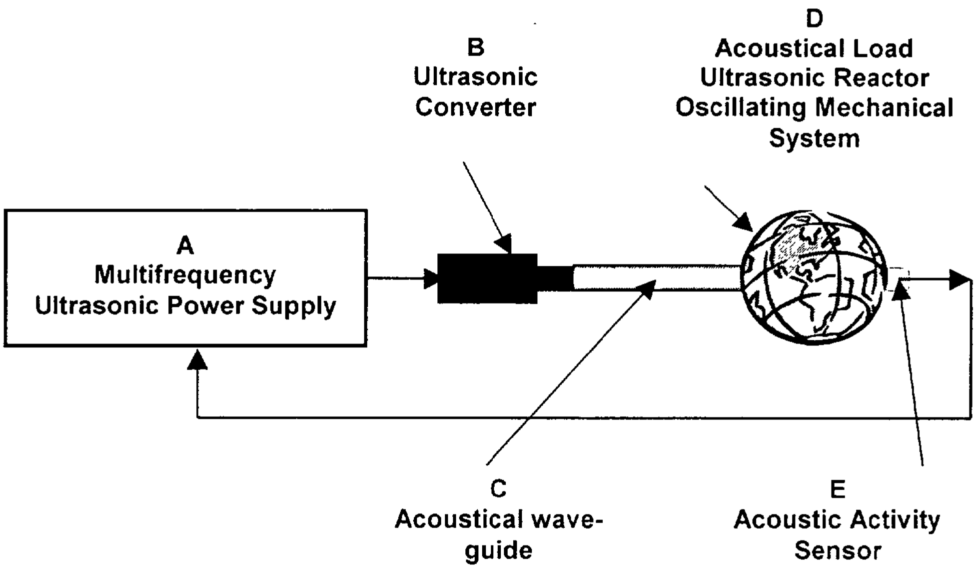


Fig. 1 Block Diagram of a Multifrequency Structural Actuator

European Patent Office

PARTIAL EUROPEAN SEARCH REPORT

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

Application Number
EP 01 81 0227

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
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 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

EPO FORM P0459

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

MPInterconsulting
ULTRASONICS - SONOCHEMISTRY - INNOVATION

Basic Elements of MMM Systems & How MMM Systems Operate

Ultrasonic systems based on our unique **MMM** (Multi-frequency, Multimode, Modulated) technology may be used as structural actuators capable of delivering high power sonic and ultrasonic energy to a large or small loads. MMM uses proprietary techniques to initiate ringing and relaxing multimode (wideband high and low frequency) mechanical oscillations in a mechanical body to produce pulse-repetitive, frequency, phase and amplitude modulated bulk-wave-excitation on that body.

***MMM** (**M**odulated, **M**ultimode, **M**ultifrequency) ultrasonic generators utilize a new and proprietary technology capable of stimulating wideband sonic and ultrasonic energy, ranging in frequency from infrasonic up to the MHz domain, that propagates through arbitrary shaped solid structures. Such industrial structures may include heavy and thick walled metal containers, pressurized reservoirs, very thick metal walled autoclaves, extruder heads, extruder chambers, mold tools, casting tools, large mixing probes, various solid mechanical structures, contained liquids, and ultrasonic cleaning systems.*

Every elastic mechanical system, body, or resonator that can oscillate has many vibrating modes as well as frequency harmonics and sub harmonics in the low and ultrasonic frequency domains. Many of these vibrating modes can be acoustically and/or mechanically coupled while others would stay relatively independent. The MMM technology can utilize these coupled modes by applying advanced Digital Signal Processing to create driving wave forms that synchronously excite many vibrating modes (harmonics and sub harmonics) of an acoustic load. This technique produces uniform and homogenous distribution of high-intensity acoustical activity to make the entire available vibrating domain acoustically active while eliminating the creation of potentially harmful and problematic stationary and standing waves structures. This is not the case for traditional ultrasonic systems operating at a stable frequency where creation of standing waves structures is the norm.

The MMM or multimode excitation techniques are very beneficial to many applications including 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, materials extrusion, wire drawing, improved molding and casting, and surface friction reduction to name a few.

***M**odulated, **M**ultimode, **M**ultifrequency sonic & ultrasonic vibrations can be excited in most any heavy-duty system by producing pulse-repetitive, phase, frequency and amplitude-modulated bulk-wave-excitation covering and sweeping an extremely wide frequency band. Every elastic mechanical system has many vibration modes, plus harmonics and sub harmonics, both in low and ultrasonic frequency domains. Many of these vibrating modes are acoustically and/or mechanically coupled, others are relatively independent. The MMM multimode sonic and ultrasonic excitation has the potential to synchronously excite many vibrating modes through the coupled harmonics and sub harmonics in solids and liquid containers to produce high intensity vibrations that are uniform and repeatable. Such sonic and ultrasonic driving creates uniform and homogenous distribution of acoustical activity on a surface and inside of the vibrating system, while avoiding the creation of stationary and standing waves, so that the whole vibrating system is fully agitated.*

Every MMM system consists of (see Fig. 1, below):

A) A Sweeping-Frequency, Adaptively Modulated Wave Form generated by an MMM Ultrasonic Power Supply (including all regulations, controls and protections);

B) High Power Ultrasonic Converter(s);

C) Acoustical Wave-Guide (metal bar, aluminum, titanium), which connects the ultrasonic transducer with an acoustic load, oscillating body, or resonator;

D) Acoustical Load (mechanical resonating body, sonoreactor, radiating ultrasonic tool, sonotrode, test specimen, vibrating tube, vibrating sphere, a mold, solid or fluid media, etc.);

E) Sensors of acoustical activity fixed on, in, or at the Acoustical Load (accelerometers, ultrasonic flux meters, cavitation detectors, laser vibrometer(s), etc.), which are creating regulation feedback between the Acoustical Load and Ultrasonic Power Supply. In most of cases the piezoelectric converter can function as the feedback element, avoiding installation of other vibrations sensors.

A strong mechanical coupling between the high power Ultrasonic Converter (B) to the Acoustical Load (D) is realized using a metal bar as an Acoustic Wave-Guide (C).

The Ultrasonic Converter (B) is electrically connected to the Ultrasonic Multimode Generator Power Supply (A).

The Acoustic Activity Sensor (E) relays physical feedback (for the purpose of automatic process control) between the Acoustical Load (D) and Ultrasonic Power Supply (A).

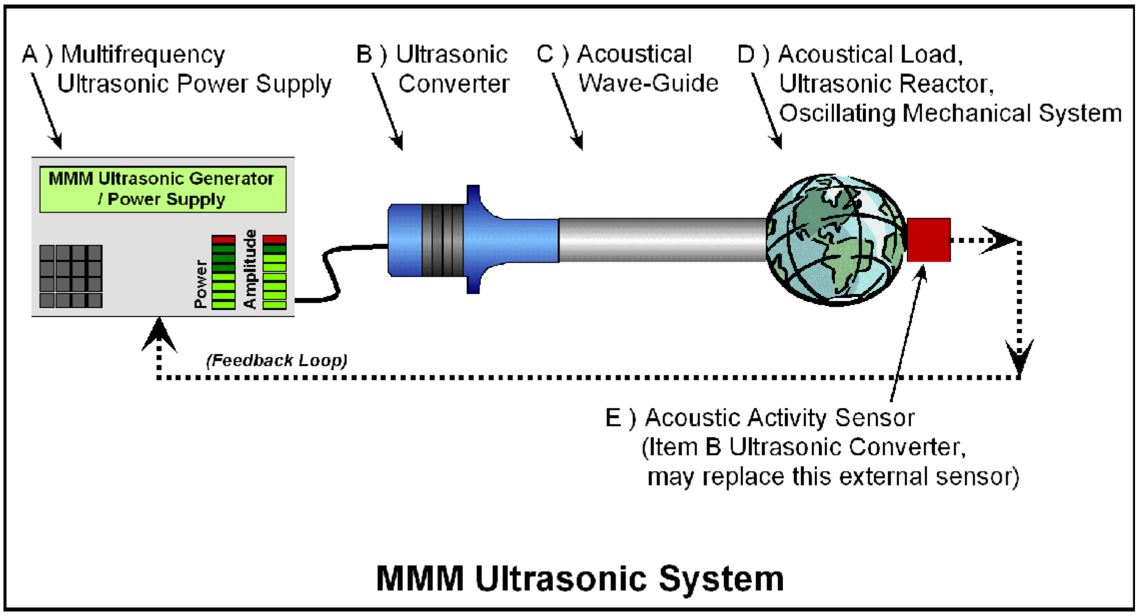


Fig. 1

MMM Generator Technology:

A new approach to Ultrasonic power supplies and systems

As depicted in Figure 1 above the Ultrasonic Converter (B), driven by Power Supply (A), is producing a sufficiently strong pulse-repetitive multifrequency train of mechanical oscillations or pulses. The 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 natural 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.

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

Every mechanical system (in this case the components B, C and D) has many resonant modes (axial, radial, bending, and torsional) and all of them have higher frequency harmonics. Some of the 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 and these will tend to couple particularly well.

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 the ultrasonic converter (B) is normally found when the 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.

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).

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 at the same time or successively, producing uniform amplitude distributions of acoustic waves in the acoustic load (D). For the same reasons, we also have permanent phase modulation of ultrasonic traveling waves since opposite-ends of the 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. In the case of MMM systems we, generally speaking, do not care much about the specific 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.

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 the MMM Ultrasonic Power Supply (A)).

It is important to note that by exciting an acoustical load (D) we could produce relatively stable and stationary oscillations and resonant effects at certain frequency intervals, but also a dangerous and self-destructive system response could be generated at other frequencies. The choice of the central operating frequency, sweeping-frequency interval and ultrasonic signal amplitudes from the ultrasonic power supply (A) are critical elements to be carefully selected. 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 the 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 electric output 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. In other words, low thermal dissipation on the 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. Its possible 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.

Traditionally, in high power electronics, when driving complex impedance loads (like ultrasonic transducers) in resonance, a PLL (Phase Locked Loop) is related to a power control where load voltage and current have the same frequency. 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 the 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.

We can summarize the traditional PLL concept as:

Input values, Source CAUSE ⇒ (driving voltage)	Produced Response CONSEQUENCE/s (output current)	Regulation method for maximal Active Output Power
Square (or sine) shaped driving-voltage on the output Power Bridge	Sinusoidal output current	Control the driving-voltage frequency for 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	Control the current and/or voltage amplitude/s for necessary Active Power Output (and to realize correct impedance matching)

The new MMM concept can be summarized as:

Input values, Source CAUSE ⇒ (driving voltage)	Produced Response CONSEQUENCE/s (output current)	Regulation method for maximal Active Output Power: The average phase differences between the output HF current and voltage and the sub-harmonics, 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 to produce Active Load Power 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 a 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 (sub-harmonic) 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).

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.

The MMM concept is the most general case of Maximum Active Power Tracking and it covers the Traditional PLL concept. A number of variations of MMM concept 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 MMM 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 MMM systems operate.

In conventional Ultrasonics technology the transducers and connected elements are designed to satisfy precise resonant conditions. To achieve maximum efficiency, all oscillating elements must be tuned to operate at the same resonant frequency. In contrast the patented MMM technology was developed to breakaway from this restrictive "tuned mode" by using advanced Digital Signal Processing (DSP) techniques to implement an intelligent feedback loop that allows adaptation to most any un-tuned, changing, or evolving mechanical system. Instead of optimizing acoustic elements to accept a specific resonant frequency operation, MMM systems use the intelligent DSP to adapt to the un-tuned load. The system continuously analyzes system feedback and optimizes a complex shaped electrical driving signal customized to each specific oscillating structure.

To remain compatible with standard transducers the MMM generators use an adjustable primary resonant frequency as a central carrier frequency that efficiently drives standard transducers in a modulated mode. The MMM driving oscillations are not fixed or random, rather they follow a consistent and evolving pulse-repetitive pattern, where frequency, phase and amplitude are simultaneously modulated by the control system. The optimized modulations provide a highly efficient transfer of electrical to mechanical energy and prevent the creation of problematic stationary or standing waves as typically produced by traditional ultrasonic systems operating at a single frequency.

MMM systems offer a high level of control through regulation and programming of all vibration, frequency, and power parameters using either a handheld control panel or a Windows PC software interface. The system's fine control extends excellent repeatability and produces highly efficient active power that may range from below 100 W up to many kW. MMM technology can drive, with high efficiency, complex mechanical system up to a mass of several tons and consisting of arbitrary resonating elements.

Due to the flexible nature of the MMM technology, a wide range of new or improved applications are possible. For example applications requiring high temperatures represent a problem to conventional transducers that are extremely sensitive to heat. Since MMM systems are not restricted to specific tuned elements it is now possible to address high temperature applications through the use of extended acoustic wave-guides (e.g. 1 to 3 meters in length). An extended wave-guide puts the necessary physical distance between the heat sensitive transducer and the high temperature load. A long wave-guide also provides a convenient mounting point for cooling jackets that will draw away excessive heat and protect the transducer. Other fields of possible MMM Technology application are: Advanced Ultrasonic Cleaning, Material Processing, Sonochemistry, Liquid Metals and Plastics treatment, Casting, Molding, Injection, Ultrasonically assisted sintering, Liquids Atomization, Liquids Mixing and Homogenization, Materials Testing, Accelerated Aging, and Stress Release.

Please make contact with us to discuss any new or challenging application (www.mpi-ultrasonics.com)

Example Ultrasonic Applications That Can Benefit From MMM Systems

1. Ultrasonic liquid processing
   a. mixing and homogenization
   b. atomization, fine spray production
   c. surface spray coating
   d. metal powders production and surface coating with powders
2. Sonochemical reactors
3. Water sterilization
4. Heavy duty ultrasonic cleaning
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
    a. surface hardening (implementation of hard particles)
    b. capillary surface sealing
    c. impregnation of aluminum oxide after aluminum anodizing
    d. surface transformation, activation, protection
11. Material aging and stress release on cold
    a. Shock testing. 3-D random excitation
12. Complex vibration testing (NDT, Structural defects detection, Acoustic noise...)
    a. accelerated 3-dimensional vibration test in liquids
    b. leakage and sealing test
    c. structural stability testing of Solids

d. unscrewing bolts testing

13. Post-thermal treatment of hardened steels (cold ultrasonic treatment)
    a. elimination of oxides and ceramic composites from a surface
    b. profound surface cleaning
    c. 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
    a. abrasive and liquid treatment
    b. active liquids (slightly aggressive)
    c. combination of active liquids and abrasives
16. Surface transformation and polishing
    a. combination of abrasives and active liquid solutions
    b. electro-polishing and ultrasonic treatment
17. Extrusion (of plastics and metals) assisted by ultrasonic vibrations
    a. special ultrasonic transducers in a direct contact with extruder
18. Founding and casting (of metals and plastics) assisted by ultrasound
    a. vacuum casting, homogenization, degassing
    b. micro-crystallization, alloying, mixing of different liquid masses
19. Adhesive testing
    a. aging test
    b. accelerated mechanical resistance testing
    c. accelerated moisture and humidity testing
20. Corrosion testing
    a. in different liquids
    b. in corrosive liquid, vapor phase

MMM GENERATOR SELECTION GUIDE

Products, Applications, & Understanding Acoustical Loading

We offer a complete line of ultrasonic generators to address a wide range of traditional and new ultrasonic applications. Due to the complex nature of the applications we address our ultrasonic generators are available with a variety of standard and custom features. This guide will help you understand our unique features and help you define the best feature set for your application.

Active Ultrasonics' generators are based on our unique and proprietary MMM technology (**MMM** = **M**ulti-frequency, **M**ultimode, **M**odulated)**. This technology employs advanced Digital Signal Processing (DSP) for input signal analysis and output signal conditioning techniques to produce wideband sonic and ultrasonic Vibrations in acoustic loads. (See the detailed explanation of MMM technology below)**

Open Frame MMM Modules for OEM, ODM, & System Integrator Clients

MMM open frame generator modules (OF and OW models) are available to clients producing equipment or systems requiring integration of ultrasonic generators into their own cabinets or housings. Our open frame generators are available without the manufacturers brand mark meaning that clients can use them as a component part of a system marked with the client's private label. Although these generator modules offer a full set of programmable functions and features the housing and interface options are simplified to make them cost competitive. The simplified design uses terminal block connectors and requires our clients to have sufficient technical background and experience to safely make all electrical connections. Open Frame generator clients are often in the business of producing ultrasonic related equipment for various applications (Cleaning, Water Processing, Sonochemistry, etc…), and are experienced in systems integration including installation of transducer elements, source power, additional sensors, PLCs, automatic controls.

The greatest advantage of Open Frame MMM generators is that they are easily adjusted to drive almost any kind of piezoelectric transducers, including single transducers or arrays of transducers operating in parallel mode. As such our generators have the flexibility to drive a client's existing transducers. In most cases clients can make adjustments and settings by carefully following the instructions given in our equipment operation manuals. In some cases the necessary impedance adjustments to adapt to a clients transducer may be outside the range of our standard equipment and will require a simple factory modification.

Our systems also provide a programmable frequency adjustment for adapting to shifting system resonant frequency due to changes in the acoustic load. Open Frame generators allow user frequency tuning within a 5 kHz window (e.g. 17.5 kHz – 28.5 kHz), or much more. This frequency window may be customized in our factory to address your application needs.

Fully Featured MMM Generator IX Models for R&D or Application Development

For laboratory and scientific research, extraordinary, challenging, unusual, or complex high-tech applications we are delivering fully featured version of the MMM generator. Standard systems labeled as IX models are housed in a finished stainless housing with standard connectors for power, transducer, and controller electrical connections. IX models have front panel controls for basic power ON/OFF and ultrasonic power output adjustment.

Advanced features and parameter settings including frequency controls, power adjustments, modulations, modulation timing, digital and smooth frequency settings are controlled via a hand-held control panel or user friendly Windows PC interface. The PC adapter may also be used by clients for development of custom software control using external PC, PLC, or mechanical relay controls. This complete feature set plus advanced overload protection circuits allow clients to quickly become fully-operational, fully-protected and fully-independent in the initial system development phase.

We can also offer customized versions to address unusual applications. In such cases we recommend our clients consult with us to define the requirements and the desired ultrasonic goal.

MMM Generator Control

RS485 Interface: All MMM generators may be ordered with an optional RS485 interface used for connection to our hand-held control panels or PC interface adaptor for Windows PC software control or a custom developed PLC or PC software control. With these tools clients may perform external manual control, remote control, PLC control, or utilize our software graphic-interface control on a Windows PC.

RS458 Network Adapter: This optional adapter is connected to generator RS485 connector and allows connecting up to 16 MMM generators in a single network. We also have an adapter for a network of up to 64 generators.

MMM Generator Set-Up

Our MMM generators are able to drive heavy and arbitrary-shaped solid masses, however due to physics and acoustics certain limits must be respected. In unusual applications it is highly recommended that clients review all available MMM information and consult with Active Ultrasonics. There is no universal answer, solution, or recommendation for driving arbitrary and complex mechanical systems that usually have number of resonances and harmonics since in every specific case the "acoustic-reality" is different. Based on our experience and knowledge we can advise clients on the best possible hardware options and system set-up.

Resonant Frequency: **If you would operate a single piezoelectric converter in resonance, and your converter by its design/geometry has a well-defined and sharp resonance, 20 kHz for example, you would need an MMM generator that is factory set with a frequency window covering 20 kHz (e.g. 18 kHz to 22 kHz). Having a wider interval of carrier frequency range will not offer additional benefit for your application, and you could only destroy, overload, or over-heat your mechanical system by trying to drive it against its "acoustical-nature". In such cases it is always better to consult with Active Ultrasonics to make a factory adjustment of frequency interval range to match your system. If your converter would have 30 kHz resonant frequency, then we will limit carrier-frequency settings to a window covering 30 kHz (e.g. 28 kHz to 32 kHz). This allows for safe operation while giving some flexibility to adjust to shifts in the resonant carrier frequency.**

As a special order we can provide a custom MMM generator that has a wide window of frequency adjustment up to 24 kHz (e.g. 18 kHz to 42 kHz). Although such custom systems offer increased research and development flexibility they also offer a much greater risk of damage to the generator and acoustic system. Driving a transducer/converter outside of its primary resonant frequency will likely damage your equipment if operation is forcing unnatural, acoustically-unacceptable operating

regimes. To recognize and avoid such regimes you would need a great deal of specific ultrasonic system experience and we do not recommend that you take such actions without consulting Active Ultrasonics.

Generator Adjustment to Various Transducers: **All MMM generators offer some flexibility to adapt to transducer/converter changes. Any change of transducers/converters within the range of the generators capabilities will require performing important inductive compensation adjustments. The adjustments are detailed in the generator Operations Manual and require some level of electronics knowledge for safe operation. The range of possible adjustment is a factory setting based on an installed inductive component. When ordering the MMM generator you will need to specify the primary type of transducer(s) used in your system.**

If you would like to drive different ultrasonic transducers, each of them having different resonant frequencies and very different input capacitances, one single MMM generator will most likely not have the necessary range of adjustment for proper operation. Operating transducers/converters without optimum impedance matching may cause inefficient power consumption and damage to the transducer. Electronically we could try to drive a resonant system in a frequency band larger than its "acoustic-nature" is dictating but the mechanical system itself would not accept to be driven too far from its resonance, regardless how many of signal-modulating tricks we would apply. In unusual or demanding applications we strongly recommend that clients consult with Active Ultrasonics and provide details of the transducers/Converters to be used and the systems physical environment including boosters, sonotrodes, tools, and mechanical devices ("Acoustic Load") to be driven. Such consulting is necessary to avoid non-realistic and out of "acoustics-reality" expectations and situations.

Systems Set-Up: **To reduce new application development time and create safer operating systems we are often providing initial consulting services to clients. In many cases we are making complete mechanical systems or critical component parts and making initial MMM generator testing to realize the best adjustments and tuning in our laboratories. Clients without previous experience in ultrasonics or with our new MMM technology normally experience problems and make mistakes that give less that desirable results or damage equipment. In other cases we cooperate with clients who produce mechanical parts or devices to our specification and they send these parts to us for final fitting of an appropriate converter, making the best inductive compensation, optimizing the generator operating regime, and making the best tuning.**

Although the generator parameters are well defined in the Operations Manual we find that clients are often accidentally, naively, and in some cases against our specific instruction trying some exceptional operating situations that are damaging to the system. Due to the wide range of options available to the MMM generator we strongly recommend that clients first consult with Active Ultrasonics about the application and operational environment before exploring risky options. We have implemented many levels of internal overload protections to protect our equipment from mishandlings and possible mistakes, however, over zealous clients can find a way to damage the MMM generator.

MMM Technology

While the MMM technology (MMM = Multifrequency, Multimode, Modulated Sonic & Ultrasonic Vibrations) is the industries most flexible sonic & ultrasonic solution it is very important to understand the underlying concept to avoid unrealistic expectations. Physics and acoustics dictate the applications that may be addressed by our MMM technology. Following are some important technical points to be considered and understood:

a) *Carrier Frequency:* **Every MMM generator has a predefined factory set carrier frequency interval window (e.g. 18 kHz to 42 kHz, or 17.5 kHz to 22.5 kHz). The generator may be set to operate at a specific constant frequency inside of the factory set window. It is not possible to operate the MMM generator outside of the factory predefined carrier frequency range.**

b) *Frequency Modulations:* **In addition to the pre-defined carrier frequency setting, there are number of user-selectable frequency-modulating options such as mathematically-predefined modulation and MMM-dynamic (time-evolving and load-dependant) carrier-frequency modulating options.**

  a. **For optimum system set-up the user should first test and select the best central operating (carrier) frequency for every particular application.**

    i. **While performing such initial frequency settings the generator power setting should be limited to between 10% and 30% of its maximal output power to avoid sudden overloads and system damage.**

    ii. **All modulating parameters should be initially disabled or giving a zero values.**

  b. **Once the converter is producing measurable, constant-frequency amplitudes, start gradually implementing different MMM modulating parameters.**

    i. **When optimal acoustic regime is reached and well tested, user can gradually increase the output power. If in process of power-increasing we notice that system is not optimally tuned, carrier frequency and frequency-modulating parameters should be slightly readjusted.**

c) Multifrequency Effects: **The MMM generator itself is not operating in a large frequency band, but the acoustical load attached to the transducer, especially arbitrary shaped elements, can effectively-oscillate in a large frequency band when complex frequency modulations are applied (modulating the carrier or central operating frequency = MMM modulations). This means that a constant carrier frequency generator with MMM modulation can excite a wide range of resonant modes and harmonics in the acoustic load. The multifrequency effect is coming form the excited acoustic spectrum inside of an acoustic load as the consequence of applying MMM modulation. The width of the acoustic loads frequency spectrum is depend on acoustic and mechanical properties of the load, on its geometry, and on the MMM parameters-settings. For example, we can use a 20 kHz piezoelectric transducer, connect it to a certain mechanical load, drive it with 20 kHz carrier signal, then start performing different MMM-modulations, and conclude by applying spectral measurements (microphones, hydrophones, accelerometers, laser vibrations meters, etc.) that our mechanical load starts vibrating uniformly, without creating standing waves if MMM modulating parameters are optimally selected. We can also see that the system is generating a large band of many resonant frequencies. In other words, MMM-modulated acoustic loads are becoming dynamically-controlled multi-resonant systems producing complex acoustic spectrum, starting from very low frequencies until very high frequencies (often from several Hz to MHz). If a mechanical system in its static (non-vibrating) state can be characterized by lumped-circuit models and constant electromechanical parameters, after applying MMM modulation, the same system is manifesting interval-type parameters definition, producing extraordinary wide-frequency band effects, eliminating standing waves and**

giving an impression that the complete acoustic load is vibrating uniformly. In some applications, such as Liquids-processing, Sonochemistry, and Cleaning, applying a constant carrier frequency anywhere in the range between 20 and 40 kHz plus MMM modulation we can measure acoustic spectral components from infrasonic vibrations until MHz range, being produced as secondary effects of MMM modulation, and being mixed with other acoustics-related effects that are naturally producing large frequency band emission (e.g. cavitation).

d) Acoustic Loads and Multifrequency Effects: **Acoustic loads or solid objects that already have many different resonant frequencies and harmonics are preferable loads for MMM technology. Spectral (mechanical) complexity of the acoustical system is very important if we would like to realize very large-band and uniformly distributed sonic and ultrasonic oscillations (without creating standing waves). In other words, well tuned mechanical systems that have strong and single resonant frequency (like constant frequency plastic welding sonotrodes) would not be the best choice as acoustic loads for MMM systems. In contrary, non-tuned and complex geometry objects have a strong chance to be well driven by MMM Power Supplies. MMM signal processing is able to initiate strong oscillations in many resonant frequencies and their harmonics at the same time, giving the impression that the complete object under such vibrations is oscillating uniformly (externally and internally). Hollowed objects with circular and cylindrical holes and slits are normally showing excellent performances regarding MMM, multifrequency operating regimes.**

e) *MMM Operating Regime:* **Every well-selected MMM operating regime can be recognized by smooth, uniform and easy-going load-oscillations. If in any part of a mechanical system (converter-wave-guide-acoustic-load) excessive heat is being generated, this is usually the sign that operating parameters are not well selected. If the mechanical system is producing randomized, cracking, braking or impulsive, low-frequency noise, this is also the sign that operating regime is not well selected and that MMM parameters should be changed. Monitoring of such regimes and detecting zones of high stress and overheating could be realized using real-time infrared cameras. A hot spot having a significantly different temperature compared to its surrounding area is a sign of a poorly selected operating regime or a sign of structural/mechanical defects.**

f) MMM generators can also operate as ordinary constant-frequency ultrasonic generators if we disable or set to zero all modulating parameters (in such cases operating on given carrier frequency).

g) MMM technology is highly recommendable primarily for unique, extraordinary and new applications, where the user is expecting results that could not be reached by using standard, traditional ultrasonic technologies. MMM technology is also providing superior performance in most liquid processing and cleaning applications.

h) Meaning of Loading of piezoelectric transducer/s in traditional ultrasonic technologies (constant operating frequency systems) is a very complex subject and can be explained as follows:

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 higher). In recent time, some new transducer designs can be driven on sweeping frequency intervals (applied to a single transducer).

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).

Also, multi-frequency concept is 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).

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:

- The best operating frequency regime in order to stimulate only desirable vibrating modes.

- To deliver a maximum of real or active power to the load (in a given/found operating frequency domain/s).

- 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: overvoltage, overcurrent, overheating, etc.

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:

a) Up to a certain (first) level, with the design and hardware, we try to insure/incorporate the most important controls and protecting, (automatic) functions.

b) At the second level we include certain logic and decision-making algorithm (software) which takes care of real-time and dynamic changes and interconnections between them.

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

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 reactive/imaginary 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

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).

It is important to know that Impedance-Phase-Frequency characteristics of one transducer (measured on a low sinus-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.

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.*

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.

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 permanently 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.

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 elastomechanical energy.

Resonant frequency control under load

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 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

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.

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).

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 elastomechanical 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).

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).

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 depend 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.

In conclusion, it is correct to say that: *active electrical power & 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).

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, which 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.

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

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).*

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 cannot 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).

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 and new R&D tasks

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 digital-modulation in low and high frequency domains. 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). Discussing such situations can be a subject of a special chapter.

MMM, Wideband (Multi-Frequency) Ultrasonic Power Supplies

Our Wideband (Multi-Frequency) Generator employs a completely new approach to frequency generation, frequency sweeping, frequency tracking, applied power, and most importantly a new way of adapting to large or varying loads. It's unique feature set makes it well suited for unusual application where ultrasonics must be applied to a large mass, a thick walled chamber, or dynamic loads that present an un-tuned mechanical system that normal generators cannot drive efficiently.

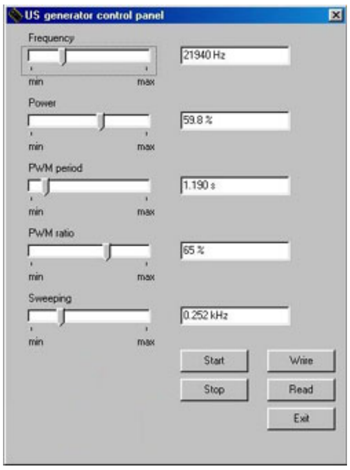
Key Features

- Wideband Multi-Frequency Effect (300 Hz to > MHz)

  - Adaptive and rapidly shifting frequency and phase modulation creates a highly efficient power shifting distribution across a broadband of harmonic and sub-harmonic frequencies.
- Adaptive to large and heavy loads
  - *The Problem:* Other conventional ultrasonic systems must work in a tuned mechanical

environment. Careful selection of sonotrodes and reaction chamber designs are critical. Changes to the load or large loads create conditions that are destructive to the transducers and generators of other traditional systems.

- *The Solution:* Our new technology eliminates these problems by monitoring and adapting to the natural harmonics of the mechanical system. The adaptive modulation techniques mimic feedback of harmonic signals from the mechanical systems and use these signal to drive the system in a highly efficient and synergistic manner. More about the MMM technology....
- *The Result:* We can apply effective ultrasonic power to un-tuned mechanical systems such as large heavy industrial tanks, thick walled chambers, complex forms, and large metal masses like extruders and injection mold tools.



Windows PC Software Control Option

- Power Options from 100 watts to 120,000 watts
- Advanced option programming via handheld control panel or PC Windows's software.
- Complete System Protection Circuits for Over Voltage, Over Current, and Driver fault.
- Modular options for industrial applications.
- Reactor Options:
  - This Multi-Frequency Generator greatly increases our options for reaction chamber design.
  - Now we can make most any size or shape and provide the necessary power to meet your complex needs.
- Compatible with all transducers options

MMM, Universal and Wideband Multifrequency Power Supplies

Multiple modulations operation: MMM technology
MMM, Universal Ultrasonic Power Supplies are replacing all other types of constant or sweeping frequency power supplies for driving all kind of piezoelectric transducers, submersible transducers, bench top cleaners, Sonochemical reactors… bringing number of advantages and new options.

(OF) **(OW)** **(IX)**

OF, MMM Power Supplies

Technical characteristics	MSG.300.OF	MSG.600.OF	MSG.1200.OF
Main Supply Voltage	220/230 V; 50/60 Hz	220/230 V; 50/60 Hz	220/230 V; 50/60 Hz
Max. Input Power	400 W	700 W	1300 W
Non-modulated, carrier frequency range	19.020kHz ÷ 46.728 kHz	19.020kHz ÷ 46.728 kHz	19.020kHz ÷ 46.728 kHz
Modulated acoustic frequency range	Wideband, from Hz to MHz	Wideband, from Hz to MHz	Wideband, from Hz to MHz
Average Continuous Output Power	300 W	600 W	1200 W
Peak Output (max. pulsed power)	1500 W	3000 W	6000 W
Output HF Voltage	~ 500 V-rms	~ 500 V-rms	~ 500 V-rms
Dimensions (h x w x d)	170x150x150mm	250x150x150mm	230 x 160 x 370
Weight	2 kg	3.6 kg	4 kg

MasterSonic open frame generator modules (OF series) are designed for internal mounting in the control cabinets of Ultrasonic Systems. Such cabinets should be very well ventilated, protecting the generator module from excessive dust, moisture, and harmful chemical agents. The installation and electrical connections of the generator should be performed by a qualified specialist in electronics who is experienced in Power Ultrasonics. MSG.X00.OF is designed as a component part for integration into Ultrasonic systems. Therefore it is not equipped with a Power Supply ON/OFF switch. Make sure the Ultrasonic System you are assembling is provided with such switch. Please read manuals for more information.

OW, MMM Power Supplies


Technical characteristics	MSG.300.OW	MSG.600.OW	MSG.1200.OW
Main Supply Voltage	220/230 V; 50/60 Hz	220/230 V; 50/60 Hz	220/230 V; 50/60 Hz
Max. Input Power	400 W	700 W	1300 W
Non-modulated, carrier frequency range	21.435kHz ÷ 40.560 kHz	21.435kHz ÷ 40.560 kHz	21.435kHz ÷ 40.560 kHz
Modulated acoustic frequency range	Wideband, from Hz to MHz	Wideband, from Hz to MHz	Wideband, from Hz to MHz
Average Continuous Output Power	300 W	600 W	1200 W
Peak Output (max. pulsed power)	1500 W	3000 W	6000 W
Output HF Voltage	~ 500 V-rms	~ 500 V-rms	~ 500 V-rms
Dimensions (h x w x d)	170x150x150mm	250x150x150mm	230 x 160 x 370
Weight	2 kg	3.6 kg	4 kg

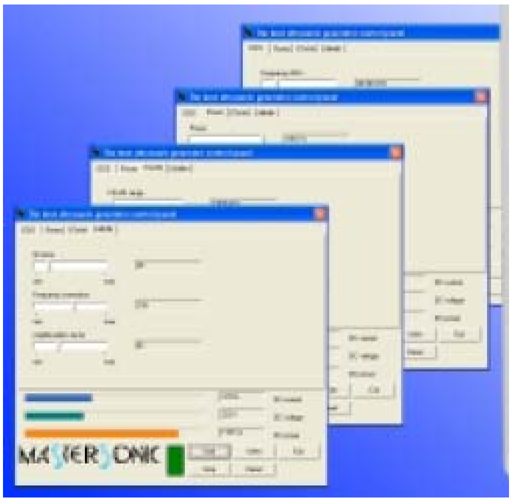
All MSG modular ultrasonic generators, MSG X00.OW, utilize the MMM Technology and are constructed with an open frame design intended for integration into Ultrasonic Systems providing appropriate housing and protection. OW series generators have much higher frequency resolution than OF series generators, making them convenient when precise frequency settings are important. The MSG.X00.OW generators are intended mainly for application in ultrasonic cleaning tanks and systems. MasterSonic generator modules (OW series) are designed for internal mounting in the control cabinets of Ultrasonic Systems. Such cabinets should be very well ventilated, protecting the generator module from excessive dust, moisture, and harmful chemical agents. The installation and electrical connections of the generator should be performed by a qualified specialist in electronics who is experienced in Power Ultrasonics. MSG.X00.OW is designed as a component part for integration into Ultrasonic systems. Therefore it is not equipped with a Power Supply ON/OFF switch. Make sure the Ultrasonic System you are assembling is provided with such switch. Please read manuals for more information.

IX, MMM Power Supplies

Technical characteristics	MSG.1200.IX
Main Supply Voltage	220/230 V; 50/60 Hz
Max. Input Power	1300 W
Non-modulated, carrier frequency range	19.020kHz ÷ 46.728 kHz
Modulated acoustic frequency range	Wideband, from Hz to MHz
Average Continuous Output Power	1200 W
Peak Output (max. pulsed power)	6000 W
Output HF Voltage	~ 500 V-rms
Dimensions (h x w x d)	250mm x 150mm x 450mm
Weight	10 kg

MSG modular ultrasonic generators (MSG XXX.IX) utilize the MMM Technology and are constructed with a separate housing as an independent power supply of piezoelectric acoustic loads. IX series generators have maximum of available options of MMM technology (practically all of the best options of OF and OW series generators, including many of new options), and can be operated by people without background in High Power Ultrasonics. IX series power supplies are also very convenient for challenging R&D projects, laboratory applications and other scientific projects. IX generators are fully protected against overloading and load short-circuits. Please read manuals for more information.

ACCESSORIES, INTERFACES, REMOTE, PLC AND PC CONTROLL TOOLS FOR ALL MMM GENERATORS



Handheld Control Unit
For manual control and settings

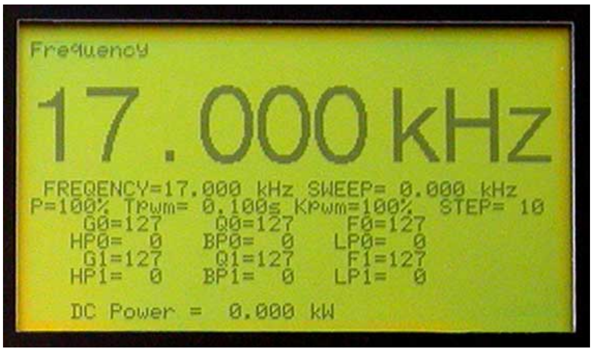
All Mastersonic, MMM generators can be controlled, being connected by RS485 link to a PC, using the software interface for enabling easy visual and multi-parameter control and settings.

Home page: http://www.mpi-ultrasonics.com
Server: http://www.mastersonic.com
E-mail: mpi@mpi-ultrasonics.com
mpi@bluewin.ch

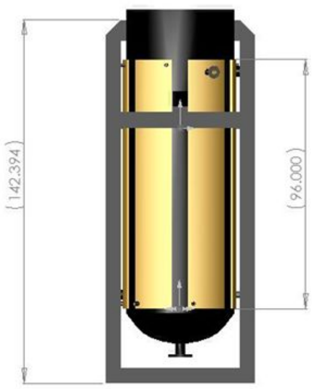
MMM-Link-2339 Adapter RS485 / RS232C+software
MMM-Link-2339_16 Option RS485 Link extender16 generator
MMM-Link-2339_64 Option RS485 Link extender16 generator
Interface cable

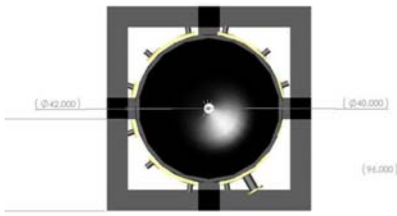
Also available single Power Supply units until 100 kW

PS Cabinet



PS Programming Interface and Display





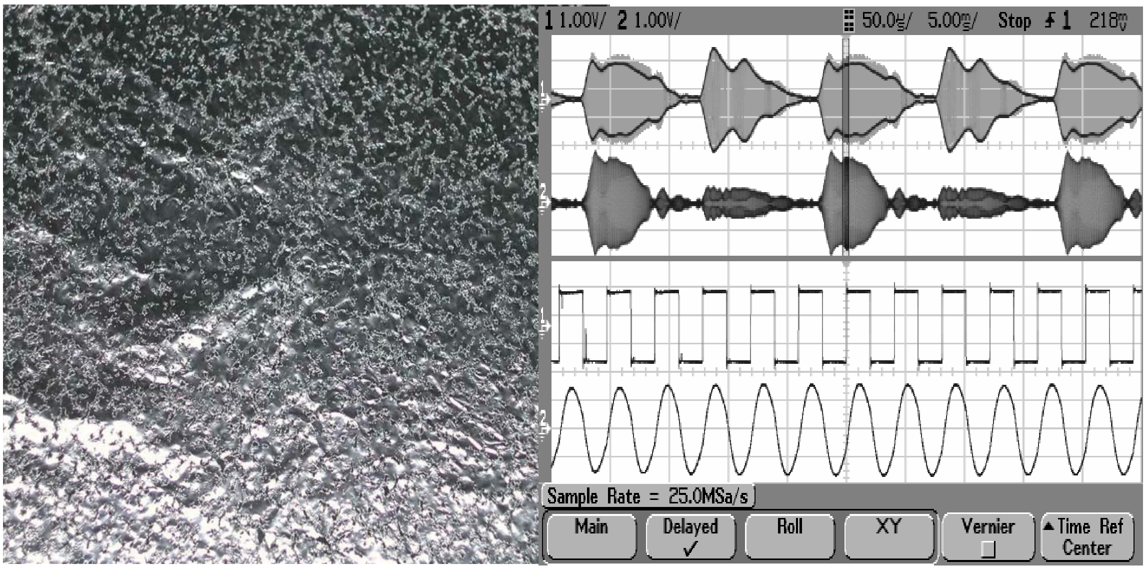
15 kW acoustic load (Extractor: H = 3.6 m, OD = 1 m)

MMM SONIC & ULTRASONIC CLEANING & LIQUID PROCESSING

MMM Technology: Multifrequency, Multimode, Modulated Sonic & Ultrasonic Technology

No other manufacturer has yet achieved and matched MMM exciting standards in precision cleaning. MMM is not only more efficient and effective than any other ultrasonic cleaning technology, it is UNIQUE.

- **Seeing is the believing! Try the aluminum foil test for yourself! Place the foil sample into our ultrasonic bath and hold the foil for approx. 5 -10 seconds and you'll discover why there's simply no comparison with any other conventional ultrasonic cleaning machine.**



Left: Perfectly, uniformly perforated aluminum foil, after 5 to 10 seconds of exposure to MMM ultrasonic vibrations in an ultrasonic cleaner. Frequency Range: From Hz to MHz; From Infrasonic to Supersonic. Right: Load current and voltage shapes (modulated and carrier).

- **Superior and deep penetration, independent of water levels.**
- **Reliability with extra power spread throughout the bath.**
- **Even distribution of ultrasonic energy throughout the liquid gives uniform and thorough cleaning of the surface without the risk of damage to fine parts and sensitive instrument.**
- **Extremely efficient electronics and transducer coupling to ultrasonic bath (overall approx. 95% efficiency) eliminates or reduces the additional need for heating.**
- **Spatial distribution of ultrasonic activity inside of a cleaning liquid is homogenous (no dead zones, no standing waves, fast and large frequency sweeping, broadband spectrum, complex modulation).**

- **Cleaning solvents, detergents and additives can be significantly reduced, or even eliminated because of the very high cleaning activity of the acoustic broadband spectrum.**
- **Cleaning time can be several times shorter comparing to traditional ultrasonic cleaning technology.**
- **Fast liquid conditioning and degassing because of very large regulating zone between maximal and average ultrasonic power and because of the ability to switch instantaneously between acoustic spectrums.**
- **Smooth Ultrasonic, PWM-power regulation from 1% to 100%. Ultrasonic energy can be easily adjusted in order to clean very fine and sensitive parts**

- Superior and deep penetration, independent of water levels.
- Reliability with extra power spread throughout the bath.
- No risk of damage to fine parts and sensitive instrument.
- Extremely efficient electronics and transducer coupling to ultrasonic bath.
- Homogenous spatial distribution of ultrasonic activity (no dead zones, no standing waves, fast and large frequency sweeping, broadband spectrum, complex modulation).
- Fast liquid conditioning and degassing.

Smooth Ultrasonic, PWM-power regulation from 1% to 100%.

- Fast and automatic ultrasonic-power and high-activity recovery.
- Cavitation level control.
- Wide bandwidth, programmable carrier frequency
- Programmable frequency, phase and PWM modulation
- Remote control, RS 485, RS 232C, handy keyboard, manual control…

- Overload protections: Over voltage, over current, thermal, short circuit
- Using the state-of-the-art MMM technology, “standing waves” do not exist and the efficiency goes well up!
- Applications: Sonochemistry, Cleaning, Sieving, Filtering, Metallurgy and Nanometallurgy, Catalysts and Free Radicals generation…

Important Background regarding Settings of the MMM-technology Ultrasonic Power Supply based systems
Modulated Multimode Multifrequency

The technology was originally developed for application of ultrasonics to large and arbitrary shaped mechanical systems. It turns out that water tanks and submersible box transducer are essentially arbitrary shaped mechanical systems where all of the MMM technological advantages are exhibited. We find that in liquid baths or liquid processing chambers our systems greatly improve basic cleaning and more complex functions like sonochemical reactions. Following is a brief comparison between our MMM system and conventional ultrasonic systems. For more information please have a look at our web site www.mpi-ultrasonics.com and for details on or MMM technologies go directly to:
http://mastersonic.com/documents/mmm_basics_presentation.pdf

Conventional Ultrasonics Cleaning Systems:

As you may know, conventional ultrasonic systems are based on the relatively-fixed resonant frequency of the transducers used. The generator drives the transducers at the fixed frequency without regard to the attached mechanical system including the steel tank surface and walls, the water, the parts loaded in the tank, temperature changes, etc. Each of these factors can significantly shift the resonant frequency of the transducers and conventional ultrasonic generators are not equipped to adapt to the change. The problem is compounded because industrial systems are continuously acoustically-evolving causing all of the load parameters to change. The result is inefficient transducer driving and reduced cavitation capabilities.

Conventional fixed frequency systems are also creating standing waves with areas of high acoustic activity and areas of low acoustic activity. When cleaning parts or making sonochemical treatment these problematic standing waves can over treat or damage some areas and leave other areas untreated. Some systems try to solve this problem with a small amount of generator frequency sweeping around the fixed center frequency. This method helps but does not normally correct the problem.

MMM Ultrasonic Liquid Treatment Systems:

Unlike conventional systems the flexibility of our generators starts with an adjustable primary frequency option. This feature allow us to consider shifts to the system resonance (e.g. 28 kHz shifting to 28.7 kHz) caused by the entire load factors mentioned above. Such adjustment and fine-tuning to the primary driving signal will greatly improve efficiency and improve the system response.

The MMM generator uses the adjusted resonant frequency (e.g. 28.7 kHz) as an improved carrier frequency that is further modified by special system feedback techniques to create an optimized and complex driving signal. We have developed advanced Digital Signal Processing techniques to monitor transducer(s) response to the load, and to follow the evolving changes of the load. Using such a real-time feedback loop the system creates an evolving and complex Modulated Multimode driving signal to stimulate coupled harmonics in the mechanical load (bath or chamber) to produce an effective wideband Multi-frequency acoustic field from infrasonic up to the megahertz range. As a result MMM systems using conventional transducers are capable of producing a very wide range of cavitation bubble sizes and a greater density of cavitation bubbles. This provides faster and better cleaning, faster sonochemical reactions, faster physical reactions, and faster liquid degassing.

Furthermore our unique Modulation methods use wide frequency sweeping and signal phase shifting techniques to eliminate the standing waves typically seen in fixed frequency systems. This advantage allows our systems to clean or process materials evenly with reduced risk of parts damage. Our systems can provide homogeneous energy throughout the sonication chamber resulting in faster and more uniform reactions.

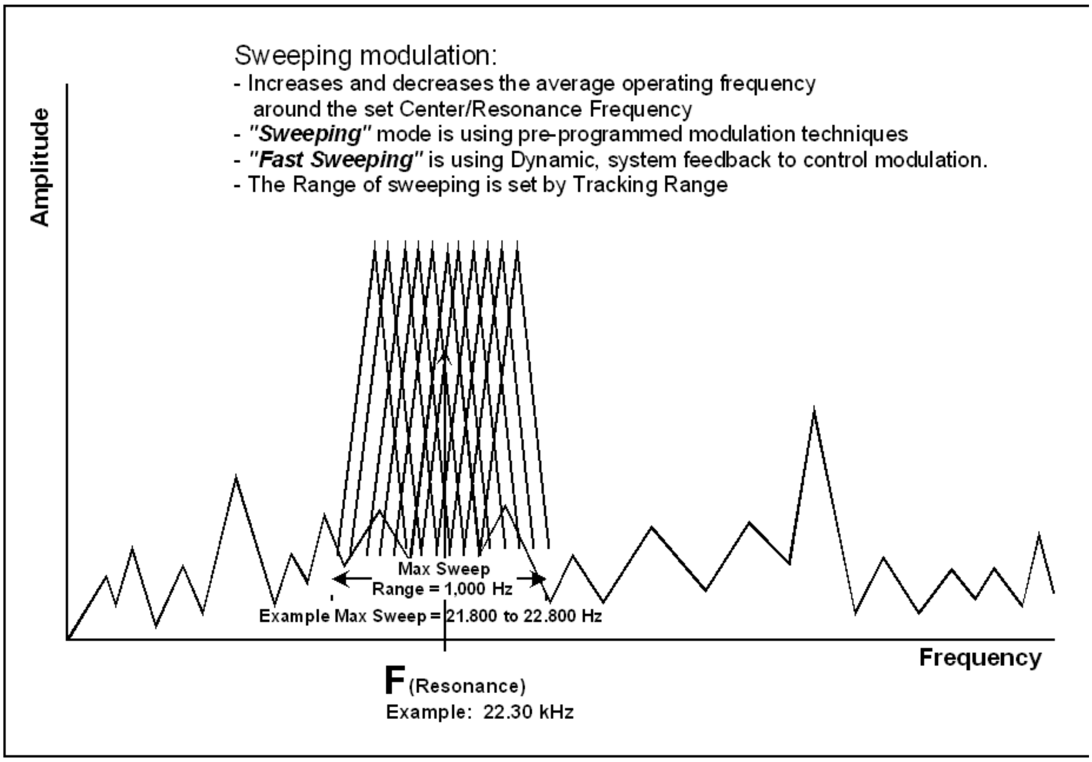
CRITICAL SETTINGS EXPLANATIONS

PWM is Pulse Width Modulation.

- This feature allows Low Frequency ON / OFF Pulsing of the ultrasonic power. It works very well to make strong shocking of the mechanical system.
- During the ON period the system is delivering modulated high frequency ultrasonic power. During the OFF period no ultrasonic power is given.
- The total maximum PWM Period is 1 second (1,000 ms).
- Using the PC Software control window the minimum PWM Period Steps adjustment is 10 ms. (use keyboard arrow key or mouse scroll wheel to make 10 ms fine tune adjustment)
- The PWM Ratio is the relative ON/OFF time. A 50% setting gives 50% ON Time and 50% OFF Time.

What does “sweeping” and “fast sweeping” mean?

Answer: Sweeping and Fast Sweeping are additional modulation techniques added to the fixed-frequency carrier signal. In other words, we start with a fixed-frequency signal adjusted to the system resonance (example: 21.3 kHz) to work as a primary signal carrier (or central operating frequency). Then by using one of the following methods we make complex modulations to cause shifting and sweeping of the primary fixed-frequency signal. This gives many benefits including reduce or eliminate standing waves, better ultrasonic stimulation of large and arbitrary shaped mechanical systems.



- "Sweeping" is a forced or static pre-programmed method of sweeping and modulating the carrier signal (central operating frequency) within an interval of up to 1,000 Hz. The sweeping is symmetrically placed, equally wide on both sides of the carrier frequency, and may be selected to cover frequency intervals from 0 Hz to 1,000 Hz. The mathematical function describing this sweeping is pre-programmed to produce large frequency-band acoustic-response effects in the mechanically-oscillating system including many harmonics and sub-harmonics.
    - When set to "0" (zero) there is no sweeping applied (system oscillates only on constant carrier frequency).
    - When set to the maximum the sweep range is 1,000 Hz.
        - OF generator model sweeping steps are 0 to 7.
        - OW generator model sweeping steps are 0 to 255.
        - IX generator model sweeping steps are 0 to 1.000 kHz.
- "Fast Sweeping" is a load-dependent Dynamic method of sweeping the carrier signal. This method is monitoring signal response from the mechanical load and using special algorithms to extract several resonant modes of the load. This information is transformed into a convenient time-evolving voltage signal that is used to make dynamic changes and modulated driving of the carrier frequency signal.
    - When set to "0" (zero) there is no dynamic sweeping applied.

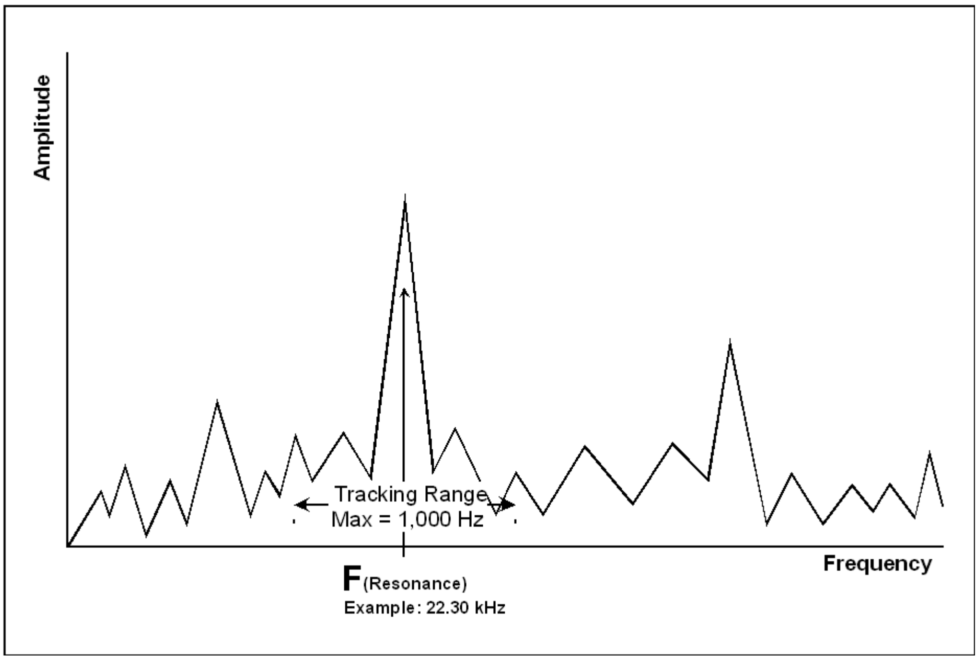
- When set to highest value the maximum dynamic sweeping effect is applied.
  - OF and OW generator model sweeping steps are 0 to 255 (0 to 1,000 Hz).
  - IX generator models sweeping steps are 0 to 1,000 Hz.

- Sweeping + Fast Sweeping: It is also possible to make a modulated signal that is a combination of forced pre-programmed "sweeping" plus dynamic "fast sweeping". When both are turned on, the system makes a complex hybrid signal modulation using both techniques at the same time.

What does "Tracking Range" mean?

Answer: MMM generators use system feedback signals (phase between current and voltage on the transducer) to keep the central operating frequency close to the resonant frequency of the transducer (operating in parallel resonance). The "Tracking Range" correction is minimized when set to 0 units. The "Tracking Range" correction is maximized when set to 30 units. One unit is approximately 100Hz. So when the "Tracking Range" is set, for example to 12, the central operating frequency will be corrected (if it is necessary, regarding the phase between current and voltage) in the range of +- 1200 Hz. The "Tracking Range" is a very important feature of MMM generators, because it makes them self adaptive to the mechanical changes of the load, for example when you put parts in a cleaning tank.

- When set to "0" (zero) no tracking is implemented.
- When set to 30 (1,000 Hz on IX models) the tracking range is set to the maximum correction mode. The internal oscillator, which is generating carrier frequency-signal, is trying to follow wide-band oscillations of the mechanical system. This maximum setting may be inefficient for many applications. Consequently, the optimal tracking range should be experimentally adjusted.



- In general systems using one or few transducers (e.g. Pipe-Clamp or Sieving systems) will work well if the Tracking Range is set to a narrow small range.
- Systems using many transducers (e.g. Cleaning Bath or Submersible Transducer Arrays) often benefit from wider Tracking Range settings.

Please visit our website for more details, or contact us directly with any inquiries: www.mpi-ultrasonics.com & www.mastersonics.com

(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 1 238 715 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
11.09.2002 Bulletin 2002/37

(51) Int Cl.7: **B06B 1/02**

(21) Application number: **01810227.7**

(22) Date of filing: **05.03.2001**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
Designated Extension States:
AL LT LV MK RO SI

(71) Applicant: **Miodrag Prokic**
2400 Le Locle (CH)

(72) Inventor: **Miodrag Prokic**
2400 Le Locle (CH)

(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 oscillating 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.

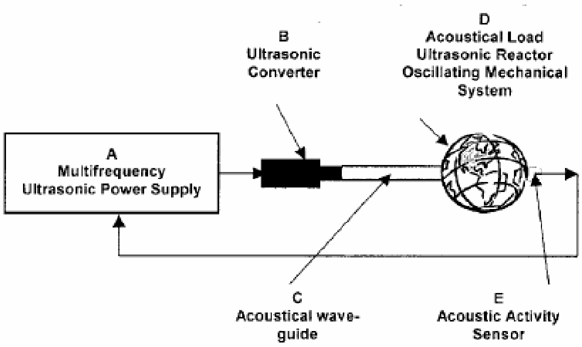


Fig. 1 Block Diagram of a Multifrequency Structural Actuator

EP 1 238 715 A1

Printed by Jouve, 75001 PARIS (FR)