HOW TO SELLECT MMM GENERATOR FOR DIFFERENT APPLICATIONS & MEANING OF ACOUSTICAL LOADING

MMM = Multifrequency, Multimode, Modulated Sonic & Ultrasonic Vibrations (MMM Technology)

MPI has many MMM generators for different Sonic and Ultrasonic applications, and also number of customized MMM Power Supply versions.

People who are ordering our open frame generators (OF and OW models) are usually producing their own equipment, and installing such generators in their own cabinets, housings and boxes (open frame generators have no name of the producer, meaning that every client can declare them as its own products, and such generators are presenting simplified, minimal, low-priced configurations…). Usually users of MMM generators are already in business of producing ultrasonic equipment for different technological applications (Cleaning, Water treatment, Sonochemistry…), installing additional sensors, PLC-s, computerized automatic control , and they have a lot of basic knowledge regarding Ultrasonic products. We are giving complete manuals and already experienced users can easily make their products using our MMM generators. The biggest advantage of open frame MMM generators is that they could easily be adjusted to drive almost any kind of piezoelectric transducers (particularly well applicable when arrays of transducers are operating in parallel), and if the client already has its own transducers, we could always make small modifications and settings making MMM generators compatible to clients' hardware. In most of cases, clients can make all modifications and settings alone (without our assistance), just following instructions given in our manuals. In cases of unusual applications it is recommendable to ask MPI for assistance.

For laboratory and scientific research, as well as for different extraordinary, challenging and unusual, complex and high-tech applications, we are delivering full version of the MMM generator (MSG 1200-IX, for instance) with all possible frequency controls, modulations, timings, digital and smooth frequency settings, and all overload protections, made in a entirely-closed metal box., including modules for external PC, PLC, and manual controls, and number of other options. Client is fully-operational, fully-protected and fully-independent when using such generators. Here we can also offer number of customized versions and different settings in order to satisfy needs of certain

demanding application, and in such cases we recommend to our clients to tell us what they would like to realize. We are also giving complete manuals describing the structure and operations with such generators.

For all of our MMM generators we are offering number of modules and adapters in order to perform: external manual, remote control, or PLC control, or to have everything controlled from the software graphic-interface on a PC, to connect many of MMM generators in a large network controlled from the single PC etc. (for getting more of relevant information you could visit: ftp://mastersonic.serveftp.net and make downloads, or www.mpi-ultrasonics.com).

There is no universal answer, solution and 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). Our MMM generators are able to drive arbitrary-shaped solid masses, but still certain limits coming from physics and acoustics should be respected… and the best would be to consult MPI, but only after reading all of information offered to you, such as this one (visit: ftp://mastersonic.serveftp.net and make downloads, or www.mpi-ultrasonics.com).

If you would operate certain single piezoelectric converter in resonance, and your converter by its design/geometry already has well-defined and sharp resonance, 20 kHz for instance, you would need MMM generator that is covering relatively close vicinity of 20 kHz (for instance from 18 kHz to 22 kHz), since having wider interval of carrier frequency-settings will not make any benefit for your application (and you could only destroy, overload, or over-heat your mechanical system, trying to drive it against its "acoustical-nature"). In such cases it is always better to ask MPI to make different frequency-intervals pre-settings for you (factory-made settings). If your converter would have 30 kHz resonant frequency, then we will limit carrier-frequency settings to cover close vicinity of 30 kHz. If you insist to get full frequency range of carrier, central-operating frequency settings (for instance from 18 kHz until 42 kHz), and you know that you will use certain type of converter which is operating well only on certain constant frequency, you would be faced with a possibility to damage your equipment forcing unnatural, acoustically-unacceptable operating regimes, and for recognizing and avoiding such regimes you would need a lot of specific experience (we

do not recommend that you take such freedom of decision without asking MPI for assistance). If you would like to use and drive different ultrasonic transducers, each of them having different resonant frequencies and different input capacitances, again to repeat, one single MMM generator, as it will be delivered to you, can not drive number of such transducers (one by one) without you every-time performing important modifications inside of the generator (such as **inductive compensation** etc.). Electronically we could try to drive your resonant system in a larger frequency band (then its “acoustic-nature” is dictating), but 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 such cases we are usually asking (ambitious and demanding) clients to explain what they would like to realize (to give application details) and which kind of sonotrodes, tools and mechanical devices (named acoustic load) they would like to connect to the converter… (in order to help them to avoid non-realistic, science-fiction, too-imaginative, and out of “acoustics-reality” expectations and situations). In many cases we are making complete mechanical system or its most-important parts for a client, realizing the best adjustments and tuning in our laboratories (since clients without previous experience in Ultrasonics could and would have problems, and will make number of mistakes). Also in many cases clients are sending us their mechanical parts and devices that should be ultrasonically agitated, and we are realizing the rest (fixing the converter, optimizing the operating regime, making the best tuning, best inductive compensation…).

Many of such situations are well-explained in our manuals, but we know that clients are always able to find or try some exceptional operating-situations that are still not-explained or not-covered by our specifications (even against our suggestions), and we strongly recommend them to ask MPI for advices by explaining their application (before exploring risky options). We tried to predict all of such clients’ mishandlings and possible mistakes and we implemented many levels of internal overload protections, but still, “very-ambitious” client could sooner or later find a way how to disable MMM generator (what we do not recommend).

Since we have enormous number of demands regarding here-mentioned situations, and we are physically not able to answer every request for information, we strongly recommend to our clients, first to read all materials (similar to this one) we are offering to them, by visiting: ftp://mastersonic.serveftp.net and making downloads, or www.mpi-ultrasonics.com, and then to start asking specific and still-unanswered questions.

Understanding correctly MMM concept (MMM = Multifrequency, Multimode, Modulated Sonic & Ultrasonic Vibrations = MMM Technology) is also very important, in order to avoid expecting being able to realize all non-realistic, science-fiction and too-imaginative, or out of “acoustics-reality” situations. There are few of important technical-specification points and advices to be considered and respected:

a) Every MMM generator has certain factory-predefined carrier-frequency-interval settings (for instance from 18 to 42 kHz, or from 15 to 25 kHz etc.), and it can operate only in any constant frequency inside of factory-given limits. If somebody likes to operate MMM generator outside of factory-predefined carrier frequency range, this is not possible.

b) In addition to carrier frequency settings, there are number of frequency-modulating (user-selectable) options, such as mathematically-predefined, and MMM-dynamic, time-evolving and load-dependant, carrier-frequency modulating options. User should first select the best central operating (carrier) frequency, for every particular case (keeping all modulating parameters disabled, or giving them zero values), and then, after converter is already producing certain measurable, constant-frequency amplitudes, start gradually implementing different MMM modulating parameters. While performing such initial frequency settings, generator should be limited to produce between 10% and 30% of its maximal output power, in order to avoid sudden overloads and system damages. 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 no more optimally tuned, carrier frequency and frequency-modulating parameters should be slightly readjusted.

c) MMM generator itself is not operating in a large frequency band, but its acoustical load (in fact transducer connected to acoustical load), can effectively-oscillate in a large frequency band after different frequency modulations are applied (modulating the carrier or central operating frequency = MMM modulations). That means that only acoustical results (acoustic spectrum inside of an acoustic load) are covering large frequency band, only as the consequence of applying MMM modulation (and how large acoustic-load frequency spectrum would be will depend on acoustic and mechanical properties of the load, on its geometry, and on MMM parameters-settings). For instance, we can use 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…) that our mechanical load starts vibrating uniformly, without creating standing waves (if MMM modulating parameters are optimally selected), and covering large band of many resonant frequencies. In other words, MMM-modulated acoustic

loads are entering into different "acoustic-reality" and becoming dynamically-controlled multi-resonant systems, which ordinary mechanical parameters are also slightly modulated or modified, comparing them to static mechanical parameters and constant-frequency operations (and knowledge about how to realize such MMM-regimes is the core-business of MPI). If certain 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 complete acoustic load is vibrating uniformly). In certain applications (such as Liquids-processing, Sonochemistry, Cleaning…), while applying constant carrier frequency anywhere in the range between 20 and 40 kHz, and additional MMM modulation, we could 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 (for instance cavitation).

d) **Every well-selected MMM operating regime can be recognised 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 mechanical system is producing randomized, cracking, braking and impulsive, low-frequency noise, this is also the sign that operating regime is not well selected and that MMM parameters should be changed.**

e) **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).**

f) **MMM technology is recommendable only for unique, extraordinary and new applications, where user is expecting results that could not be reached by using standard, traditional ultrasonic technologies. Of course, also in comparison with every other, traditionally-known ultrasonic application, MMM technology has its dominant place.**

g) **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:

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

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

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

It is necessary to have in mind that in certain applications (such as ultrasonic welding), operating and loading regime of ultrasonic transducer changes drastically in relatively short time intervals, starting from a very regular and no-load situation (which is easy to control), going to a full-load situation, which changes all parameters of ultrasonic system (impedance parameters, resonant frequencies...). In a no-load and/or low power operation, ultrasonic system behaves as a typically linear system; however, in high power operation the system becomes more and more non-linear (depending on the applied mechanical load). The presence of dynamic and fast changing, transient situations is creating the absolute need to have one frequency auto tuning control block, which will always keep ultrasonic drive (generator) in its best operating regime (tracking the best operating frequency).

The meaning of mechanical loading of ultrasonic transducers:

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

Optimal driving of ultrasonic transducers:

For optimal transducer efficiency, the best situation is if/when transducer is driven in one of its mechanical resonant frequencies, delivering high active power (and very low reactive power) to the loading media. Since usually resonant frequency of loaded transducer is not stable (because of dynamical change of many mechanical, electrical and temperature parameters), a PLL resonant frequency (in real-time) tracking system has to be applied. When we drive transducer on its resonant frequency, we are sure that the transducer presents dominantly resistive load. That means that maximum power is delivered from ultrasonic power supply (or ultrasonic generator) to the transducer and later on to its mechanical load. If we have a reactive power on the transducer, this can present a problem for transducer and ultrasonic generator and cause overheating, or the ultrasonic energy may not be transferred (efficiently) to its mechanical load. Usually, the presence of reactive power means that this part of power is going back to its source. The next condition that is necessary to satisfy (for optimal power transfer) is the impedance matching between ultrasonic generator and ultrasonic transducer, as well as between ultrasonic transducer and loading media. If optimal resonant frequency control is realized, but impedance/s matching is/are not optimal, this will again cause transducer and generator overheating, or ultrasonic energy won't be transferred (efficiently) to its mechanical load. Impedance matching is an extremely important objective for realizing a maximum efficiency of an ultrasonic transducer (for good impedance matching it is necessary to adjust ferrite transformer ratio and inductive compensation of piezoelectric transducer, operating on a properly controlled resonant frequency). Output (vibration) amplitude adjustments, using boosters or amplitude amplifiers (or attenuators) usually adjust mechanical impedance matching conditions. Recently, some ultrasonic companies (Herman, for instance) used only electrical adjustments of output mechanical amplitude (for mechanical load matching), avoiding any use of static mechanical amplitude transformers such as boosters (this way, ultrasonic configuration becomes much shorter and much more load-adaptable/flexible, but its electric control becomes more complex). By the way, we can say that previously given conditions for optimal power transfer are equally valid for any situation/system where we have energy/power source and its load (To understand this problem easily, the best will be to apply some of the convenient systems of electromechanical analogies).

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

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

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

> When transducers are driven full power, it happens in the process of harmonic oscillation, so input electrical energy is permanently transformed to mechanical oscillations. What happens when we stop or break the electrical input to the transducer? - The generator no longer drives the transducer, and/or they effectively separate. The transducer still continues to oscillate certain time, because of its elastomechanical properties, relatively high electro-mechanical Q-factor, and residual potential (mechanical) energy. Of course, the simplest analogy for an ultrasonic transducer is a certain combination of Spring-Mass oscillating system. Any piezoelectric or magnetostrictive transducer is a very good energy transformer. It means that if the input is electrical, the transducer will react by giving mechanical output; but, if the active, electrical input is absent (generator is not giving any driving signal to the transducer) and the transducer is still mechanically oscillating (for a certain time), residual electrical back-output will be (simultaneously) generated. It will go back to the ultrasonic generator through the transducer's electrical terminals (which are permanently connected to the US generator output). Usually, this residual transducer response is a kind of reactive electrical power, sometimes dangerous to ultrasonic generator and to the power and frequency control. It will not be synchronized with the next generator driving train, or it could damage generator's output switching components.
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> Most existing ultrasonic generator designs do not take into account this residual (accumulated) and reversed power. In practice, we find different protection circuits (on the output transistors) to suppress self-generated transients. Obviously, this is not a satisfactory solution. The best would be never to leave the transducers in free-running oscillations (without the input electrical drive, or with "open" input-electrical terminals on the primary transformer side). Also, it is necessary to give certain time to the transducers for the electrical discharging of their accumulated elasto-mechanic energy.

Resonant frequency control under load:

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 elasto-mechanical properties of total mechanical system (under high power driving) are accumulating enough (electrical and mechanical) potential energy, and the system is again coming back, mechanically decoupling itself from its load (for instance from liquid) and/or starting to present typical R-L-C structure that is easy for any PLL resonant frequency control (having, again, real/recognizable resonant frequency).

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 transients 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.

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