Innovative multifrequency, multimode, modulated (MMM) sonic & ultrasonic vibrations for food-processing applications
MMM - Wideband Sonic and Ultrasonic Technology

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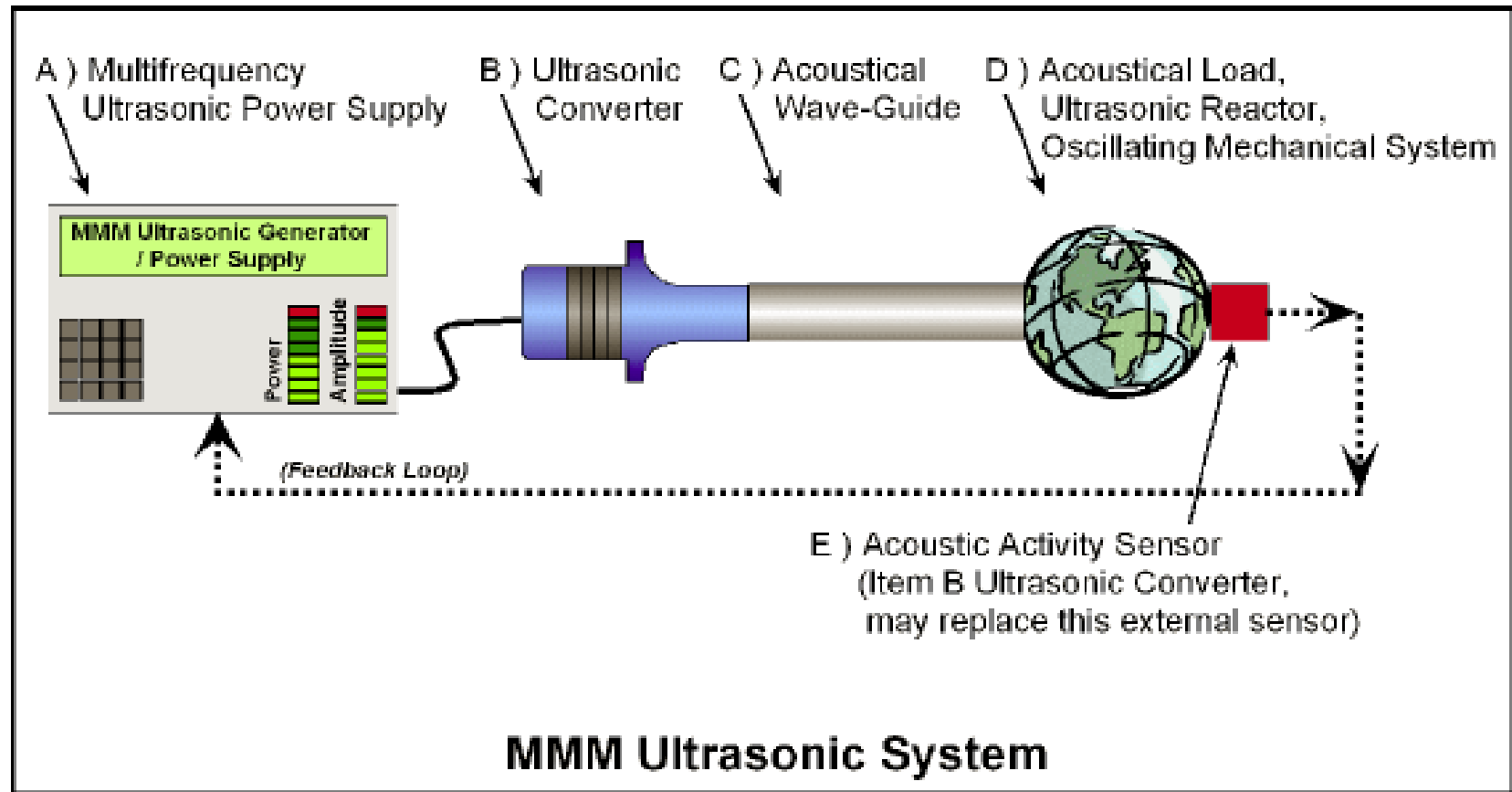
Until recently, traditional high intensity and fixed-frequency ultrasound has been applied in fields like cleaning, plastic welding, mixing and homogenization. However, new industrial ultrasound-related applications, such as sonochemistry, extractions, waste water treatment, etc., are becoming increasingly important, where fixed-frequency traditional ultrasonic systems are showing certain limitations.

The majority of the above-mentioned, old and new ultrasonic applications are presently based on fixed-frequency, well-tuned ultrasonic sources where a large number of design and matching parameters must be respected. These basic requirements significantly limit large scale and practical applications of the findings realized in laboratory-scale testing.
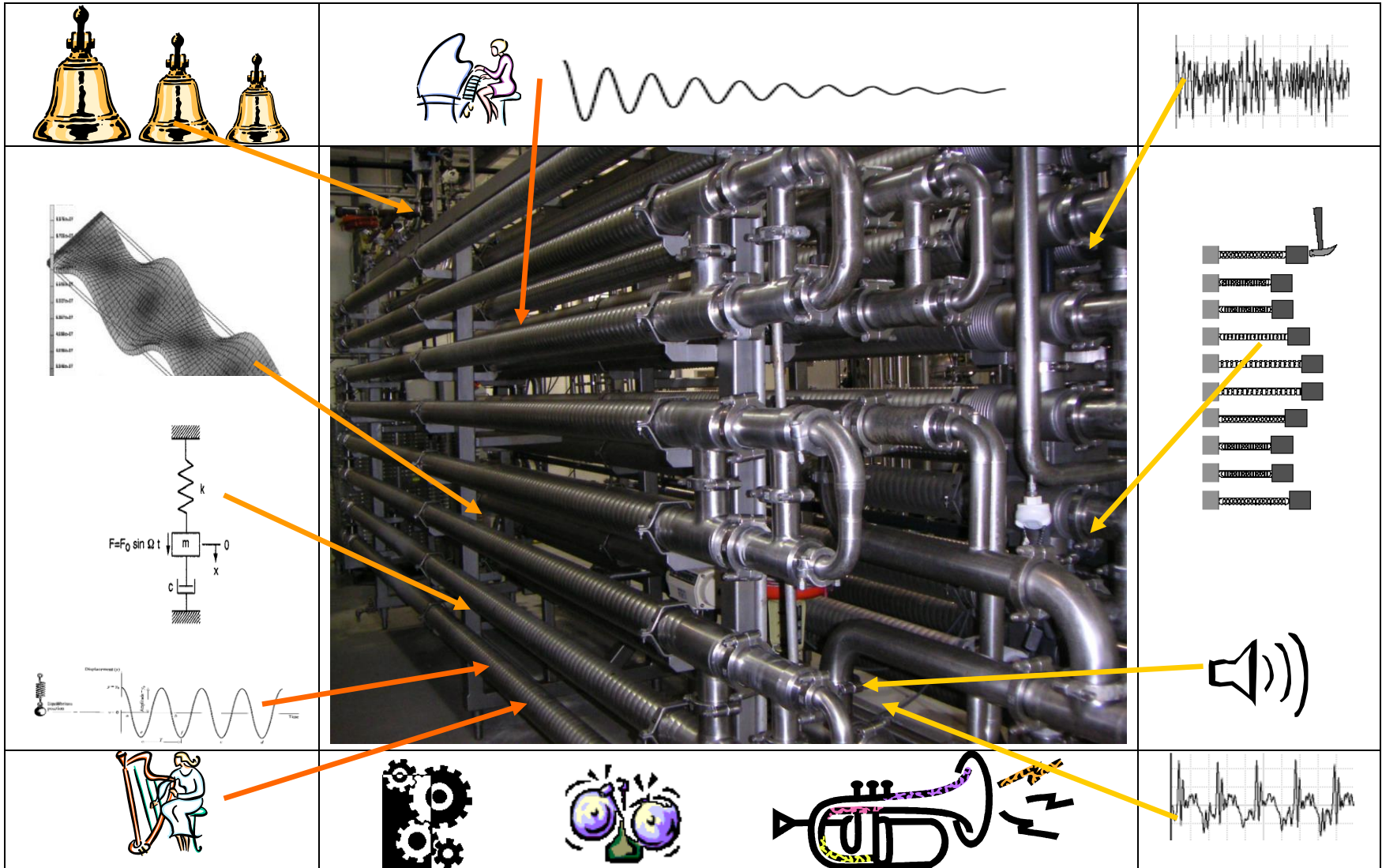
Extensive field tests conducted by experts in ultrasonics have demonstrated that in order to achieve a high efficiency, the ultrasonic systems must be well tuned to the load. Since most ultrasound units work inherently in non-stationary conditions, they have to, in theory, continuously adapt themselves to the load to maximize the efficiency, which is difficult to achieve with the fixed-frequency units. To meet this challenge, novel MMM signal processing techniques have been developed.

As a result of such an effort, the multifrequency, multimode, modulated (MMM) technology has become the first to succeed in applying "Wideband-frequency high-power ultrasonic agitation" to almost any existing ultrasonic equipment, regardless of its mass, load size and particular operating conditions. Furthermore, these new signal-processing techniques can be easily implemented without involving significant design modifications of existing systems.

In this presentation we will first give an overview of the signal processing techniques used by the "MMM technology" and show different novel and effective applications with an emphasis on food industry applications.

A) Multifrequency
Ultrasonic Power Supply

B) Ultrasonic
Converter

C) Acoustical
Wave-Guide

D) Acoustical Load,
Ultrasonic Reactor,
Oscillating Mechanical System

MMM Ultrasonic Generator
/ Power Supply

Power

Amplitude

(Feedback Loop)

E) Acoustic Activity Sensor
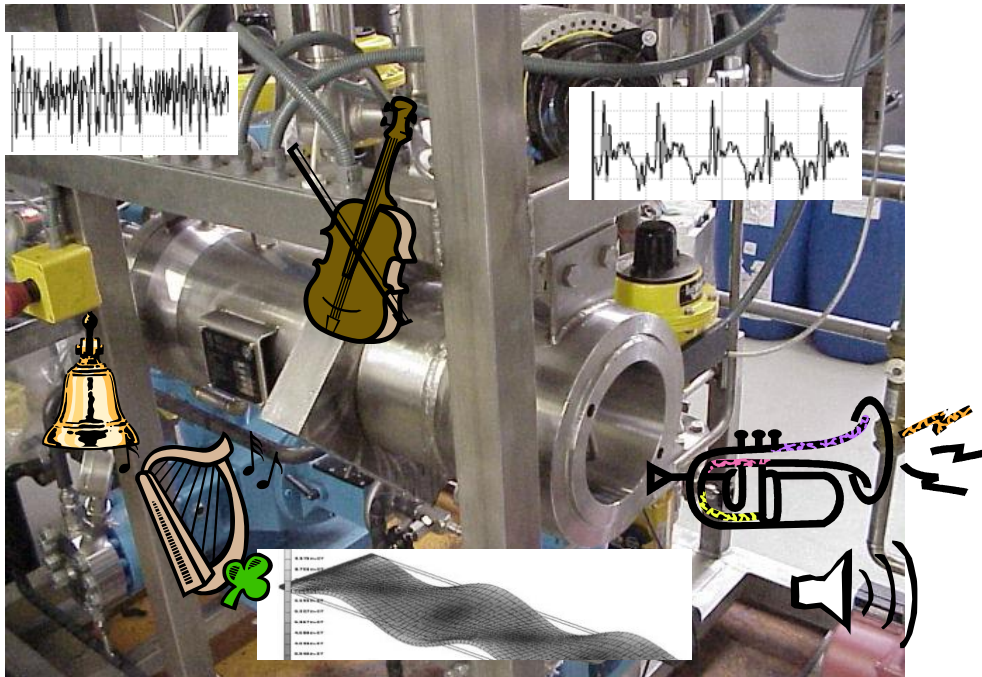(Item B Ultrasonic Converter,
may replace this external sensor)

MMM Ultrasonic System

Block diagram of MMM ultrasonic System

ILLUSTRATION OF DIFFERENT OSCILLATING MODES OF A COMPLEX MECHANICAL SYSTEM
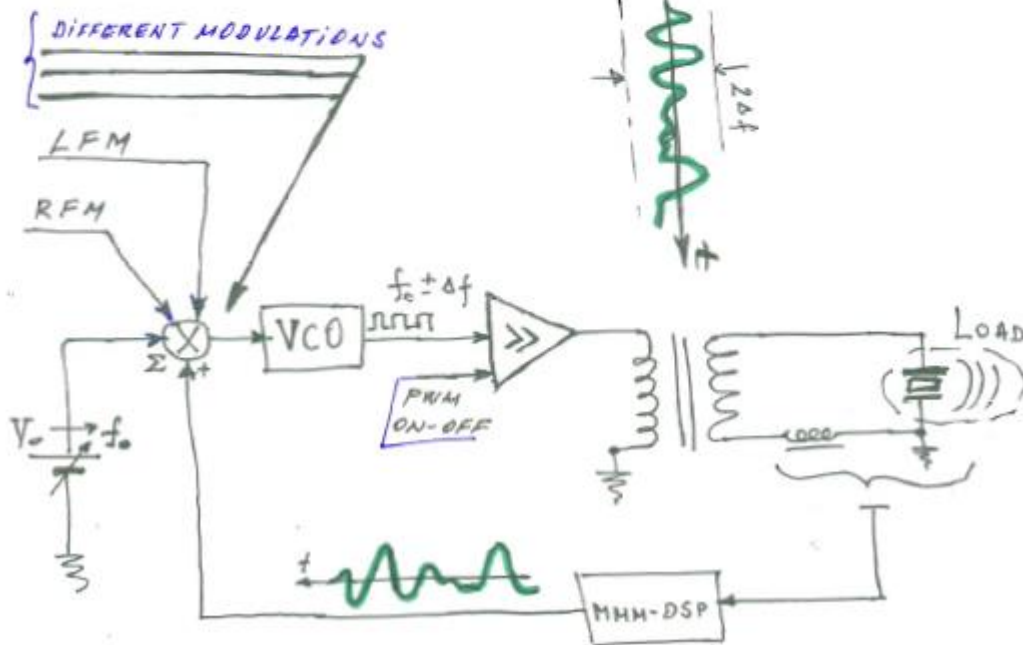
$F = F_0 \sin \Omega t$
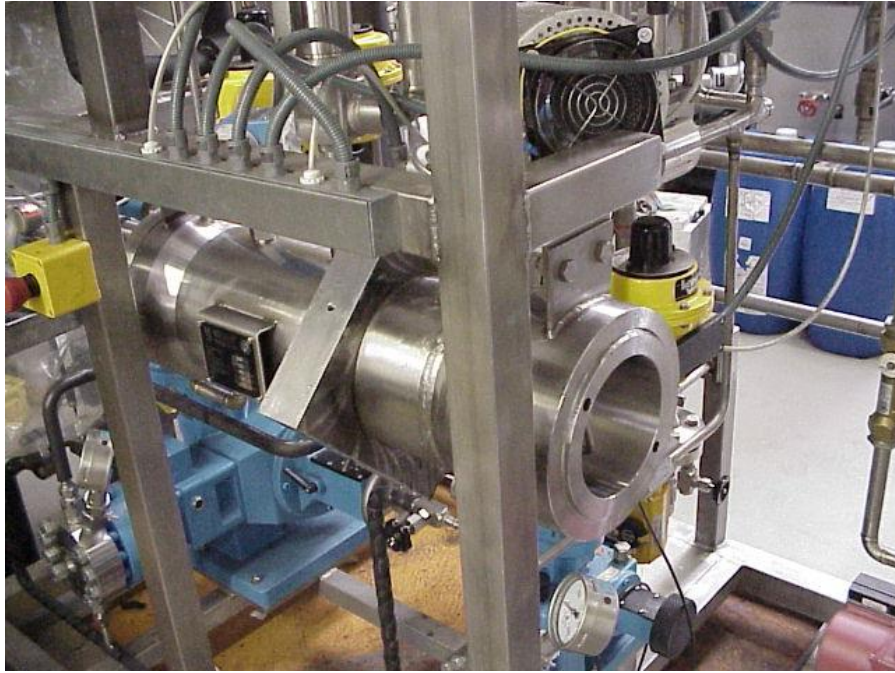
Complex mechanical system before MMM agitation

Complex mechanical system during MMM agitation

Pulse-repetitive excitation of a mechanical system

a)

Time domain: Mechanical system response

б)

Frequency domain: Mechanical system response

в)

DIFFERENT MODULATIONS

LFM

RFM

$f_c \pm \Delta f$

VCO

PWM ON-OFF

$V_o \rightarrow f_o$

LOAD

MMM-DSP

d)
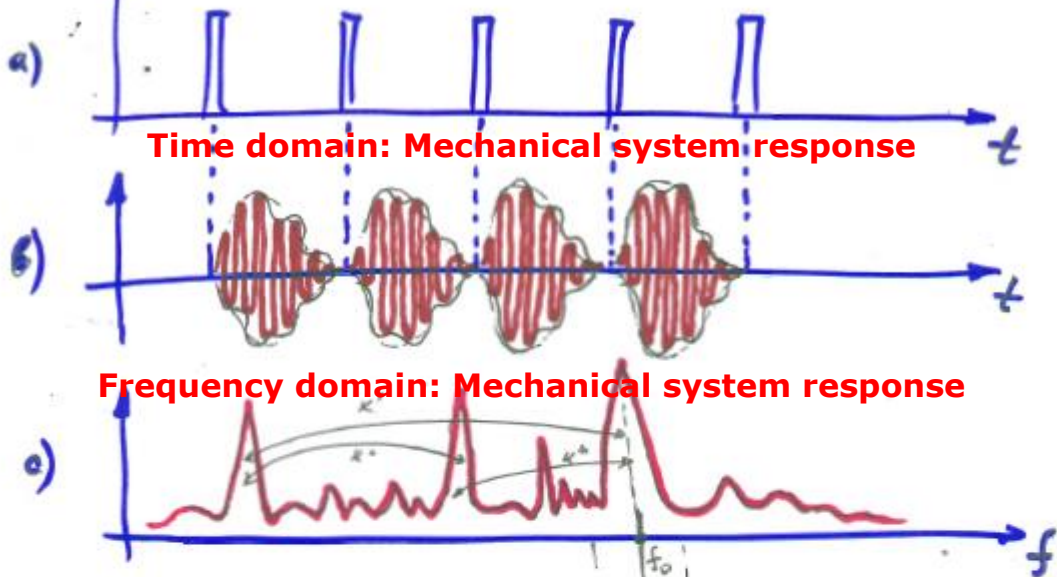
MMM Power Supply Block Diagram

With dynamic, load-dependent frequency modulation
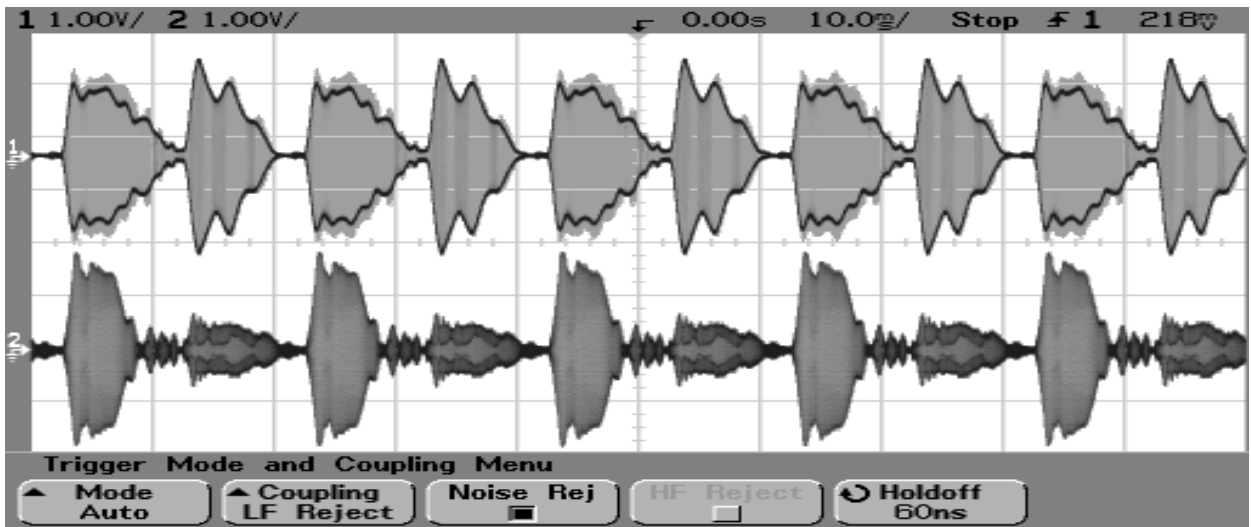
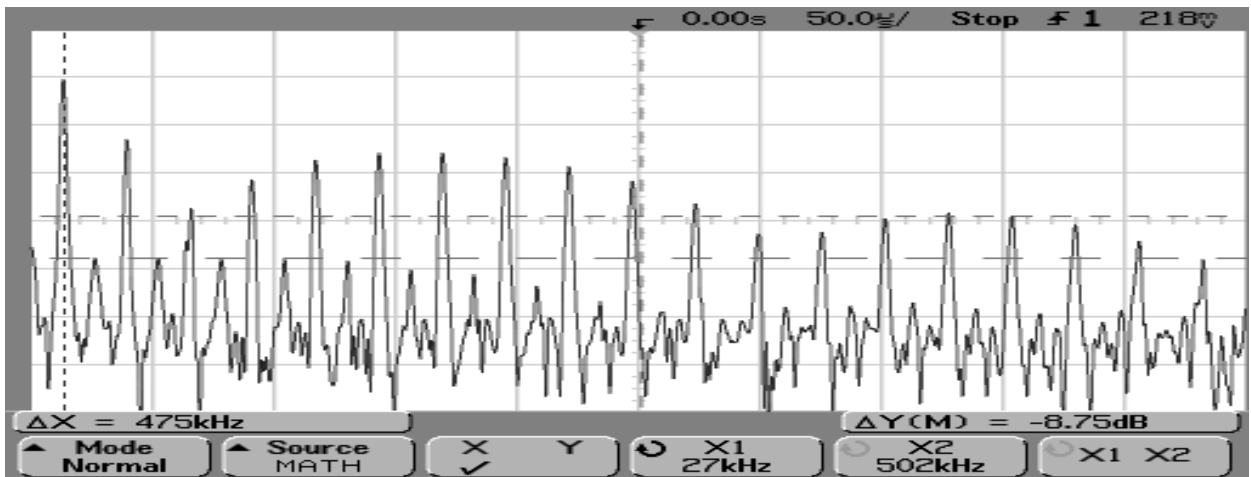**Examples of load voltage and current signals in a time domain**

Example of a Frequency Domain of Load Oscillations

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 (Modulated, Multimode, Multifrequency) 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.

> *Modulated, Multimode, Multifrequency 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).
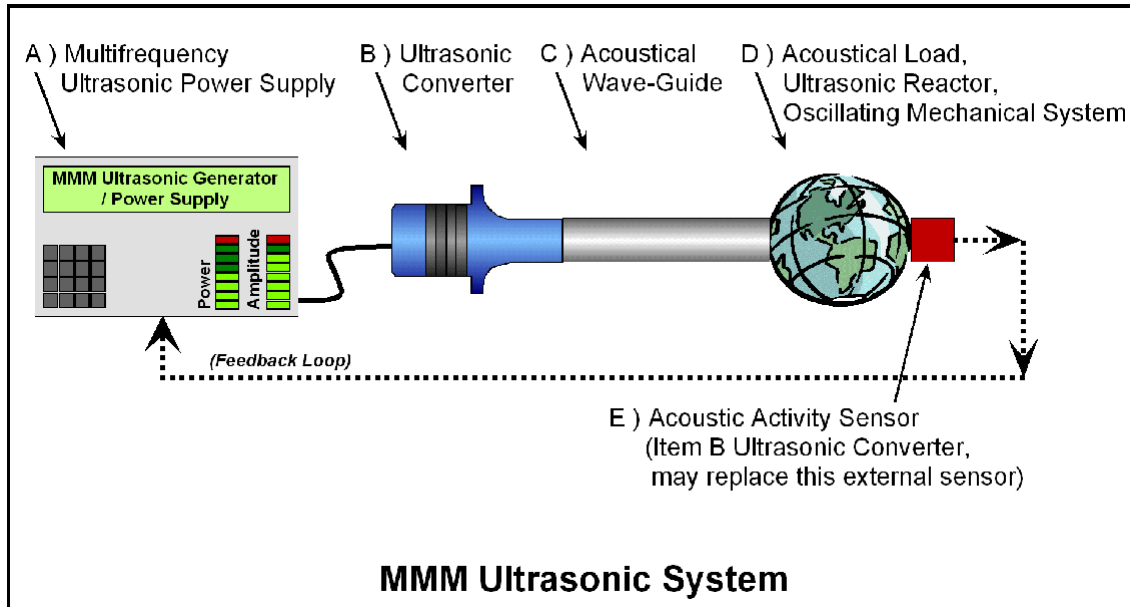
Fig. 1

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.

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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

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system (B, C, D) means that the ultrasonic power supply (A) is driving the ultrasonic converter (B) with limited current and sufficiently high voltage, <u>delivering only the active or real power</u> 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.

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 = Multi-frequency, Multimode, Modulated). 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 = M**ultifrequency, **M**ultimode, **M**odulated 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

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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

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mechanical systems and use these signal to drive the system in a highly efficient and synergistic manner. More about the MMM technology....

- o *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.

- 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:

  - o This Multi-Frequency Generator greatly increases our options for reaction chamber design.

  - o Now we can make most any size or shape and provide the necessary power to meet your complex needs.

- Compatible with all transducers options
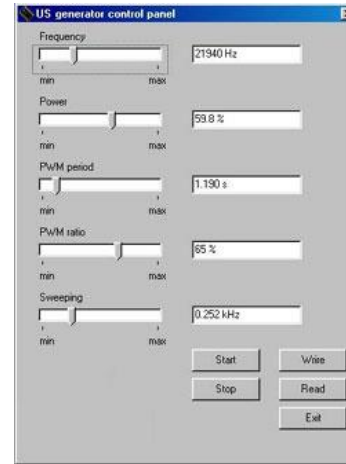
Windows PC Software
Control Option

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.

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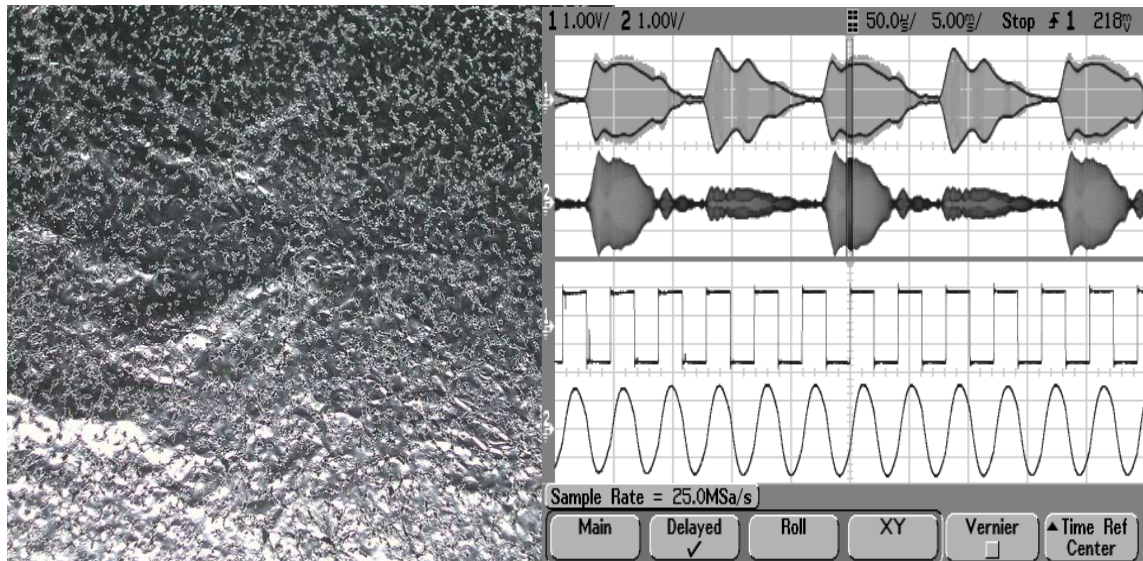
Left: Perfectly, uniformly perforated aluminum foil, after 5 to 10 seconds of exposure to **MMM** ultrasonic vibrations in an ultrasonic cleaner. Frequency Range: From Hz to MHz; From Infrasonic to Supersonic. Right: Load current and voltage shapes (modulated and carrier).

- 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.

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- **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**

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.
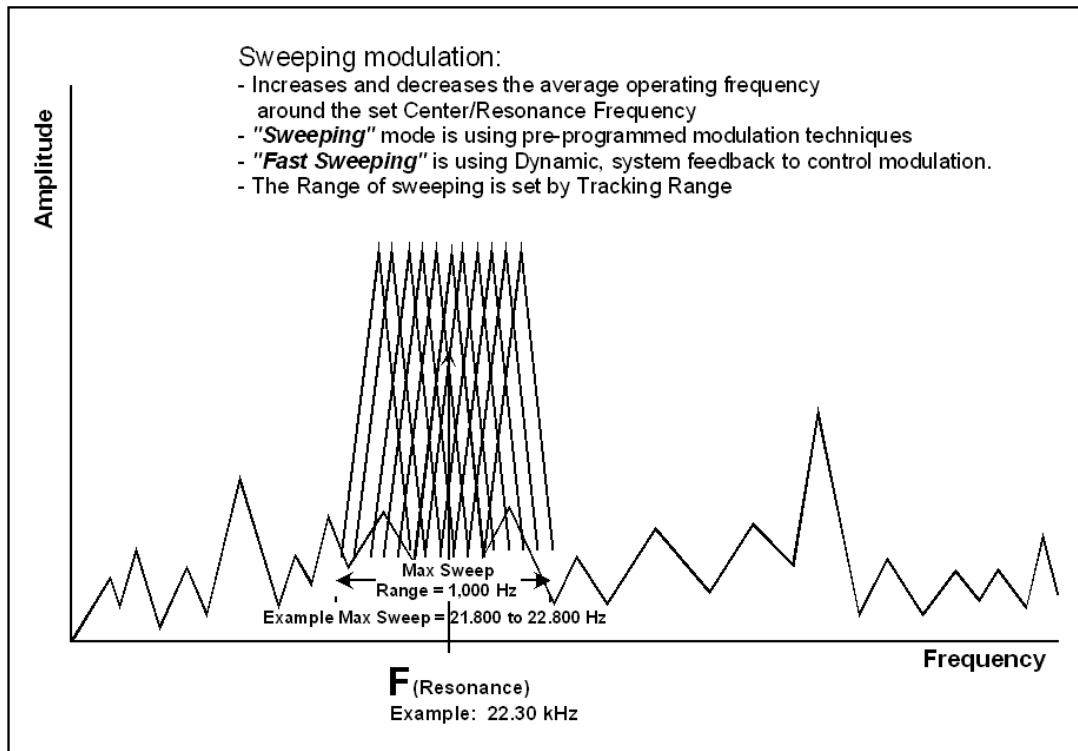
CRITICAL SETTINGS EXPLANATIONS

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 modulation:
- Increases and decreases the average operating frequency around the set Center/Resonance Frequency
- *"Sweeping"* mode is using pre-programmed modulation techniques
- *"Fast Sweeping"* is using Dynamic, system feedback to control modulation.
- The Range of sweeping is set by Tracking Range

Max Sweep Range = 1,000 Hz
Example Max Sweep = 21.800 to 22.800 Hz

F(Resonance)
Example: 22.30 kHz

- **"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.**
  - o **When set to "0" (zero) there is no sweeping applied (system oscillates only on constant carrier frequency).**
  - o **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.**
  - o **When set to "0" (zero) there is no dynamic sweeping applied.**
  - o **When set to highest value the maximum dynamic sweeping effect is applied.**

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- **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.**
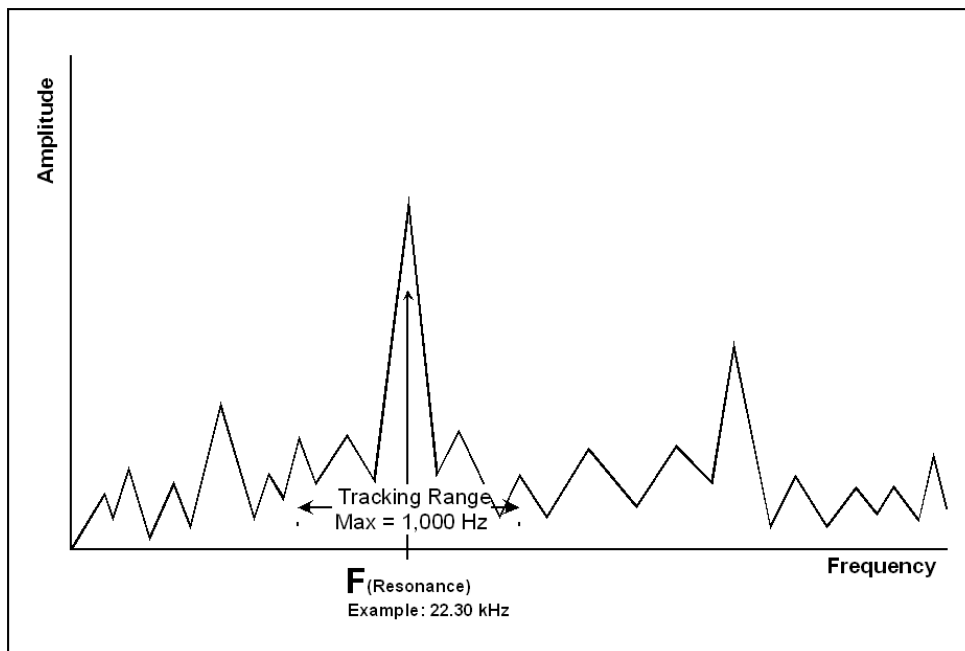
- **In general systems using one or few transducers (e.g. Pipe-Clamp or Sieving systems) will work well if the Tracking Range is set to a narrow small range.**

- **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

(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.
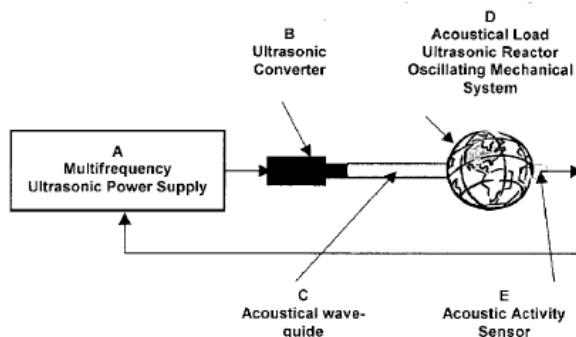
Fig. 1 Block Diagram of a Multifrequency Structural Actuator