Chapter 5
Wideband Multi-Frequency, Multimode, and Modulated (MMM) Ultrasonic Technology

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1 Introduction

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

Current ultrasonic applications are based on fixed-frequency, well-tuned ultrasonic sources where a number of design and matching parameters must be respected. These basic requirements limit large-scale and practical applications of the findings in laboratory-scale testing.

Extensive field tests conducted by experts in ultrasonics have demonstrated that in order to achieve a high efficiency treatment, ultrasonic systems must be well tuned to the load. Since most ultrasound units work inherently in non-stationary conditions, they must, in theory, continuously adapt themselves to the load to maximize efficiency, which is difficult to achieve with fixed-frequency units. To meet this challenge, multi-frequency, multimode, modulated (MMM) signal-processing techniques have been developed by MP Interconsulting (Prokic, 2001; Prokic and Sandoz, 2005).

As a result of this effort, MMM technology has become the first to achieve "wideband-frequency high-power ultrasonic agitation" in existing ultrasonic equipment, regardless of its mass, load size or particular operating conditions. In addition, the application of the new signal-processing techniques in existing systems does not involve significant design modifications.

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2 Background and Relevant Theories

In recent years, efforts have been made to explore the use of multi-frequency techniques to improve the efficiency of ultrasound treatments. A high-frequency ultrasonic field coupled with low-frequency stimulation can enhance cavitation effects with a sharp rise in both sub-harmonic and sono-luminescence intensity (Iernettia et al., 1997). A dual-frequency sonic processor has been modeled to control the mode and spatial distribution of cavitation events (Moholkar et al., 2000). Furthermore, cavitation can be enhanced by a multi-frequency sonication field in which orthogonal continuous ultrasound is applied (Feng et al., 2002). The spatial-temporal dynamics of cavitation bubbles in mono- and dual-frequency sonoreactors has also been analyzed (Servant et al., 2003).

MMM technology, on the other hand, does not focus on application of multiple ultrasound sources with different but fixed frequencies in sonication system design. Rather, it utilizes concepts from control theory, digital signal processing, and power electronics to improve the performance of an ultrasonic system and to extend its operating frequency bandwidth. In the following section, we provide a concise introduction to some of the concepts and key technologies that are used in MMM.

2.1 Closed-Loop Control

Consider an automobile's cruise control, which is a device designed to maintain a constant vehicle speed. The output variable of the system is vehicle speed. The input variable is the engine's throttle position, which influences engine torque output. A simple way to implement cruise control is to lock the throttle position when the driver engages cruise control. However, on hilly terrain, the vehicle will slow down going uphill and accelerate going downhill. This type of controller is called an open-loop controller because there is no direct connection between the output of the system and its input. In a closed-loop control system, a feedback controller monitors the vehicle's speed and adjusts the throttle as necessary to maintain the desired speed. This feedback compensates for disturbances to the system, such as changes in slope of the ground or wind speed (Fig. 5.1).

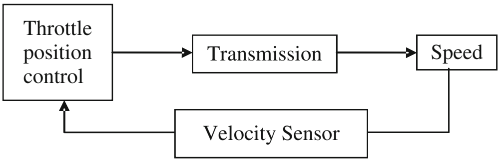

Fig. 5.1 Cruise control

Table 5.1 A summary of the traditional PLL concept (or ZPLL)

Input values, source CAUSE ⇒ (driving voltage)	Produced response CONSEQUENCE/s (output current)	Regulation method in order to obtain maximal active output power
Square (or sine) shaped driving-voltage on the output Power Bridge	Sinusoidal output current	To control the driving-voltage frequency in order to maintain stable phase difference between output load voltage and current signals.
Relatively stable driving frequency (or resonant frequency)	Load voltage and current have the same frequency	To control the current and/or voltage amplitude/s in order to get necessary Active Power Output (and to realize correct impedance matching)

Table 5.2 A summary of the new APT, multifrequency actuator concept (MMM technology) in relation to the average PLL or APLL concept

Input values, source CAUSE ⇒ (driving voltage)	Produced response CONSEQUENCE/s (output current)	Regulation method in order to obtain maximal active output power: The average phase difference between the output load current and voltage should be maintained stable (in a limited frequency interval).
Square-shaped voltage on the output Power Bridge: PWM + Band-Limited Frequency Modulation (+ limited phase modulation in some applications)	Multi-mode or single sinusoidal output current (or ringing decay current) with variable operating frequency + Harmonics	First PLL at resonant frequency: To control the central operating frequency (of a driving-voltage signal) in order to produce the Active Load Power to be much higher than its Reactive Power. To realize the maximal input (LF) power factor (Power Factor = 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 look like resistive load to the principal Main Supply AC power input. To realize the maximal input (LF) power factor (Power Factor = 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 (Power Factor = cos $\theta = 1$).

2.2 *Phase-Locked Loop*

A phase-lock or phase-locked loop (PLL) is an electronic control system that generates a signal that is locked to the phase of an input or "reference" signal. This circuit compares the phase of a controlled oscillator to the reference, automatically raising or lowering the frequency of the oscillator until its phase (and therefore frequency) is matched to that of the reference.

A phase-locked loop is an example of a control system using negative feedback. Phase-locked loops are widely used in radio, telecommunications, computers, and other electronic applications to generate stable frequencies, or to recover a signal from a noisy communication channel. Since a single integrated circuit can provide a complete phase-locked loop building block, the technique is widely used in modern electronic devices, with output frequencies from a fraction of a cycle per second up to many gigahertz (Fig. 5.2).

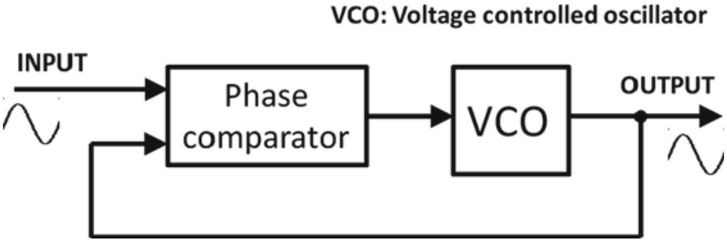

Fig. 5.2 A phase-locked loop (PLL) control

2.3 *Pulse-Width Modulation (PWM) in Power Electronics*

Pulse-width modulation (PWM) is one of the techniques used in power sources that involves modulation of its duty cycle to control the amount of power sent to a load. PWM uses a square wave with a duty cycle that is modulated, resulting in the variation of the average value of the waveform. If a square waveform $f(t)$ with a low value $y_{\min}$, a high value $y_{\max}$, and a duty cycle D is considered (see Fig. 5.3), the average value of the waveform is given by

$$\bar{y} = \frac{1}{T}\int_{0}^{T} f(t)dt \tag{5.1}$$

where $f(t)$ is a square wave, and its value is $y_{\max}$ for $0 < t < D \cdot T$ and $y_{\min}$ for $D \cdot T < t < T$. The above expression then becomes

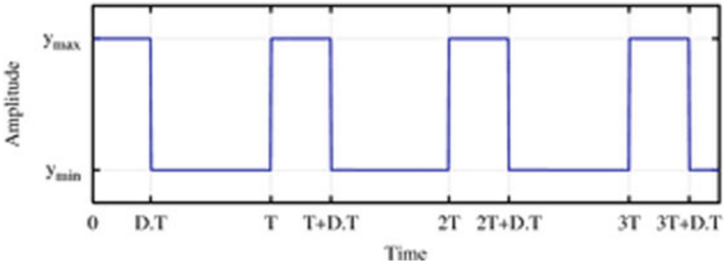

Fig. 5.3 Pulse-width modulation

$$\bar{y} = \frac{1}{T}\left(\int_{0}^{DT} y_{\max}\mathrm{d}t + \int_{DT}^{T} y_{\min}\mathrm{d}t\right) = \frac{D \cdot T \cdot y_{\max} + T \cdot (1 - D) \cdot y_{\min}}{T} \tag{5.2}$$

$$= D \cdot y_{\max} + (1 - D) \cdot y_{\min}$$

This latter expression can be simplified in many cases where $y_{\min} = 0$ as $\bar{y} = D \cdot y_{\max}$. From this, it is obvious that the average value of the signal ($\bar{y}$) is directly dependent on the duty cycle D.

3 MMM System and How the MMM System Operates

3.1 System Components

An MMM system consists of (see Fig. 5.4a and b):

(A) A sweeping frequency, adaptively modulated waveform generated by an MMM ultrasonic power supply;
(B) High-power ultrasonic converter(s);
(C) Acoustical waveguide (metal bar), which connects the ultrasonic transducer to an acoustic load, an oscillating body, or a resonator;
(D) Acoustical load (mechanical resonating body, sonoreactor, radiating ultrasonic tool, sonotrode, test specimen, vibrating tube, solid or fluid medium, etc.); and
(E) Sensors of acoustical activity fixed on, in, or at the acoustical load (accelerometers, ultrasonic flux meters, laser vibrometer, etc.), which create regulation feedback between the acoustical load and ultrasonic power supply. In most cases *the piezoelectric converter can function as the feedback element*, thus avoiding the installation of other vibration sensors.

A mechanical coupling between the high-power ultrasonic converter (B) and the acoustical load (D) is realized with the metal bar as an acoustic waveguide (C). The

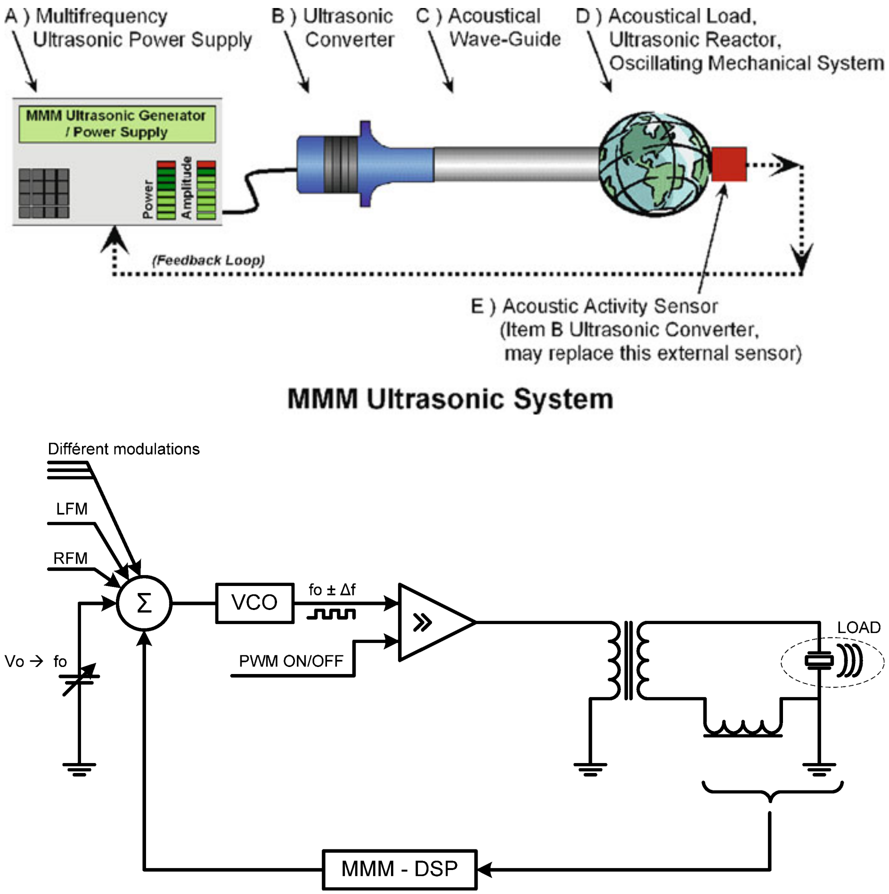

Fig. 5.4 (**a**) An MMM system. (**b**) MMM power supply block diagram. LFM – Low-frequency modulation, RFM – Randomized-frequency modulation; VCO – Voltage-controlled oscillator or DDS frequency source; and MMM–DSP – MMM digital signal processing

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 process control) between the acoustical load (D) and the ultrasonic power supply (A).

3.2 *Operation Mechanisms*

As depicted in Fig. 5.4, the ultrasonic converter (B), driven by power supply (A), produces 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 to produce 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 sweeping frequency pulse train, the amplitude in these modes will undergo exponential decay while other modes are excited. At the same time, the acoustic load will experience interference and superposition effects, which will generate new oscillatory products and dynamically modify its elastic and mechanical properties.

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.

3.2.1 Open-Loop Problems

Each mechanical system (in this case components B, C, and D) has many resonant modes (axial, radial, bending, and torsional) and all of these systems 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 which tends to couple particularly well.

Since the acoustical load (D) is connected to an ultrasonic converter (B) by an acoustical waveguide (C), acoustical relaxing and ringing oscillations are traveling back and forth between the load (D) and ultrasonic converter (B), interfering mutually along the 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, while the effects of thermal dissipation in all oscillating elements are minimal. The ultrasonic converter (B) is initially creating a sweeping frequency of repetitively pulsing mechanical excitation, resulting in generation of back-and-forth traveling waves, which can have much more complex frequency content because of the associated interference and superposition effects.

There is another important effect related to the ringing resonant system described above. An imminent and self-generated multifrequency Doppler effect (additional frequency shift, or frequency and phase modulation of traveling waves) can be 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 to successively produce uniform amplitude distributions and phase shifts in the acoustic load (D).

3.2.2 Benefits of the Feedback Loop

It should be underlined that the oscillating system described here is different from the typical and traditional half-wave ultrasonic resonating system, where the total axial length of the ultrasonic system consists of an integer number of half-wavelengths. In MMM systems, the specific ultrasonic system geometry and its axial (or any other) dimensions are not very important. 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, and has a phase and amplitude-modulated output signal, where the frequency of amplitude modulation follows sub-harmonic low-frequency vibrating modes. Thus, the ultrasonic power supply (A) is also contributing to the multi-mode ringing response or the 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, no stable nodal zones can be found 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 the acoustical load (D), relatively stable and stationary oscillations and resonant effects at certain frequency intervals can be produced (Fig. 5.4a, b). However, 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 crucial to the operation of MMM systems. Because of the complex mechanical nature of different acoustic loads (D), the best operating regimes of the ultrasonic system must be carefully tested (B, C, D), starting with low driving signals (i.e., with low ultrasonic power). An initial test phase is thus required to select the best operating conditions, using a resistive attenuating dummy load in serial connection with the ultrasonic converter (A). This test phase minimizes the acoustic power produced by the ultrasonic converter and can also dissipate accidental resonant power. When the best driving regime is found, the dummy load can be disconnected and full electrical power can then be introduced into the ultrasonic converter.

3.2.3 Real-Time Load Parameter Estimation

In order to follow the evolving frequency of the load, certain real-time load parameter estimation mechanisms must be implemented in the power source to make proper adjustments. A quasi-instantaneous estimation of load parameters using band-limited Hilbert transformation was used in this study (Prokic and Sandoz, 2005). Figure 5.5 shows the basic block diagram that will be considered. The use of "Resonant Load" assumes that the global quality factor will be at least greater than or equal to 4.

Let $i(t)$ and $u(t)$ be expressed as follows:

$$i(t) = \hat{I}(t) \cos \left(2\pi fo\left(t\right)t + \phi_i\left(t\right)\right) \tag{5.3}$$

$$u(t) = \hat{U}(t) \cos \left(2\pi fo\left(t\right)t + \phi_u\left(t\right)\right) \tag{5.4}$$

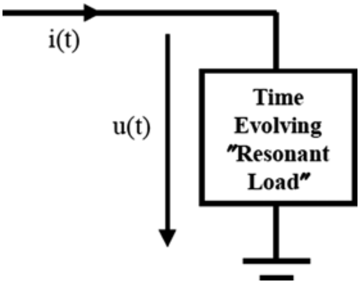

Fig. 5.5 Basic structure bloc diagram for time evolving resonant load

where $\hat{I}(t)$: instantaneous current envelope, $\phi_i(t)$: instantaneous current phase, $\hat{U}(t)$: instantaneous voltage envelope, $\phi_u(t)$: instantaneous voltage phase, and $fo(t)$: instantaneous driving signal frequency. It should be noted that all these instantaneous parameters are low-passed processes with cut-off frequencies well below $fo(t)$. Then, $i(t)$ and $u(t)$ can be represented in their respective analytical forms:

$$i(t) \Rightarrow i_{\text{analytic}}(t) = i(t) + j \cdot \tilde{i}(t) \tag{5.5}$$

$$u(t) \Rightarrow u_{\text{analytic}}(t) = u(t) + j \cdot \tilde{u}(t) \tag{5.6}$$

where

$$\tilde{i}(t) = \hat{I}(t)\sin(2\pi fo(t)\,t + \phi_i(t)) \tag{5.7}$$

$$\tilde{u}(t) = \hat{U}(t)\sin(2\pi fo(t)\,t + \phi_u(t)) \tag{5.8}$$

From trigonometric properties, the following relationships can be derived:

$$\sin(\phi_u(t) - \phi_i(t)) = \frac{i(t)\cdot\tilde{u}(t) - \tilde{i}(t)\cdot u(t)}{\sqrt{i(t)^2 + \tilde{i}(t)^2}\cdot\sqrt{u(t)^2 + \tilde{u}(t)^2}} \tag{5.9}$$

$$M_{stZ}(t) = \frac{\sqrt{u(t)^2 + \tilde{u}(t)^2}}{\sqrt{i(t)^2 + \tilde{i}(t)^2}} \tag{5.10}$$

The estimated load parameters are given by voltage and current phase difference $= \phi_{stZ}(t)$, i.e., "Short-Time" argument of the impedance, and ratio of voltage envelope to current envelope $= M_{stZ}(t)$, i.e., "Short-Time" magnitude of the impedance. Thus, $\phi_{stZ}(t)$ and $M_{stZ}(t)$ can be estimated in "Real-Time" with a minimum of basic arithmetic functions.

3.2.4 Band-Limited Hilbert Transformer

A band-limited Hilbert transformer (BL-HT) is realized with one second-order all-pass filters and two unit delay elements. This solution has the double advantage of simplicity and very low group delay. Figure 5.6 shows a structure in which

$$x(n) : \text{Input}, x_{\text{analytic}}(n) = x_{\text{R}e}(n) + j \cdot x_{\text{I}m}(n) \tag{5.11}$$

$$H(z) = \frac{-0.713 + z^{-2}}{1 - 0.713 \cdot z^{-2}} \tag{5.12}$$

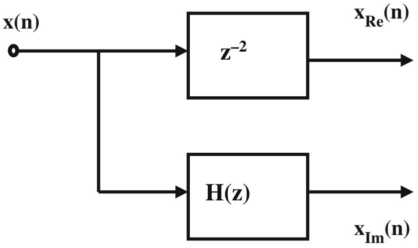

Fig. 5.6 Band-limited Hilbert transformation

An ideal HT has a 90° phase difference between its in-phase and quadrature outputs, i.e., between xRe(n) and xIm(n). Moreover, both output amplitude transfer functions are constant and independent of the frequency. This result is naturally the case with the structure shown in Fig. 5.6.

The BL-HT has the following parameters:

- sampling rate: 320 kHz
- frequency range: 16 kHz up to 25 kHz
- absolute phase error: less than 1 degree
- group delay: 6.25 μs (constant)

Even small changes in phase difference can be detected, which means that the "detectability" threshold is quite low with this method.

3.2.5 Maximum Active Power Tracking

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. A low thermal dissipation in the mechanical system (B, C, D) indicates that the ultrasonic power supply (A) is driving the ultrasonic converter (B) with limited current and sufficiently high voltage, delivering only the active or real power to a load. The multi-frequency ultrasonic concept described here is a Maximum Active Power Tracking System, which combines several PLL and PWM regulating loops.

In most traditional ultrasonic power supplies, the function of PLL is to keep the phase difference between electric current and voltage on ultrasonic converters close to zero, forcing the ultrasonic converter to maximize consumption of active or real power. Such resonant frequency control can be labeled as Zero-Phase-Locked Loop (ZPLL). Contrary to such traditional concepts, in MMM ultrasonic systems the average phase difference is kept stable and controllable inside certain frequency intervals, which can be called Average-Phase-Locked Loop (APLL). Averaged phase function or output voltage representing such frequency-modulated phase difference is frequency dependent, and if certain phase value is controlled to be inside certain frequency interval, control over average operating or driving frequency of the ultrasonic generator can be achieved at the same time. Since ultrasonic converter impedance is also frequency dependent, the converter or load current and voltage can also be controlled, and the control of the load power can be obtained by properly applying PWM power regulation concepts.

The actual size and geometry of the acoustical load are not directly or linearly proportional to the delivered ultrasonic driving power. It is possible that with a low-input ultrasonic power, a bulky mechanical system (B, C, D) can be 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 the load voltage and current have the same frequency. In order to maximize the active load power, a zero-phase difference between time domain current and voltage signals is used to control the driving-voltage frequency. Switch-mode operating regimes are employed for driving half or full bridge or other output transistor configurations. The voltage 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, which have resistive, inductive, and capacitive elements, usually have a close to sinusoidal shape.

MMM technology uses active power tracking (APT) as the most general case for efficient transducer driving in the case of wide-frequency-band driving of complex R-L-C resonant circuits such as ultrasonic transducers, while maintaining stable average phase difference between the load current and load voltage.

The special MMM ultrasonic power supply in Fig. 5.4a and b delivers square-shaped PWM and modulated frequency output so that the output current presents multifrequency and multi-component signals. The objective in MMM regulation is to maximize the active load power, while not using the simple and traditional PLL concept in making the phase difference between the output voltage and current to be zero. The complex R-L-C oscillating circuits usually have coupled and mutually dependent sub-harmonics and higher frequency harmonics. They are also present at the load side, visible as load-current and load-voltage modulations. The discussions here deal with the time and frequency domains of real-time output-power signals, as well as with time domains of corresponding load current and voltage signals and their harmonics. The APT effectively realizes closed-loop multiple PLLs and PWMs between output load signals and driving frequency modulating signal, combined with APLL or average phase PLL between the resonant frequency output load current and voltage. The second objective for APT is to force the power inverter/converter or MMM power supply to behave as a 100% resistive load (Power Factor $= \cos\theta = 1$) for a principal main AC power input.

4 Application of MMM Technology

Since MMM technology is based on different agitation mechanism and system designs, and does not depend on certain special system configurations, it is compatible with most existing applications with no major changes needed. MMM technology can be applied to virtually every area in which traditional ultrasonic technology is used. For instance, MMM technology has been applied to extrusion of composite plastic materials, cleaning processes using pressurized liquid carbon dioxide as a solvent, liquid waste material incineration assisted by an ultrasonic MMM atomizer, and continuous casting of molten metal for grain modifications. Small solid parts is successfully stress-relieved in MMM ultrasonic chambers, bringing in benefits such as increased fatigue limits, reduced cracking, artificial materials aging, increased dynamic load-bearing capacity, improved corrosion resistance, increased weld strength, and increased operating and service life. More information regarding the application of MMM in (a) ultrasonic cleaning, (b) treatment and testing, (c) powder sieving and screening, and (d) ultrasonic drawing, machining and extruding is given in the following sections.

4.1 Ultrasonic Cleaning with MMM Technology

Conventional ultrasonic generators drive the transducers at a fixed frequency without paying attention to the attached mechanical system including the steel tank, water, the parts loaded in the tank, and temperature. 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 in industrial systems the load parameters continuously change. The result is inefficient transducer driving and reduced cavitation capabilities. Conventional fixed-frequency systems also create standing waves with areas of high acoustic activity and areas of low acoustic activity. When cleaning parts, the standing waves can over-treat or damage some areas while leaving 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.

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

Using 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, the unique modulation methods eliminate the standing waves typically seen in fixed-frequency systems. The strong and uniform acoustic field in an MMM cleaning unit will make it especially useful for food and food processing surface cleaning where microbial safety is the main concern (Fig. 5.7).

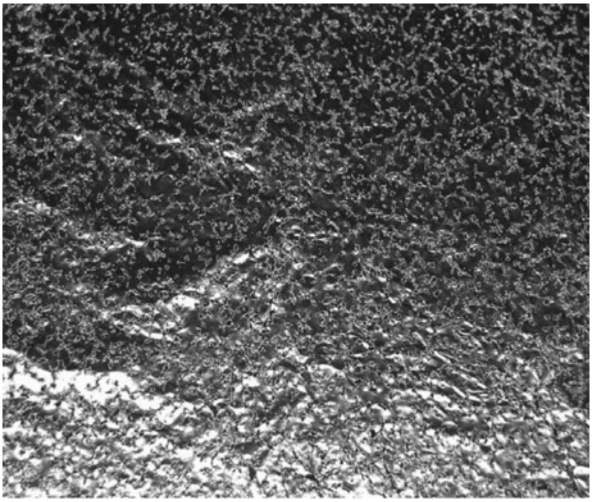

Fig. 5.7 MMM-treated aluminum foil for 5–10 s

4.2 Ultrasonic Treatments and Screening Using MMM Technology

MMM is used in a number of treatments and screening applications, which may find applications in the fabrication of food processing equipment. For instance, an improved coating of metal parts under vibrations can be achieved by immersion in coating liquid and/or by dry ball peening in an MMM ultrasonic chamber. In coating applications, deeper coating and particle implementation can be realized. An accelerated stabilization of the coating layer is also observed. In treating welds by ultrasonically vibrating the parts, an extension of fatigue life of welds several times (3–5 times) can be obtained. Such treatment also causes a redistributing and minimizing of stress concentration caused by welding. A shot peening was used in applications where the effects of fatigue were caused by grinding, electrical discharge- and electrochemical-machining (EDM and ECM), electroplating, anodizing, thermal spraying, and welding. It also can help increase resistance to fretting, galling, cavitation erosion, stress-corrosion cracking, intergranular corrosion, and hydrogen embitterment.

4.3 Ultrasonic Powder Sieving and Seed Processing

Sieving is an important unit operation in flour processing. For traditional fixed-frequency ultrasonic sieving systems, the generators and the ring resonators must be tuned to operate at the system resonant frequency. In comparison, properly adjusted MMM ultrasonic generators can stimulate highly efficient wideband (sonic to megahertz) acoustic energy to nearly any sieve or screen shape. Wideband (sonic to megahertz) acoustic energy provides greater sieve/screen stimulation to improve process volumes (kg/h), beyond the limitations of standard fixed-frequency systems. MMM eliminates the standing waves seen in fixed-frequency systems, which reduces bending in low amplitude nodal points and damage to screens at high amplitude nodal points. Normal MMM factory options allow for system resonant frequency adjustment within a 12 kHz window (e.g., 25–37 kHz). Such agility allows fine tuning for optimum performance.

Ultrasound is an excellent method for agitating powders, seeds, and fluids. With MMM technology, it is easy to make large arbitrarily shaped (un-tuned) mechanical elements vibrate at ultrasonic frequencies. Normal ultrasonic generator systems cannot make the transition because they rely on carefully tuned mechanical elements of fixed size and shape that limit the scope of their use in large-scale applications.

4.4 Ultrasonic Drawing and Extruding

Application of ultrasonic extrusion and drawing include food extrusion, plastic extrusion, metal extrusion, glass extrusion, tube extrusion, wire drawing, glass drawing, and fiber-optic drawing. MMM ultrasonic generators have the unique ability to apply high-power ultrasonic energy to large mechanical systems like extruder heads and drawing dies, which will help to reduce friction between the tool and the extruded or drawn material, improve material flow, improve surface quality of extruded or drawn material, and reduce pressure. In the case of drawing, less

Fig. 5.8 Example plastic extruder head

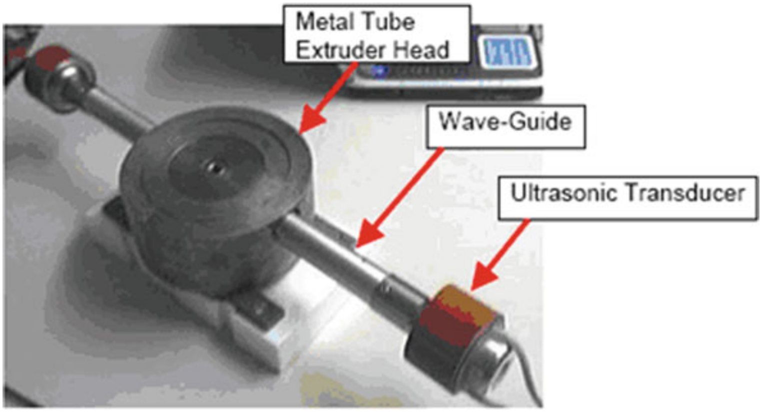

Fig. 5.9 Tube extruder die shown with dual driving transducers

breakage will improve production yield. In some processes the material structural characteristics may be improved (Figs. 5.8 and 5.9).

5 Conclusions

MMM technology, as a new method to continuously change ultrasound frequency in both time domain and frequency domain, provides numerous possibilities to fully utilize the potential of acoustic energy. It is foreseeable that MMM will find more applications in the food and bio-processing industries.

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