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Technical Support Package

Manipulation of Liquids by Use of Sound: Part I

NASA Tech Briefs
LEW-16470

National Aeronautics and
Space Administration

Technical Support Package

for

MANIPULATION OF LIQUIDS BY USE OF SOUND:

PART I

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NASA Tech Briefs

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Manipulation of Liquids by Use of Sound: Part I

A. General Purpose

The purpose of the invention is to control or manipulate liquids by using an acoustic phased array that produces high-intensity acoustic waves which create a force called "acoustic radiation pressure" and a nonlinear effect called “acoustic streaming.” An array of acoustic transducer elements may be arranged in a linear one-dimensional array or a two-dimensional array, or even an annular array of concentric transducer rings. The array elements are electrically driven as individual channels but under a central controller. The timing of the acoustic-wave emission is controlled by delaying or advancing the emission time event based on a set reference. By adjusting the time shift or “phase shift” the elements emit a wavelet pattern such that the constructive and destructive interference causes a single wave pattern to emerge (as shown in Figure 1). Thus, the phase-shifted array can synthesize a wave or wave pattern that can be steered at angles relative to the axis of the array to cause a divergence or convergence at a predetermined focal point. Acoustic waves converging on a focal point create the high intensity necessary to generate acoustic radiation pressure and nonlinear acoustic streaming.

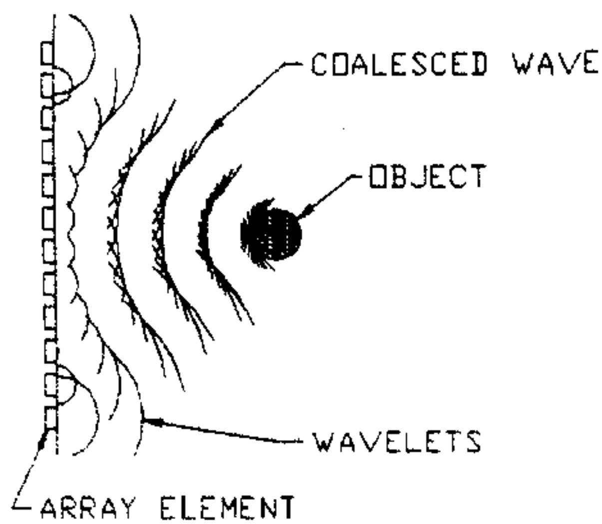

Figure 1
Acoustic Radiation Pressure Phased Array

B. PRIOR ART METHODS

The majority of alternative prior art involved mechanical devices or systems that intrude into liquid volume.

1. PRIOR ART AGITATION OF LIQUIDS

Agitation is typically achieved by a mechanical propeller or similar rotating or oscillating device that induces a flow which in turn causes mixing. Another approach in the prior art is to pump the liquid continuously into an external system which introduces other materials into the liquid. The action of the pump and the natural turbulence of the flow through pipes and orifices agitate the liquid.

2. PRIOR ART SEGREGATION OF GAS BUBBLES AND SOLIDS IN LIQUIDS

The prior art generally employs methods of trapping bubbles and solids by using mechanical filters to stop the passage of these objects while permitting the liquid to pass. Other methods used gravity or buoyancy to segregate objects. Settling tanks are an example where the liquid flow is temporarily halted so that relatively dense objects will migrate to the bottom toward gravity, while relatively light objects, such as bubbles, will migrate to the top away from gravity. Other applications use centrifugal force induced by rotation of the system and thus artificially create the effects of gravity. Another approach employs electric or magnetic fields to act on charged objects.

3. PRIOR ART LIQUID DROP EJECTION

Common spraying techniques can produce large numbers of droplets but if droplets of uniform size and velocity are needed then the approaches used by ink-jet printing are the most prevalent in the prior art. In some embodiments a steady stream is emitted from the orifice and capillary waves are induced by an external vibration or pressure perturbation. The drops form as surface tension acts to drive the waves unstable until droplets form. In other embodiments, a small volume of liquid is contained in a reservoir that has an orifice or nozzle that is juxtaposed to a pressure pulse source. The pressure source emits a mechanically or thermally induced pressure wave that causes high pressure transient at the orifice which ejects a small volume of liquid as a drop.

Acoustic radiation pressure provides a nozzleless way of ejecting drops and eliminates most of the risk of clogging. Droplets are ejected by acoustic radiation pressure where a high-intensity beam of acoustic waves is focused at the surface from a submerged acoustic source. The waves impinging on a small area of the liquid surface produce acoustic radiation pressure which raises a column of liquid. With a short, high-intensity burst, this column breaks from the liquid surface to produce a drop. The drops are ejected against surface tension and gravity with surface tension being the dominant force for small droplets. This approach has been used as a form of ink printing. For a so-called “diffraction limited” focusing lens, the droplet size is defined by the focal zone size, which in turn, is dependent on the acoustic wavelength in the liquid. Therefore, the drop size is a function of acoustic wavelength which can be controlled by the user. Since the energy of the acoustic tone burst can be controlled by burst duration and amplitude, the velocity of ejection can be controlled within a range that is usually much slower than nozzle-based techniques.

4. PRIOR ART FREE SURFACE MANIPULATION

Free surface manipulation such as formation of standing waves for applications of coatings or for mass solder operations such as the so-called “wave soldering” usually rely on a liquid jet. A stream of liquid is propelled from the bottom of a free surface pool. The stream is directed at the surface and creates a small fountain which appears as a standing wave.

5. PRIOR ART DROP AND BUBBLE DEPLOYMENT

Drops dispensed in gas or gas bubbles deployed in liquid media typically use a needle to control the placement. The drop or bubble is deployed at very low velocity to prevent splatter or excess material dispensing. A volumetric pump or a pressure driven displacement mechanism is used to form the drop. Gravity or inertia is used to separate the drop, but frequently the drop is dispensed by direct wetting against the target surface. For space applications, the prior art involves matched needles that form a drop between them. The needles are retracted at high speed, and the drop is left in a stationary position.

6. PRIOR ART MANIPULATION OF IMMERSED OBJECTS

Manipulation or the active control of the position of an object in a liquid is usually done by an intrusive mechanical means. Probes and needles can be used to propel objects and control their placement. Jets of liquid from nozzles can also be used. Beams of high-intensity sound that produce acoustic streaming and radiation pressure may be used to propel and manipulate objects.

C. DISADVANTAGES OF PRIOR ART

1. DISADVANTAGES OF PRIOR ART AGITATION OF LIQUIDS

The use of rotating and oscillating propelling devices in prior art requires mechanical hardware to intrude into the liquid volume. In externally pumped systems, the propelling hardware operates outside the main volume but requires external plumbing to convey the liquid to and from the agitation system.

Further, the mechanical devices are usually driven by a motor which means that bearings and seals are used. The seals wear and leak and the bearings need lubrication, thus creating a need for monitoring and servicing over long periods. Space application systems are frequently inaccessible and unserviceable, particularly on unmanned flight systems.

In industrial systems, the use of mechanical devices with their attendant bearings and seals are subject to attack when liquids contain abrasives or are chemically aggressive. Further the mechanical approach often introduces contaminants into the liquid from seal leakage, bearing lubricants, and particle contamination due to wear. These same mechanical parts usually complicate the cleansing of fluid systems between usage.

2. DISADVANTAGE OF PRIOR ART SEGREGATION OF GAS BUBBLES AND SOLIDS IN LIQUIDS

The mechanical filters used to trap particles and bubbles require moving liquid. To filter the entire volume, the entire liquid volume must pass through the filter. Filtering of simple containers of liquid requires that the liquid be transported to another container by pouring or by pumping the liquid through the filter to the second container.

In space, gravity cannot be relied upon to separate the particles or bubbles from a fluid due to buoyancy. On Earth, gravity-driven buoyancy has little influence on objects that have a density close to that of liquid. Simple buoyancy-driven separation is not effective when turbulent flows act to keep the objects suspended. Centrifugal segregation has been used in space but its effects cease when the system rotation stops. Further, rotating complex and sometimes large liquid volumes and attached machinery, create added complexity for supporting fluid, electrical, and mechanical systems.

3. DISADVANTAGE OF PRIOR ART LIQUID DROP EJECTION

Common spray processes produce a wide distribution of droplets at high velocity and over a wide pattern. In order to be used to apply coatings, paints, and adhesives to specific areas on a surface, it is necessary to mask or shield the areas that are not intended to receive the liquid. This causes the liquid that falls on the masked areas to be lost and incurring waste in terms of liquid and masking material.

Jetting techniques such as continuous stream and drop-on-demand can operate without masks but have a very small orifice or nozzle diameter which is usually smaller than the drops produced. The small orifice is easily clogged by solid particles. The continuous ejection mode has a narrow operating range which normally requires an ejection velocity of several meters per second. To produce uniform drops, the process must keep up with the jet velocity which in turn means that the droplet production rate may be as high as 100,000 drops per second or more. This high production rate makes it difficult for most existing systems to use all the drops. Some ink jets may use as little as 2% of the drops produced while the rest are collected and recycled.

The drop-on-demand drop ejectors produce only the drops needed, but the pressure of ejection must be achieved instantaneously. The high-pressure transient may be absorbed easily by a gas bubbles in the system, so bubbles cannot be tolerated in the system. This approach has had little success with high-density and high-surface tension liquids.

A simple focused acoustic beam in burst mode can achieve droplet ejection in a wider range of operating conditions and can be adjusted during operation. The primary limitation we have experienced is the sensitivity to liquid surface position relative to the focal length. The liquid surface must be within a wavelength of the maximum intensity to achieve drop ejection. As a result, the process is sensitive to surface waves and variations in the surface position.

4. DISADVANTAGES OF PRIOR ART FREE SURFACE MANIPULATION

The mechanical methods of manipulating liquid surfaces share problems with mechanical agitation. Like prior art agitation, the problems with seals, bearings, and their intrusive nature creates serviceability problems and limits its effectiveness. The inability to sense the position of the surface and respond to changes is a limitation that prevents the widespread use of surface manipulation.

5. Disadvantages of Prior Art Drop and Bubble Deployment

The use of needles for deployment of drops and bubbles in space and the dispensing on Earth is very restricted. Normally gravity or surface tension are the forces that control the drop size and deployment. On Earth, the drop deployment occurs when the drop grows until its weight exceeds surface tension. In space, the inertia of the drop is used to overcome surface tension when the matched needles are retracted. The need to overcome surface tension which is a property of material that is not easily controlled limits the useful application of this form of dispensing.

6. Disadvantages of Prior Art Manipulation of Immersed Objects

Like the prior art in agitation, the intrusive mechanical approach incurs the ongoing problems with seals, bearings, and mechanical linkage, leakage, and wear servicing. Further, the limited mobility of mechanical prior art restricts the ability to manipulate objects that may move to outside the working range of the mechanical devices. Although acoustic streaming and acoustic radiation pressure may be used, the limitations of beam mobility and the tendency of a high-intensity beam to attenuate quickly limit their effectiveness.

To be effective, the system needs the ability to quickly sense the position or consequence of applying manipulative forces. The lack of appropriate sensing and feedback control makes the approach difficult to control without a great deal of operator intervention. Thus, mechanical manipulation of immersed solid, liquid, or gas bodies in liquid media has seen widespread use.

D. Identification of Component Parts

1. Components

a. *Acoustic Components*

The acoustic transducer array is made up of individual transducer elements that operate on independent power and signal sources. The number of elements and the arrangement of elements may vary, depending on the particular application. The larger the number of elements in the array the more precisely it can be controlled. However, the larger the number of elements the greater the electrical complexity.

The array elements may be made from a variety of piezoelectric materials that are capable of converting electrical energy to acoustic energy. This includes single-crystal elements, polycrystalline ceramic elements, and amorphous polymer elements.

The transducer array may be arranged as a linear or single row (1-D) of transducer elements. The transducer array may be arranged in a two-dimensional (2-D) pattern. The transducer array may be arranged in a nonplanar and even randomly-placed pattern (sometimes referred to as a sparse array). The transducer array may be arranged in a set of concentric rings referred to as an annular array. Each arrangement has benefits and limitations. The linear array is simple to fabricate and uses few transducer elements but only moves the focal zone in two dimensions. The 2-D array provides the ability to move the focal zone around in three-dimensional space; however, it requires many more elements in the array. The Annular Array is simple and acts along a single axis but can only move the focal zone toward and away from the array with no side-to-side steering.

Generally, the transducers are isolated from the liquid by a barrier or wall. This permits the transducer to be electrically isolated from the liquid. A bonding layer is used to attach the transducer elements to the barrier. This bonding layer may be an adhesive or a metallic bond. The layer may also serve as one side of the set of electrodes that drive the transducer. The transducer elements are sandwiched between two electrodes. They are normally a metallic coating and, as noted above, may also provide a mechanical bond to the barrier. The voltage that the electrical system applies to these electrodes is what causes the piezoelectric material to respond mechanically and rapidly to changing voltages that cause acoustic waves to be emitted from the transducer elements.

Because the acoustic impedance of the transducer and the liquid are different, the acoustic waves will reflect from the liquid side of the wall back toward the transducer. To minimize acoustic reflection, an impedance-matching layer made of a material with an intermediate impedance value is used to increase the transmission efficiency. Further, the layer is often designed to have a thickness of 1/4 of an acoustic wavelength. The 1/4 wave thickness of the layer re-reflects the reflected acoustic energy back toward the liquid interface in phase with the waves emitted from the transducer.

Acoustic phased arrays are most commonly used for sensing and imaging applications. The transducer has the ability to sense objects or interfaces. This allows the invention to provide feedback sensing which, in turn, can be analyzed by the user to provide information about the target. This may include sensing object position, or the motion of the object, or its acoustic and fluid properties, or behavior such as oscillations. Sensing can be used to provide closed loop tracking of the target to assure that the system maintains acoustic contact with it.

b. *Electrical Components*

The overall coordination and control are performed by a Phased Array Control Computer. It is used to perform the calculation, data-handling functions, and serve as an interface for the user. The control computer acquires information from the user about the desired focal point and other parameters from input devices such as the Phased Array Control Computer's keyboard or a pointing device such as a mouse or tablet. Within the computer/controller is the control program that calculates the phase relationship of each element and determines the timing of the electrical signal. It converts the user's parameters and transmits them to the subsystems.

The phase shifting of the signals to each element is handled by a phase-shifting circuit. The conventional method uses an adjustable array of phase-shifting circuit. Each element has a separate channel and a separate phase-shifting circuit. In this invention, the preferred method is to employ a digital word generator. This device uses the pattern bit mapped in memory and outputs a digital word from a parallel port equal to the size of the array. Each bit is a channel and each channel drives an element. For high frequencies that may be much higher than the control computer, a dedicated circuit with its own memory and output port is employed. The word generator must be capable of frequencies higher than the transducer element requires.

If the wavelength is to be accurate to 1/32 of a wave, then a 5-bit word length provides sufficient resolution. In order to construct an output, the word generator must be clocked at a frequency equal to the digital word value times the array element frequency. So if a 5-bit resolution is needed and the element frequency is 1 MHz, then the clock frequency is 32 MHz.

A frequency generator provides a reference frequency that is used by the rest of the circuit. If an array of phase-shifting circuits is used, then the frequency is set to a resonant frequency of the transducer elements or perhaps a harmonic. If a digitally synthesized phase-shift control is used, then the transducer frequency times the multiplier is as described above.

An RF coupler is used to provide a tap into the amplified RF signal so that it can be monitored without a minimum impact to the signal. A bidirectional coupler permits the user to monitor and compare the forward and reverse RF signal which indicates the amount of power absorbed and thus the efficiency of the transducer. A high level of reflection indicates a mismatch in electrical impedance. The RF coupler may also be used as the means of monitoring the signal to and from the transducer. The acoustic transducer emits acoustic waves in response to the electrical signal but conversely the transducer emits an electrical signal in response to acoustic waves impinging on the transducer. The RF coupler provides an isolated tap for a monitoring device.

A monitoring device is used to monitor the signal to the transducer and the signals from the transducer to a simple oscilloscope or a data acquisition and control system.

An Impedance Matching Circuit is used to assure that the amplifier is driving a load that has a similar electrical impedance. The circuit, which is usually an inductor and capacitor network, is designed to modify the impedance of the transducer circuit so that it matches the amplifier.

c. *Steps*

The Phased Array Control Computer normally runs a control program, acquires settings from the user's interface, processes the settings, and makes the adjustments to operating parameters. Some of the settings include, but are not limited to, the following: frequency, rep rate, burst length, # of reps, power, amp gain, target focal zone, signal mode selection, such as pulse mode, continuous wave mode, and burst mode (as seen in Figure 2).

A desired focal point is set by the user which the control program uses to calculate the wave pattern required. The control system must set the timing of waves emitted from each element so that each wave converges on the focal point simultaneously. The control program calculates the time required for the wave to travel from each element to the intended focal point. This information is used to determine the precise time that each element emits a wave so that all the waves arrive at the focal point at the same time.

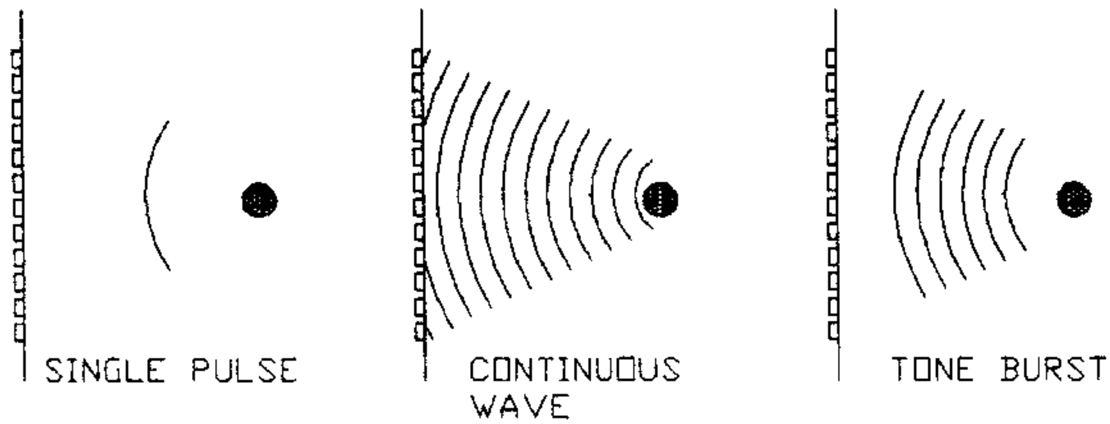

Figure 2
Wave Formation Modes

The waves of each element overlap at the focal point and interfere constructively so that the amplitude of each superimposes on the other to create high acoustic intensity and thus radiation pressure. At high intensity the nonlinear effect of acoustic streaming becomes prevalent. When acoustic streaming occurs around the focal point it may be used to apply a hydrodynamic force against the body or interface.

After taking into account the geometry, timing and wavelength considerations, the control program then converts the phased-array signal to a digital representation. Each wave is broken down into many small segments or time increments. The number of quantized segments is determined by the desired word size. If a 5-bit word is adequate then each wavelength is made up of 32 segments. Each transducer element uses the same pattern, except the timing is shifted to achieve the desired convergence. The time shift is done by shifting the channel an appropriate number of 1/32 of wave increments. Once the shift is calculated then the number of waves used is determined and a repeating pattern is mapped in the memory of the controller. This is similar to the bit-map approach used by computer printers. This pattern is stored in the memory of the control computer or is transferred to a circuit that acts as a buffer or temporary storage device.

To send the wave pattern to the acoustic transducer elements, the pattern is transferred to an output port increment by increment. The port has a channel per element and is connected to a corresponding amplifier channel. The port is updated at a frequency equal to the element frequency of the transducer times the number of increments per wave. Therefore, a 32-segment waveform requires a port to operate at 32 times the basic transducer frequency.

Each channel has a separate amplifier to convert a low voltage low power signal to a high voltage high power signal capable of driving the acoustic transducer elements. If the electrical impedance between the amplifier output and the transducer is mismatched an impedance matching circuit may be used to increase the overall circuit efficiency.

Once the signal is delivered to the transducer elements it is converted to acoustic energy and emitted from the array. The waves converge on the predetermined focal point creating the high-intensity effects of radiation pressure and acoustic streaming.

d. *Operating Modes*

1. *Tone-Burst Mode:* The primary signal mode is to emit tone bursts. The amplitude during the burst is usually fixed, and the energy is controlled by controlling the length of the burst. In a digital-controlled system, the burst duration is made up of a preset number of pulses. Each burst may have a different number of pulses and thus deliver a different energy per burst.

   Acoustic streaming is a nonlinear effect that requires high acoustic intensities to produce an appreciable effect. The high intensity, however, causes heating both in the transducer and liquid in the high-intensity region. Using tone bursts permits the user to set up a duty cycle where the transducer is active for a period and inactive for a period between bursts. This allows the transducer to achieve sufficient intensity to produce acoustic streaming during the active period, while thermal conduction is active and a chance to remove heat during the inactive or off period.

2. *Single-Pulse Mode*: The array is capable of single-pulse mode which is useful for acoustic sensing.

3. *Continuous-Wave Mode*: The array is also capable of continuous wave mode where a sine wave is emitted continuously and power is controlled through amplitude modulation. Continuous-wave mode is useful to deliver continuous power whenever reflections and standing waves are not a problem.

4. *Beam-Hopping Mode* can be achieved by rapidly changing the calculated focal point between bursts (as shown in Figure 3). Because the system is not limited to the slew rates and positioning limitations of mechanical systems, hopping between focal points

can be done on the order of milliseconds. If the beam is hopped between a repeating series of focal points at a high rate then the array will appear to be focused at multiple points.

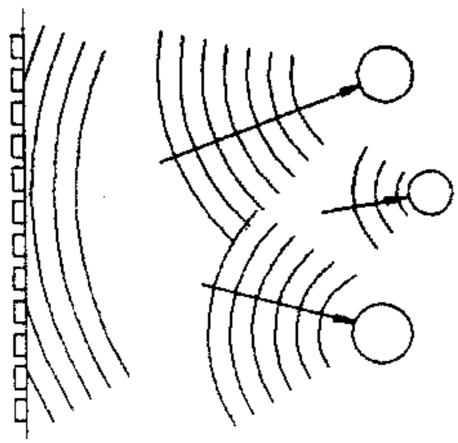

Figure 3
Beam-Hopping Mode

5. *Multiple-Beam Mode* can also be generated through element clustering. The array is treated as a set if 2 or more subarrays that may be focused at separate focal points (as shown in Figure 4).

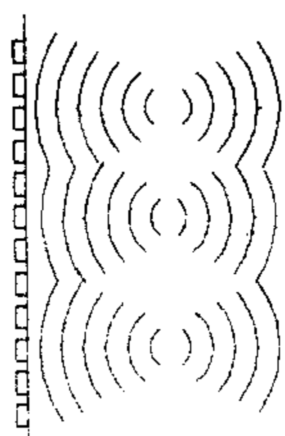

Figure 4
Multiple-Beam (Subarray) Mode

6. *Beam-Bounce Mode* may be used if the liquid system has fixed reflective surfaces where it is possible to focus a beam on a target not in direct "line of sight." By calculating a focal point that intentionally uses a reflecting surface as an acoustic mirror, the beam can be bounced and can apply radiation pressure and acoustic streaming on a target that is otherwise obscured (as shown in Figure 5).

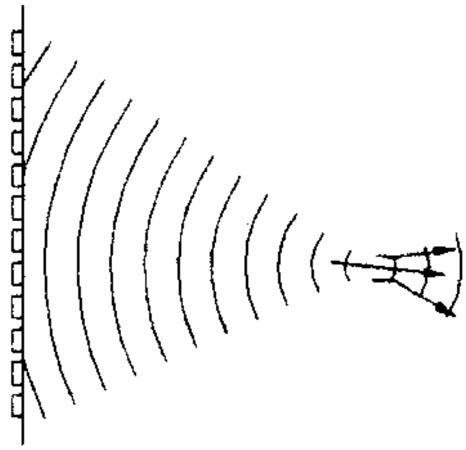

Figure 5
Beam-Bounce Mode

7. *Indirect-Streaming Mode* may be used when it is undesirable to apply a high-intensity beam directly on an object (as shown in Figure 6). The beam is focused a distance away from the object so that the beam is defocused and less intense when it impinges on the target. The streaming setup near the focal point continues on past the focal point, and the fluid dynamic forces and momentum of the stream act on the object.

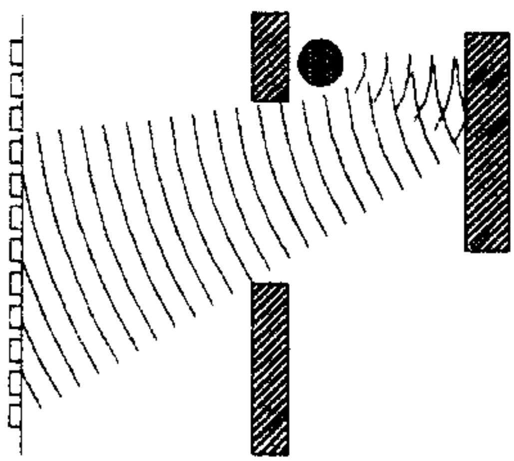

Figure 6
Indirect-Streaming Mode

8. *Matched-Counter-Beam Mode* can be produced by two opposing arrays focused on opposite sides of an object. This produces a tweezers effect which can be used to trap an object in position and against other forces. This effect can be used to manipulate the shape and movement of an object.

9. *Array-Switching Mode* is achieved by "switching" or "hopping" between multiple arrays through electronic switching methods. It is possible to use a single controller to operate two arrays.

10. *Imaging Feedback Mode* is achieved by sensing objects using conventional acoustic phased-array imaging techniques to provide the system with the ability to both see and manipulate a target object. This mode is useful in opaque liquids where optical imaging and sensing techniques are useless.

E. ALTERNATE EMBODIMENTS

The preferred embodiment is the two-dimensional array. The linear array may be considered a simplified version of an otherwise 2-D array.

<u>Focused Zero Phase Shifted Acoustic Radiation Pressured Phased Array (ARPPA) Phased Array</u> is an array that is, by either a physical arrangement or by using external focusing lenses, focused at a fixed focal length when the array has a zero phase shift among its elements.

<u>Annular ARPPA</u> consists of an array of concentric rings of transducer elements. The array is generally limited to focusing along a single axis. This set of rings may be flat where zero phase shift forms a columnar beam. Alternatively, it may be focused where the zero phase shifted signals have a normal focus due to either the lens or the natural arrangement of the array. The phase shifted focus may be moved toward or away from the transducer. Further, phase shifting may be used to change the size of the focal zone or create a beam of varying diameter. Further, phase shifting may be used to create a annular focal ring of high-intensity sound and radiation pressure.

<u>Dispersed ARPPA</u> uses an array in which the elements are not all placed in an evenly-spaced, linearly-organized pattern. The elements are placed in a near-random pattern or in a pattern intended to accommodate features that prevent the regular placement of the array elements. The array elements may be arranged conformally on a curved or irregular surface. The array elements may also be arranged around a perimeter of an angular container.

<u>Matched Counter Beam ARPPA</u> uses two physically separate and opposed arrays. The arrays apply Acoustic Radiation Pressure (ARP) and acoustic streaming on opposite sides of an object. This produces a "tweezers" effect which can be used to trap an object in position and against other

forces or to manipulate the shape and movement of an object. By electronically switching between arrays so quickly the object does not have time to respond to an individual burst, and the two arrays may be driven by single set of drive electronics.

F. ADVANTAGES OVER PRIOR ART

1. ALL OR A PORTION OF THESE GENERAL ADVANTAGES APPLY TO THE FOLLOWING APPLICATIONS

Agitation of Liquids, Segregation of gas bubbles and solids in liquids, Liquid Drop Ejection, Free Surface Manipulation, Drop and Bubble Deployment, and Manipulation of immersed objects.

The advantage of the *Non-Intrusive* aspect of ARPPA is due to the fact that acoustic waves can be transmitted through intervening walls and barriers. Therefore, the acoustic source does not need to be immersed within the liquid. Thus, the application of acoustic radiation pressure and acoustic streaming can be applied from outside of a liquid container. Therefore, the array and its electrical connections are isolated from the liquid accessible to the user. This eliminates the hardware that intrudes and interferes with the primary activity within the liquid container.

The advantage of the *No-Moving-Parts* aspect of ARPPA is due to the use of the electrically driven and the nonmechanical nature of high-frequency acoustic sources. The wear on bearings and seals of mechanical hardware has been eliminated. Further, the elimination of rotating and linear motion seals reduces the chances of liquid leakage which, in turn, reduce the health and environmental hazards of handling toxic or hazardous liquids.

Unlike the prior art, *No Added External Plumbing or Liquid Handling* equipment is required to perform the desired function. The advantage is the reduced liquid system complexity, which inherently reduces cleaning and maintenance.

Unlike the prior art, *No Filtering Components* are required to collect or trap solid or gaseous bodies. The advantage is the elimination of the filter clogging and the attendant filter maintenance. The elimination of this maintenance reduces the opportunities for liquid spillage or leakage and thus the health and environmental hazards.

The advantage of a *Steerable and Focusable Beam* is the ability to move the direction of the acoustic waves and move the focus electronically. The mechanical linkages of the prior art and their attendant wear and reliability problems are eliminated. The electronic control of focus and steering permits very rapid changes. This permits beam hopping and the creation virtual multiple beams.

The advantage of *tone-burst modulation* of the acoustic waves is the ability to use fixed amplitudes, which reduce the need for amplitude-control circuits for each channel. Further, it permits the user to incrementally alter the energy delivered to a target. Tone bursts also minimize the onset of undesired acoustic effects, such as standing waves and cavitation.

The advantage of *Acoustic Sensing* over prior art, is the ability to sense the target object or interface and provide feedback information about the properties or behavior of the target. It may be used to determine the presence and position of the target object or interface. It may provide information about the object such as translation or oscillation motion. It may also be used to determine properties of the fluid that relate to acoustic properties.

2. SPECIFIC ADVANTAGES TO USING ARPPA APPLICATIONS

a. *Specific Advantages of the Invention for Agitation of Liquids* (shown in Figure 7)

The ability of the Acoustic Radiation Pressure Phased Array to steer and focus the acoustic waves provides the advantage of mobility beyond that of mechanical means. The focus can be moved around a large volume within the liquid volume to agitate liquid more effectively in corners or around obstructions that would otherwise be inaccessible to prior-art agitation methods. The ability to transmit acoustic waves through intervening solids and liquids further improves the agitation of liquid volumes that are physically separated by one or more barriers. A further advantage is the ability to concentrate the acoustic energy at a focal point to agitate a subvolume of liquid, while minimizing the effect on the surrounding volume or disturbance of free surfaces or nearby objects.

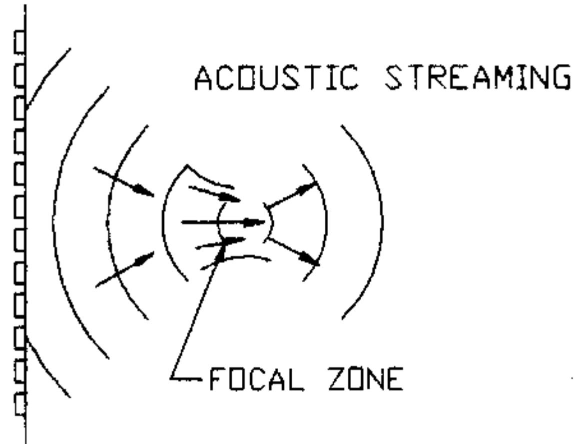

Figure 7
Agitation by Acoustic Radiation Pressure

b. *Specific Advantages of the Invention for Segregation of Bubbles and Solids in Liquids* (shown in Figure 8)

The advantage of Acoustic Radiation Pressure Phased Array for Segregation is the ability to perform a filtering or segregation function on demand. The invention provides little disturbance to the liquid system when operating and no interference to the liquid system when it is not operating. There are no filtering elements to clog or require maintenance.

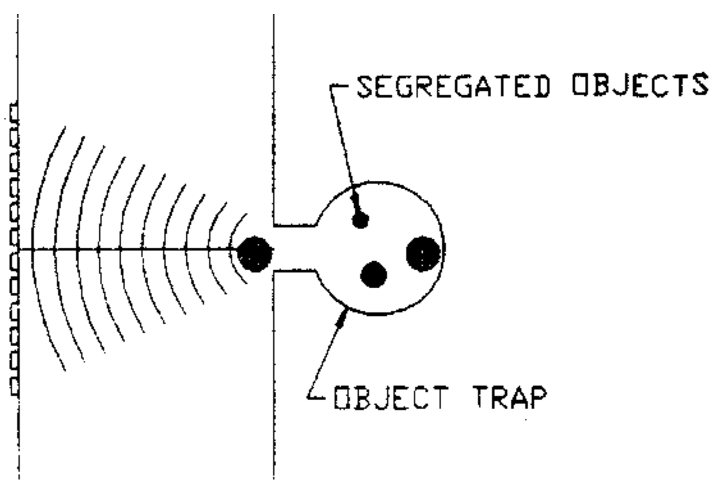

Figure 8
Segregation by Acoustic Radiation Pressure

c. *Specific Advantages of the Invention for Liquid Drop Ejection* (shown in Figure 9)

The invention has the ability to focus high-intensity acoustic waves at a liquid surface to eject droplets. The advantage over the prior art is the ability to move the focus to track the free surface even when the surface is moving or experiences level changes. This is possible because the transducer array may alternate between sensing and generating modes and the array may be used to sense the surface position and automatically be adjusted.

Further, the focus may be moved around on the surface plane to create a movable ejection point. Further, because the phased array may perform beam hopping between multiple locations it may be used to form multiple ejection sites driven from one transducer.

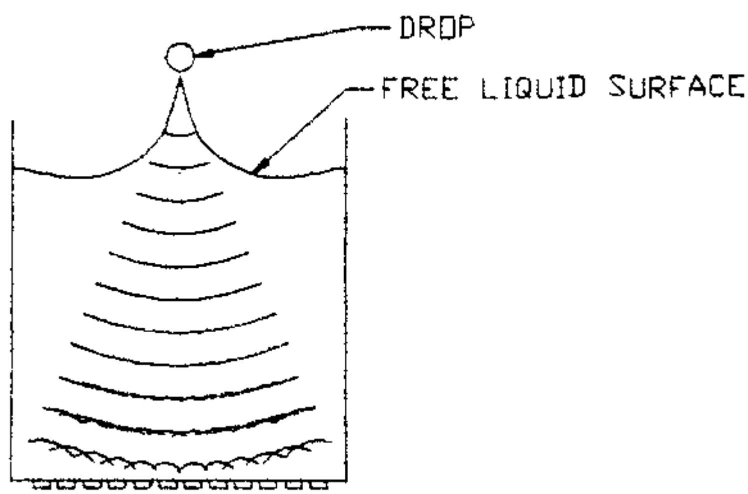

Figure 9
Droplet or Fountain Ejection by Acoustic Radiation Pressure

d. *Specific Advantages of the Invention for Free Surface Manipulation* (shown in Figure 10)

The invention provides a noncontact method of manipulating a free surface such as a liquid pool. The advantage is that no mechanical hardware is immersed in the liquid and thus even hot or chemically aggressive liquids may be worked. The invention may therefore be used for creating stationary surface waves for wetting liquids to objects for purposes of applying solders, coatings,x or cleaning. Further, the invention can generate a stationary surface wave that may vary in height. Further, the position of the wave may be moved and the shape may be altered on-demand. This allows the user to apply liquids to a surface selectively and thus eliminates the use of masks and the attendant operations and material waste. The ability to selectively apply on-demand manipulation further increases the flexibility of the process over fixed tools used in the prior art.

Further, because the focus size and shape can be altered at high speed, the array may also be used to apply acoustic radiation pressure to dampen surface waves and oscillations. This aspect can be used in conjunction with drop ejection.

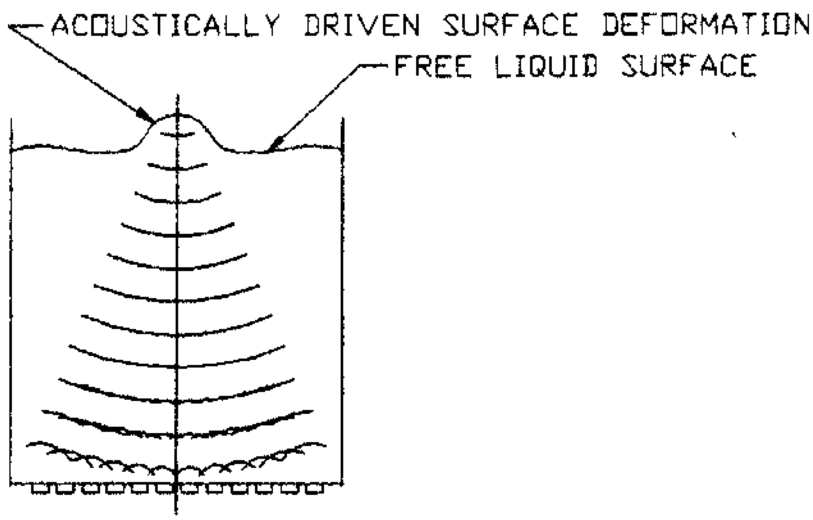

Figure 10
Surface Manipulation by Acoustic Radiation Pressure

e. *Specific Advantages of the Invention for Drop and Bubble Deployment* (shown in Figure 11)

The advantage of ARPPA is that is can be used to overcome surface tension that holds the droplet or bubble on the needle or nozzle without relying on gravity, inertia, or an opposing surface tension to force deployment. Thus, the drop or bubble can be driven from the tip on-demand. This can be used to deploy or dispense small amounts of liquid or gas in a liquid volume. This can be applied to provide small doses of drugs for medical applications or chemical agents for materials processing or manufacturing. Further, the phase array may deploy and position drops or bubbles and eliminate the needle entirely.

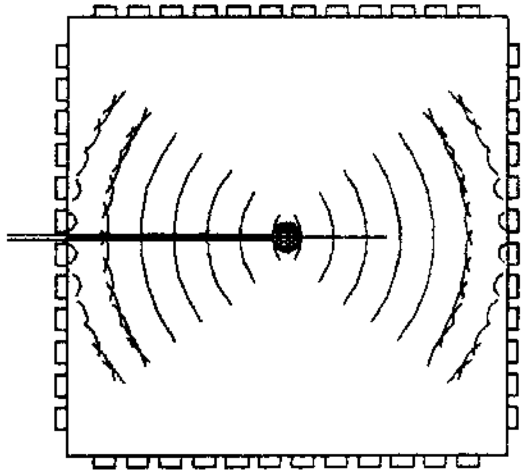

Figure 11
Drop or Bubble Deployment by Acoustic Radiation Pressure

f. *Specific Advantages of the Invention for Manipulation of Immersed Objects* (shown in Figure 12)

The advantage of Acoustic Radiation Pressure Phased Array for manipulation of objects, bodies, or liquid interfaces is its ability to apply acoustic radiation pressure or acoustic streaming forces against objects suspended in a liquid, without physically touching the object. This allows the user to place the object in a desired position or create a desired motion while minimizing the disturbance of the liquid media. The invention further provides a means of acting on a variety of points in quick succession by beam hopping. Further, the invention may sense the characteristics of the object measure position and size, and provide the user with information about the object that is not normally visible to the user. Further, the combination of sensing in this invention with the application of acoustic radiation pressure lets it adjust for changes in shape or position or behavior. Further, the application of acoustic radiation pressure may be used to induce drop or bubble oscillations which can be used to measure surface tension and viscosity.

G. FEATURES BELIEVED TO BE NEW

1. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming as a general-purpose steerable and focusable method of manipulating liquids or bodies in liquid is believed to be new.

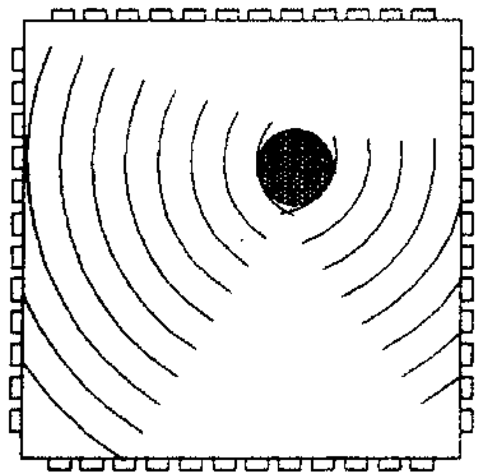

Figure 12
Object Manipulation by Acoustic Radiation Pressure

2. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to agitate liquids is believed to be new.

3. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to segregate or remove gas, solid, or undissolved liquid from a liquid is believed to be new.

4. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to eject drops and create mists of liquid from a free liquid surface is believed to be new.

5. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to manipulate the shape, position, and behavior of a liquid free surface is believed to be new.

6. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to deploy or dispense liquid drops from a needle in gas medium or liquid or gas bubbles in a liquid medium is believed to be new.

7. The use of acoustic phased arrays as a means of producing and controlling acoustic radiation pressure and acoustic streaming to propel or manipulate the position or behavior of solid, gas, or liquid bodies immersed in a liquid is believed to be new.

8. The use of tone burst modulation of the acoustic waves to control the power incrementally and to maximize the nonlinear effects of high intensity while minimizing the heating of the transducer is believed to be new.

9. The use of tone bursts to minimize the occurrence of standing waves and cavitation is believed to be new.

10. The use of beam hopping to apply acoustic radiation pressure and acoustic streaming at multiple points in rapid sequence is believed to be new.

11. The use of subarrays to create multiple simultaneous beams of acoustic radiation pressure and acoustic streaming is believe to be new.

12. The use of beam bounce or reflecting the waves on an acoustically reflective surface and redirect the waves on a surface or body not in direct line of sight is believed to be new.

13. The use of indirect acoustic streaming to apply the effects of a liquid stream against a target surface or object away from the high intensity focal point of the beam is believed to be new.

14. The combination of Acoustic Sensing as a method of acquiring information about the liquid and the target object or interface is believed to be new.

H. PAST, PRESENT OR CONTEMPLATED GOVERNMENT USE

1. SPACE APPLICATION OF THE INVENTION

ARPPA has been in development at NASA Lewis Research Center (LeRC) as a means to move and manipulate liquids for space applications as well as ground-based applications. The objective has been to develop a nonintrusive tool for manipulating liquids. The invention uses ARP with or without Acoustic Streaming generated by Acoustic Phased Arrays to perform a variety of liquid manipulation and control functions:

Agitation to obliterate thermal, concentration gradients, or mix immiscible liquids, or disperse solid particles; deploy or dispense drops or bubbles; and manipulate the shape and position of liquid surfaces, drops, bubbles, and solid objects. This can be considered as the opposite from agitation or mixing where it is desired to separate or segregate multiple phases or materials and otherwise control their placement.

In space, handling of liquids is difficult because the gravity does not act as an external stabilizing influence. Any technique that regains the control lost by the elimination of gravity is important to all space applications. In microgravity science space experiments, the problem is further complicated by the need to manipulate liquids without intruding into the liquid volume. In this invention, Acoustic Radiation Pressure and the attendant effect of Acoustic Streaming are harnessed to meet this need.

Acoustic Liquid Manipulation is an "enabling" tool that would be available for controlling liquids in space. This has profound implications in Microgravity Science but also the Human Exploration and Development of Space. Specific areas of space application are:

<u>Remote control agitation of liquid</u>
Liquid Space Experiments
Spacecraft Liquid Propellant Tanks

<u>Precise deployment of droplets in space</u>
Fluid and Drop Physics Experiments
Droplet Combustion Experiments
Containerless Processing

<u>Manipulate bubbles, drops and surfaces suspended in liquid</u>
Fluid Physics Experiments
Liquid Propellant Control

2. EARTH APPLICATIONS OF THE INVENTION

The applications for this invention is not limited to space or low-gravity environments. There are many ground based (1 - gravity) applications of this invention. It permits the user to control the behavior of liquids while eliminating or minimizing mechanical parts and their related seal components, eliminating or reducing external plumbing and pumping systems and eliminating or minimizing the need for components that intrude into the liquids containment space.

a. *Agitate Liquids*

Like space there are many processes on Earth the require agitation in sealed containers or processing systems for purposes of maintaining suspension of particles such as slurries for coatings, paints, and pastes. The nonintrusive nature eliminates the need to open sealed storage containers to perform mechanical mixing. ARP agitation of liquids may be used in chemical processing where solid precipitates are produced but must be kept in suspension against gravity. Further, the ARP agitation of liquids may obliterate thermal gradients and stratification which hinders some chemical processing.

b. *Segregate Suspended Gas Bubbles and Solids in Liquids*

Remove or segregate bubbles or solids in sealed liquids systems without using filters. ARP could be used to force bubble and solid contamination into traps where they are rendered harmless without breaking into the system. Further, the elimination of in-line filters reduces the chance for clogging or flow degradation. In turn, this may eliminate filter servicing sealed systems that contain toxic or environmentally harmful liquids.

c. *Liquid Drop Ejection and Fountaining*

Nozzleless droplet ejection from a liquid pool would be free of clogging, therefore, suspended particles and such as slurries or solid contamination would not hinder operation. The precise focus and energy control of ARP means that drops are ejected on-demand with precise size and velocity control. This can be used to apply coatings with suspended solids such as paints. This also applies to ejecting high-temperature liquids such as liquid metals. It can be used to dispense picoliter amounts of liquids (drops at 1/1,000 inch) on demand. The Directional Electrostatic Accretion Process Patent No. 5520715 employs this approach.

d. *Free Surface Manipulation*

Surface wave control for anti-slosh or active wave suppression in free surface systems. Wetting control where liquids are selectively forced into contact with solid substrates such as the wave solder systems used by electronic circuit manufacturers. This ARP driven liquid wave can be used to selectively apply coatings and adhesives.

e. *Drop and Bubble Deployment*

The ARP approach can also be used to deploy drops or bubbles from syringe needles. ARP can overcome surface tension that holds the droplet or bubble on the syringe. Thus, the drop or bubble can be driven from the tip on-demand without relying on gravity or an opposing surface tension to force deployment. This can be used to deploy or dispense small amounts of liquid or gas in a liquid volume. This can be applied to providing small doses of drugs for medical applications or chemical agents for materials processing or manufacturing. In some cases, it is possible to use the phased array to deploy and position drops or bubbles and eliminate the syringe needle entirely.

f. *Manipulation of Immersed Objects*

Position manipulation of immersed objects such as bubbles or drops of immiscible liquids, or partially buoyant solid objects. It may be applied to the manipulation of drops or bubbles in space applications such as space experiments, space materials processing, and manufacturing. This invention may also be used to control the separation of liquid and gas volumes in liquid tanks in space. The invention maybe used for micromanipulation of plant and animal tissues in liquids media. It may also serve as a medical treatment, including the repositioning (nonintrusively) detached retina in the human eye.