United States Patent

Blustain

[15] **3,688,527**

[45] **Sept. 5, 1972**

[54] **APPARATUS FOR CLEANING RESILIENT WEBS**

[72] Inventor: **Stanley Blustain,** Brooklyn, N.Y.

[73] Assignee: **Stam Instruments Corporation,** Brooklyn, N.Y.

[22] Filed: **July 13, 1970**

[21] Appl. No.: **54,172**

[52] **U.S. Cl.** ....**68/3 SS,** 68/20, 162/275, 162/279

[51] **Int. Cl.** **D06f 7/04**

[58] **Field of Search**.................................68/3 SS, 20; 162/274–279

[56] **References Cited**

UNITED STATES PATENTS

1,369,335	2/1921	Goodfellow	162/306 X
2,484,014	10/1949	Peterson et al.	68/3 SS

FOREIGN PATENTS OR APPLICATIONS

888,043	8/1953	Germany	162/275
687,970	2/1953	Great Britain	68/3 SS

Primary Examiner—William I. Price
Attorney—Blum, Moscovitz, Friedman & Kaplan

[57] **ABSTRACT**

A method and apparatus for cleaning mechanically bonded contaminants from a resilient web in a fluid medium wherein longitudinal vibrations of large displacement amplitude are radiated from the output radiator of a generator means to produce periodic perturbations of large displacement amplitude in the fluid medium. Said output radiator is positioned adjacent said web and reflecting means is disposable in facing relation with said output radiator, with said web therebetween, for reflecting said vibrations back into said fluid medium, said reflecting means and output radiator being spaced a distance apart such that the reflected vibrations are substantially in phase with the vibrations radiated into said fluid medium by said generating means output radiator.

26 Claims, 7 Drawing Figures

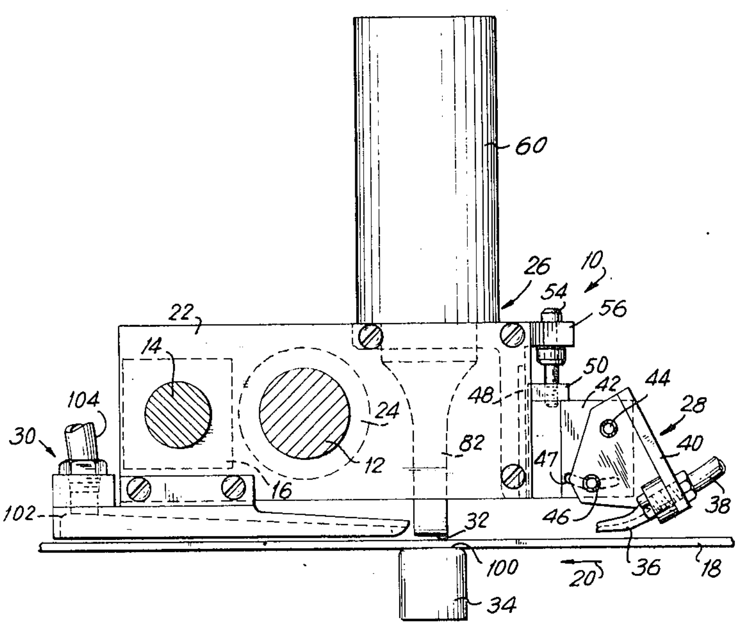


FIG. 1

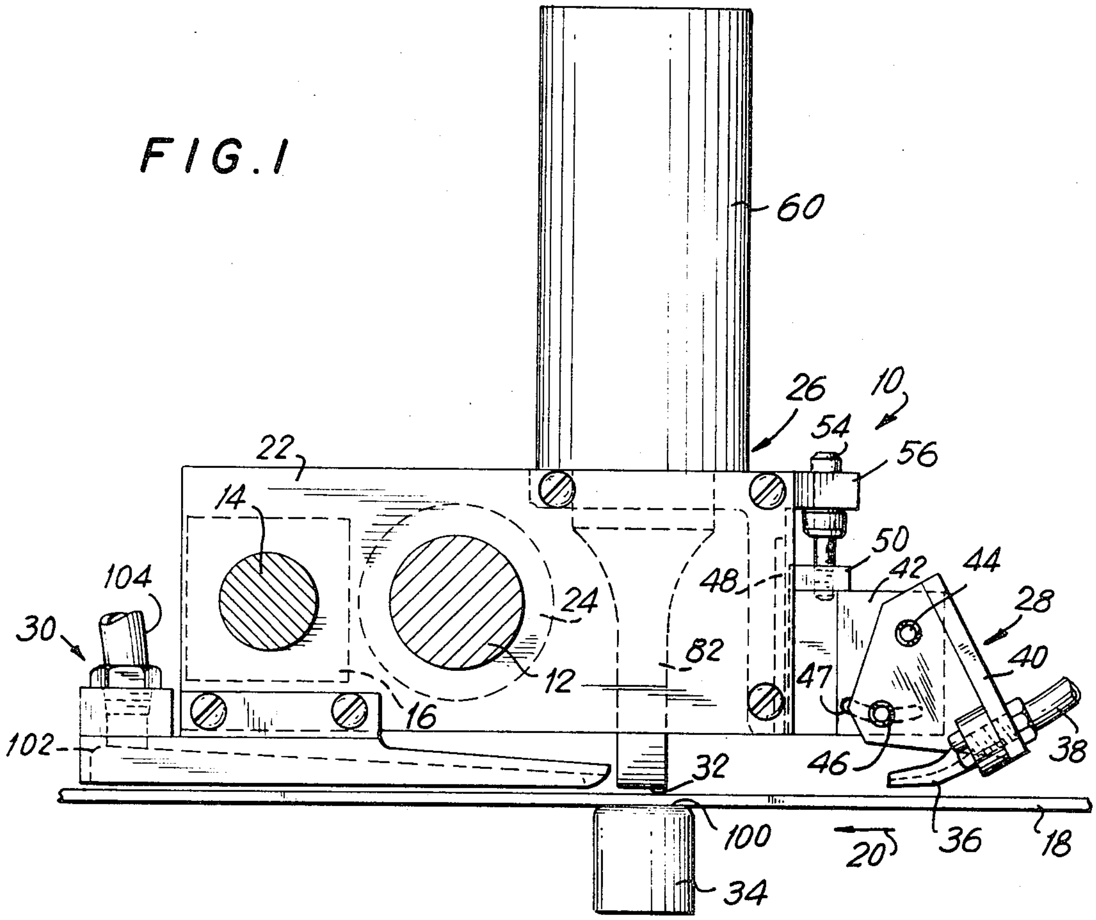
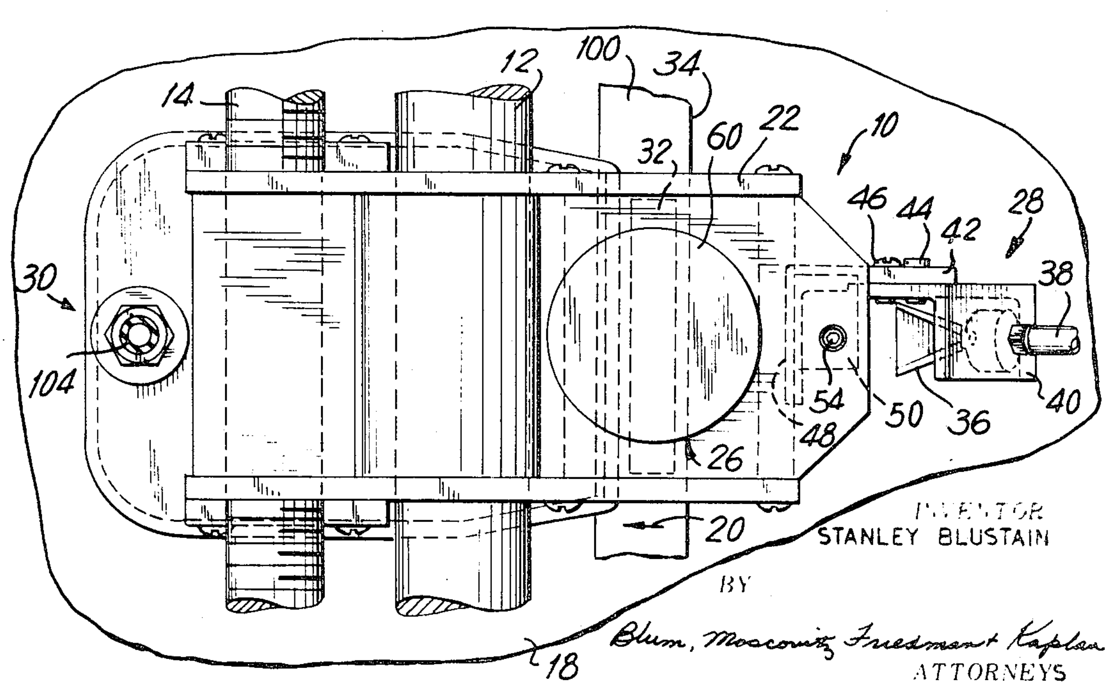


FIG. 2



INVENTOR
STANLEY BLUSTAIN

BY

Blum, Moscowitz Friedman & Kaplan
ATTORNEYS

FIG. 3

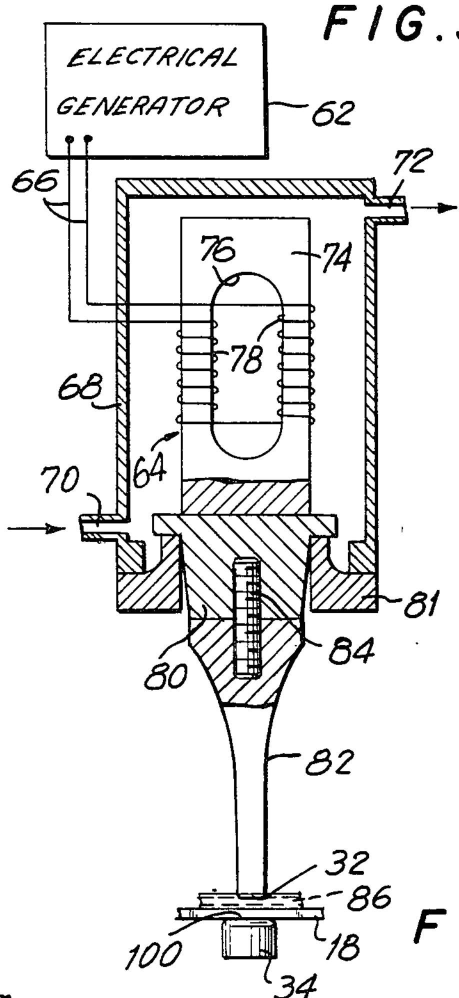


FIG. 4

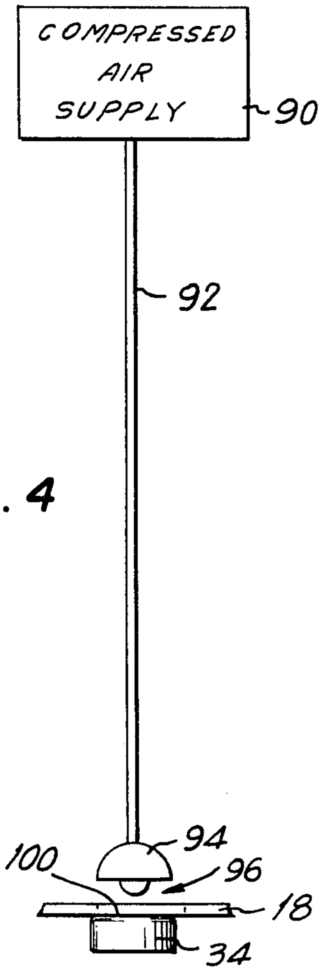
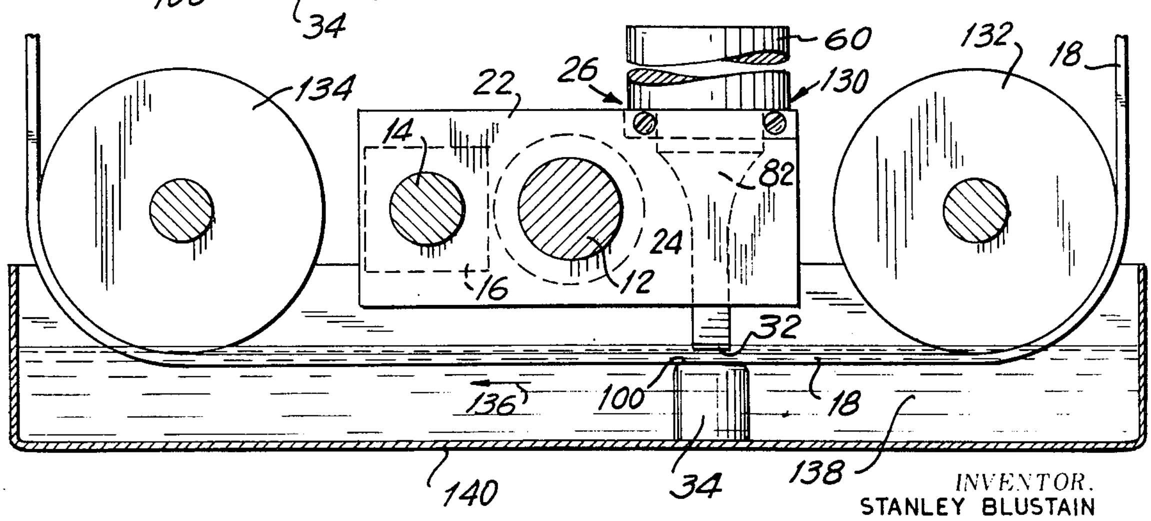


FIG. 6

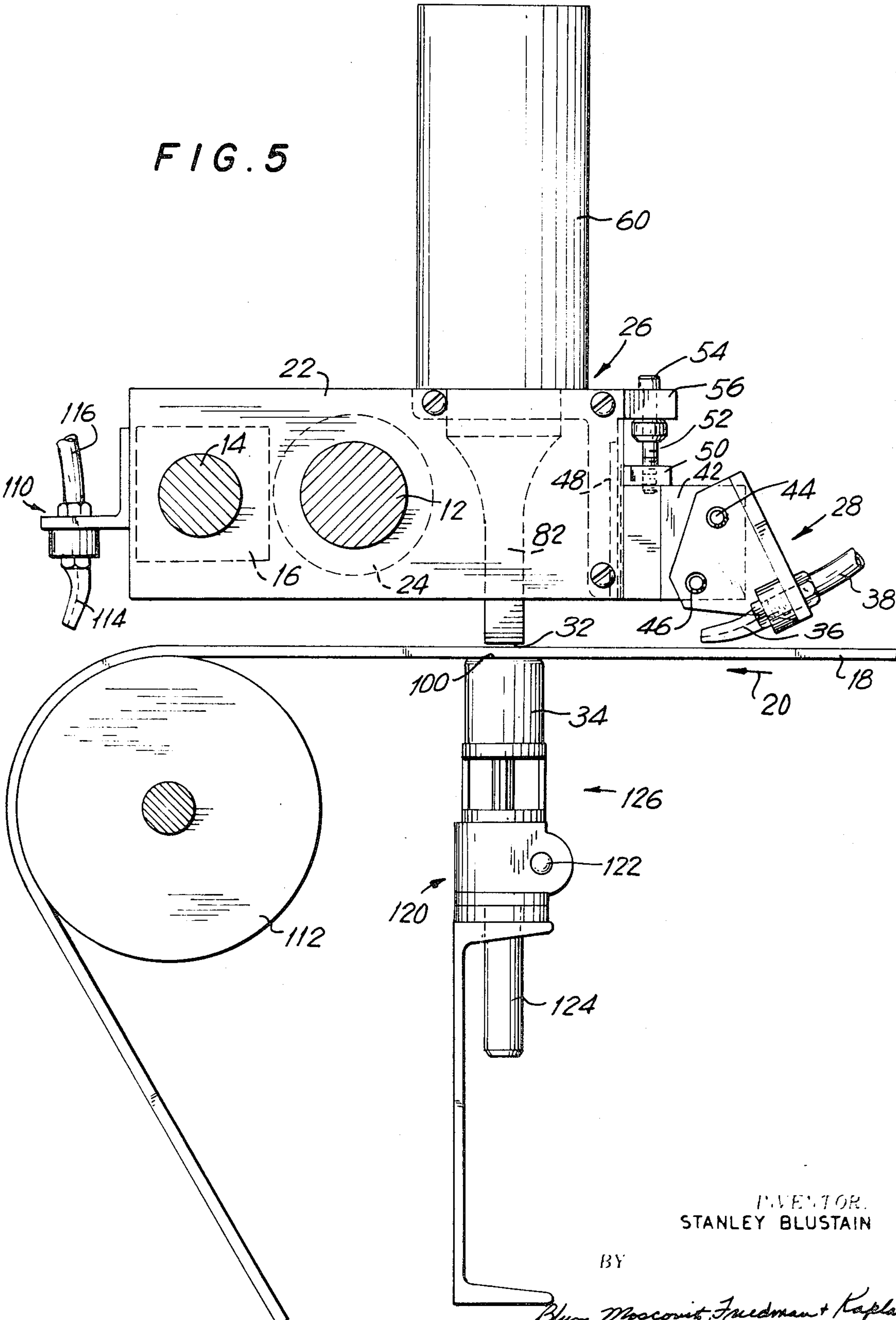


INVENTOR.
STANLEY BLUSTAIN

BY

Blum, Moscovitz, Friedman & Kaplan
ATTORNEYS

FIG. 5



INVENTOR.
STANLEY BLUSTAIN

BY

Blum, Moscovitz, Friedman & Kaplan
ATTORNEYS

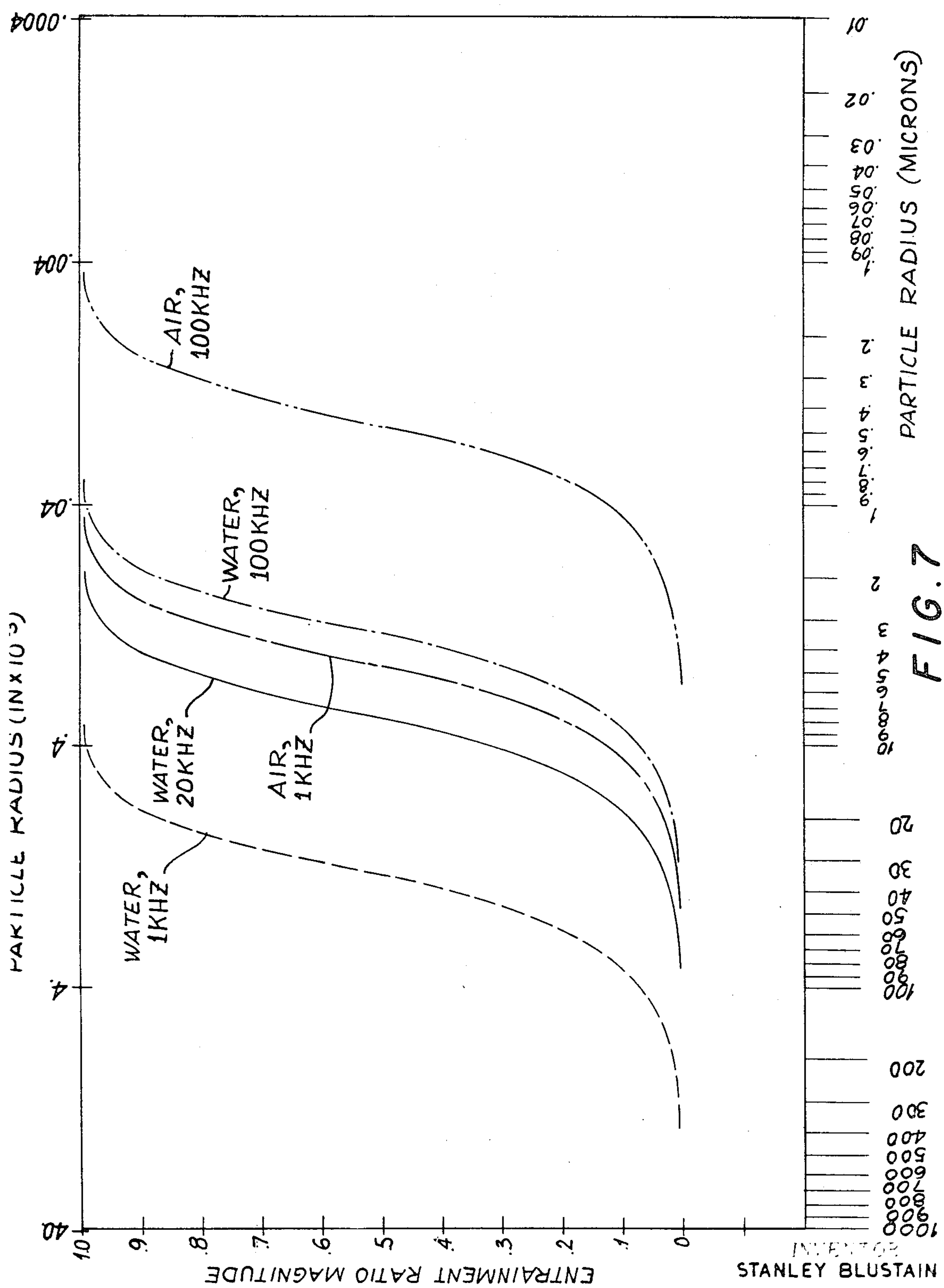


FIG. 7

INVENTOR
STANLEY BLUSTAIN

BY

Blum, Moscovitz, Friedman + Kaplan
ATTORNEYS

APPARATUS FOR CLEANING RESILIENT WEBS

BACKGROUND OF THE INVENTION

This invention relates generally to devices for cleaning resilient webs and more particularly to devices for cleaning the wet press felts utilized in the manufacture of paper. Cellulose and other constituents of the paper manufacturing process are unintentionally deposited on and adhere to the wet press felts and have proved difficult to remove. When these deposits of contaminants build up to the extent that they interfere with the production of paper, the paper manufacturing process must be interrupted and the felt cleaned or replaced, resulting in extended periods of down time for the machine. The known approaches for continuous cleaning such wet press felts during the paper manufacturing process, termed "conditioning," have also proved unsatisfactory as they have proven unsuccessful in breaking the bond between firmly encrusted contaminants and the felts. These devices do not produce complete cleaning but only serve to reduce the rate of contaminant accumulation on the felts.

Ultrasonic vibration devices have been utilized in the art in connection with the cleaning of hard elastic solid objects but have generally been deemed ineffectual if employed for the cleaning of fabrics and other highly resilient materials. In the conventional ultrasonic cleaning of solid objects, cleansing is effected by the mechanical action of a liquid medium when high frequency mechanical vibrations are propagated through it. The dynamics of this process are particularly complex. The generally accepted theory ascribes the cleansing, assuming a nonreactive chemical medium, to a number of phenomena and fluid response characteristics produce in the liquid by the introduction of ultrasonic vibrations. These include alternating pressure maxima which impart rapid oscillations to the individual liquid centers and, if the vibration intensity is above a given threshold level, the forces generated by cavitation of the liquid. It is these forces, acting in conjunction with the gross circulation currents generated in the liquid by the sound pressures, that are considered to be the principal causes of the cleansing action. Of the factors governing such cleansing action, it is generally accepted that the degree and intensity of cavitation, especially that occurring at the surface of the object being cleaned, is the most significant.

Cavitation may be defined as formation of gas filled, vapor filled, and/or empty cavities in a liquid, although the term is also used to describe effects produced in the medium or on the surroundings where cavitation occurs. Under proper conditions of temperature and pressure, cavitation will occur in any liquid subject to periodic alternating pressures of sufficiently high magnitude. The catastrophic collapse of these cavities, which are resonant at the frequency of the impressed vibrations, produces inordinately high localized temperatures and shock waves of very short duration. These shock waves are usually of considerably greater intensity than the action that initiates them. This results from the fact that the vibrations provide the necessary energy for forming the cavities at a relatively slow rate, while approximately the same energy is released almost instantaneously during the collapse of said cavities. It is the sudden collapse of these cavities that cumulatively produce the principal effects associated with cavitational cleaning.

In practice, the onset of cavitation occurs in degassed liquids at a power level far below that theoretically required to rupture the liquid due to the presence of microscopic dust particles, voids and/or other defects in the fluid. Such particles, voids and/or defects form microscopic nuclei around which cavitation pockets readily develop. Thus, for example, minute gas bubbles in the discontinuities of even the finest polished surfaces, or small metal and/or other particles adhering to metal machine parts, provide ideal sources of these nuclei. For this reason, repeated cavitational implosions will occur at the interface between a solid object immersed in a conventional ultrasonic tank cleaner and the liquid medium, provided the intensity of the vibrations applied therein is sufficiently high. The extraordinarily high instantaneous hydrostatic pressures associated with the hydraulic shocks produced by these implosions tear the adhering contaminants from the solid surface. These forces acting in conjunction with both the rapidly oscillating and gross fluid currents quickly displace the contaminants from the surface being cleaned.

However, conventional ultrasonic cleaning has its limitations. One type of deposit that cannot be mechanically dislodged from hard elastic objects solely by the effects of ultrasonic scrubbing is a viscous contaminant film well wetted to the surface being cleaned. Particles retained within this type of film also pose the same problem. When attempts are made to clean this type of contamination, the film responds to the periodic pressures and motions of the cleaning liquid by elongating and constricting in synchronism with them. The ability of the film to distort while maintaining its surface continuity serves to absorb the shock waves generated by the imploding cavitational pockets. In order to remove this type of contamination using ultrasonics, the cleaning solution must be a solvent for the film.

The resilient nature of fabrics and other pliable webs respond to ultrasonic agitation in a fashion similar to viscous films. However, to a great extent the difficulty in cleaning these materials is due to the resilient nature of the web rather than the nature of the contaminant. Since the effect of cavitational implosions on contaminants that have a tight or complex mechanical bond with a fabric or other resilient web is extremely limited, conventional ultrasonic cleaning of such webs has proved unsatisfactory and commercially impracticable.

Nevertheless, cavitation and the rapidly oscillating and gross currents produced by the introduction of ultrasonic vibrations into a fluid can be used to continuously force relatively fresh solutions past fabric fibers. Devices exist which specifically apply these mechanisms to a variety of processes. However, all of these devices are direct extentions of conventional mechanical fluid agitation techniques frequently used in the cleaning of fabrics. Arrangements of this type, such as revolving tubs, reciprocating paddles and/or pulsating liquid jets, all rely upon the forcing of cleaning solution through the permeable structure of the fabric while, if possible, simultaneously working said material. In fact, little if any difference in the actual physical cleaning mechanisms exists between the ultrasonic devices used for these purposes and their conventional mechanical counterparts.

By an arrangement and method for producing longitudinal vibrations of large displacement amplitude, which in turn produce periodic perturbations of large amplitude in a fluid medium, the cleaning of mechanically bonded contaminants from a resilient web in a fluid medium has been achieved, thereby permitting the efficient cleansing of fabrics and wet press felts.

SUMMARY OF THE INVENTION

Generally speaking, in accordance with the invention, a device for cleaning particles from a resilient web in a fluid medium is provided including generating means having an output radiator disposable adjacent said web for generating longitudinal vibrations of large displacement amplitude adapted to produce periodic perturbations in said fluid medium; and reflecting means disposable in facing relation to said generating means output radiator, with said web therebetween, for reflecting said vibrations back into said fluid medium, said reflecting means being spaced from said generating means output radiator a distance such that the reflected vibrations are substantially in phase with the vibrations radiated into said fluid medium by said generating means output radiator. In this manner, the displacement amplitude of the fluid medium perturbations are increased for the release of said particles from said web into said fluid primarily by the selective entrainment characteristics of the viscous forces generated by said perturbating medium.

A method for cleaning resilient webs is also provided wherein said resilient web is carried through a fluid medium; longitudinal vibrations of large displacement amplitude are applied to said fluid medium from one side of said web; and said vibrations are reflected at or somewhat beyond the other side of said web back into said fluid medium, said reflected vibrations being substantially in phase with the applied longitudinal vibrations thereby substantially increasing the displacement amplitude of the fluid medium perturbations, the frequency of said vibrations and the viscosity of said fluid being coordinately selected for the release of particles from said web into said fluid primarily by the selective entrainment characteristics of the viscous forces generated by said perturbating medium.

The generating means may include ultrasonic transducer means for the vibration of the generating means output radiator in a longitudinal direction along an axis extending between said output radiator and said reflecting means. The fluid medium may be a gas, a vapor or a liquid, said generating means being disposed so that the output radiator thereof lies in said fluid medium.

Where the fluid medium is a liquid, the generating means output radiator and reflector may be disposed in a liquid bath with the resilient web being carried therebetween; or means may be provided for depositing a layer of liquid on the web in advance of its passing between said generating and reflecting means so that the output radiator, liquid, web and reflector are contiguous, said deposited liquid and the particles entrained therein being substantially removed from said web after the passage thereof between said generating and reflecting means. The means for removing said liquid and entrained particles may include vacuum means for suctioning off the liquid and particles or a fluid slice means for directing a stream of fluid tangentially across the surface of the web, or directly through a permeable web, to drive the fluid medium and particles entrained therein from the web.

Where the fluid is a gas, the generating means may include an ultrasonic siren or electrodynamic transducer for generating the periodic perturbations of said gaseous medium.

Accordingly, it is an object of this invention to provide a device for cleaning resilient webs particularly adapted to break the bond between particles and a web by applying longitudinal vibrations to a fluid medium through which said web passes, to cause relatively high amplitude periodic perturbations in said fluid medium.

Another object of the invention is to provide a web cleaning apparatus particularly adapted for continuously cleaning wet press felts utilized in paper manufacturing and disposed in endless belts.

Still another object of the invention is to provide a method and device for cleaning resilient webs adaptable for cleaning such webs in gas, liquid or vapor fluid mediums.

Still other objects and advantages of the invention will in part be obvious and will in part be apparent from the specification.

The invention accordingly comprises the features of construction, combinations of elements, and arrangements of parts which will be exemplified in the constructions hereinafter set forth, and the scope of the invention will be indicated in the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

For a fuller understanding of the invention, reference is had to the following description taken in connection with the accompanying drawings, in which:

FIG. 1 is a side elevational view of one embodiment of the resilient web cleaning device according to the invention;

FIG. 2 is a top plan view of the embodiment of the resilient web cleaning device of FIG. 1;

FIG. 3 is a partial sectional view of one embodiment of an ultrasonic field magnetostrictive generator which can be incorporated in the embodiment of the resilient web cleaning device of FIGS. 1, 2, 5 and 6;

FIG. 4 is a schematic representation of an ultrasonic siren embodiment of the generating means according to the invention;

FIG. 5 is a side elevational view of a second embodiment of the resilient web cleaning device according to the invention;

FIG. 6 is a side elevational view of a third embodiment of the resilient web cleaning device according to the invention; and

FIG. 7 is a diagram showing particle entrainment as a function of particle size for a selected group of vibration frequencies and fluid mediums.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIGS. 1 and 2, a first embodiment of the resilient web cleaning apparatus according to the invention is depicted. Said cleaning apparatus consists of a cleaning head 10 mounted for longitudinal displacement along a support shaft 12. Displacement is achieved by means of a drive shaft 14 formed with a lead screw in the surface thereof adapted to cooperate with a corresponding split nut formed on the inner surface of drive assembly 16 of said cleaning head. Cleaning head 10 is disposed over a resilient web 18 such as a wet press felt or fabric which is continuously displaced in the direction of arrows 20.

Cleaning head 10 consists of a frame 22 upon which are mounted drive assembly 16, a bearing assembly 24 which receives support shaft 12 therein, a high frequency field generating device 26, a liquid medium application assembly 28, and a vacuum assembly 30, each of which will be more particularly described below. Mounted below and aligned with the output radiator 32 of high frequency field generating device 26 is a field reflector in the form of a longitudinally extending bar 34. Web 18 is carried between said output radiator and fixed reflector while said cleaning head is traversed laterally along said web along a path defined by reflector 34. Driving shaft 14 will preferably be connected to a driving motor and transmission (not shown) which will permit the displacement of cleaning head 10 in both directions, for the reciprocal traverse thereof along the width of said web. More than one cleaning head may be mounted on support shaft 12 for displacement by drive shaft 14 if desired.

Liquid medium application assembly 28 includes a liquid nozzle or slice 36 adapted to deposit a uniform thin sheet of liquid on the surface of web 18. The sheet of liquid is wide enough to encompass the length of the radiator output surface 32, and may be deposited uniformly at a velocity substantially equal to the velocity of web 18. Said liquid is supplied to said nozzle through hose 38. The hose and nozzle are both mounted on nozzle support 40 which, in turn, is hingedly mounted on displacement support 42 by means of pivot 44. A clamping device 46 riding in channel 47 is provided to secure nozzle support 40 in the proper relative position to displacement support 42 as required to deposit said thin sheet of liquid onto web 18.

Displacement support 42 is substantially L-shaped with nozzle support 40 mounted on one arm thereof and the other arm thereof received in a channel 48 in frame 22. Displacement support 42 is provided with a transverse portion 50 which bridges the arms thereof and which is formed with a threaded aperture therethrough. Adjustment screw 54 which extends through a projection 56 in frame 22 is received within transverse portion 50 of displacement support 42. By rotating adjusting screw 54 displacement support 42 is longitudinally displaced along channel 48 for the vertical positioning of nozzle 36 relative to web 18.

Turning now to FIG. 3, the structure of high frequency field generating device 26 and the cleaning operation of the apparatus according to the invention will be more particularly shown. A transducer as shown in FIG. 3 is utilized to initiate the generation of the high frequency field. Said transducer is of the electro-acoustic type adapted to convert electrical energy into mechanical vibrations; a type frequently referred to in the art as ultrasonic transducers. While in the configuration of FIG. 3, a magnetostrictive transducer 64 is shown by way of example, like fields can also be produced by other electro-acoustic transducers such as electrostrictive and piezoelectric transducers, which are equally applicable to the arrangement according to the invention. All of these transducers have in common the ability to produce longitudinal vibrations of a fixed preselected fundamental frequency.

External to said high frequency field generating device 26 is an electrical generator 62 shown schematically. Electrical generator 62 is adapted to produce a signal of predetermined frequency which is applied along leads 66 as the excitation for said transducer. The excitation may either have a conventional sinusoidal waveform or may have other waveform configurations such as sawtooth or squarewave.

Said magnetostrictive transducer 64 is of a conventional design and is mounted within inner housing 68 which in turn is mounted within outer housing 60. Said inner housing is provided to retain circulating cooling water which enters through port 70 and leaves the chamber defined by said inner housing through port 72. Received within inner housing 68 is a stack of laminations 74 formed from a ferromagnetic material and having a central opening 76 therethrough. Along the vibration propagation axis, said stack of laminations is mechanically resonant at the fundamental frequency of the applied excitation, said axis being perpendicular to the plane of the output radiator surface 32. Leads 66 connect with coils 78 which serve to apply the signal of electrical generator 62 to the stack of magnetostrictive laminations 74 to cause the elogation and constriction thereof in a manner well known in the art.

The magnetostrictive transducer is preferably designed and operated as an apolarized vibrator. This mode of operation requires the coils 78 surrounding stack 74 to be energized with a biasing direct current in addition to the high frequency signal of electrical generator 62. The bias current creates a permanent magnetic field that fixes the polarity of the stack. For a given set of input conditions, this mode of operation allows the transducer stack to vibrate both at the maximum amplitude possible, and in synchronism with the frequency of the applied alternating current.

Magnetostrictive stack 74 is mechanically mounted on and bonded to a coupling stub 80 which in turn is mounted to inner housing 68 by means of a quarter-wave isolator 81 which serves to prevent the transmission of vibrations to the housing while supporting the vibrating components of the transducer.

In general, the oscillating stack of magnetostrictive laminations 74, cannot by itself produce the fluid displacement amplitude normally required for the purposes of the arrangement according to the invention. Other devices are utilized to increase the displacement amplitude of the vibrations generated thereby. In addition to reflector 34, these devices include coupling stub 80 and vibration radiator/amplifier 82 which is mechanically secured to said coupling stub by a connecting stud 84. Said vibration radiator/amplifier and coupling stub serve to transmit the longitudinal vibrations from the magnetostrictive stack to the end surface thereof defining output radiator 32 of field generating means 26 while amplifying said longitudinal vibrations due to the shapes thereof in a manner well known in the art. Output radiator 32 of field generating device 26 is disposed within the sheet of liquid medium 86 deposited by liquid medium application assembly 28. The longitudinal vibrations transmitted into the fluid from output radiator 32 serve to establish corresponding high frequency perturbations in liquid medium 86 in a direction toward and away from field reflector 34.

FIG. 3 shows merely one embodiment of the field generating device which may be utilized in the resilient web cleaning apparatus according to the invention. Said embodiment is particularly adapted for use in conjunction with liquid mediums. However, the radiation impedance of the field generating device according to the invention must be matched with the characteristics impedance of the fluid medium. When so matched, the vibrational energy gathered by the device is coupled to the fluid. Due to radical differences between the characteristic impedance of liquids and gases, field generating devices of different design must be used in conjunction with such gases and vapors, one embodiment of such a device being shown in FIG. 4. In this embodiment a compressed air supply 90 is coupled by conduit 92 to an acoustic siren 94 disposed in facing relation with reflector 34, with web 18 therebetween. The acoustic siren is adapted to produce high frequency mechanical vibrations in a gas or vapor medium located in the region 96 intermediate said siren and field reflector 34. Since cavitation does not occur in a gas, the ability of the embodiment of FIG. 4 to clean resilient webs points up the differences between the arrangement according to the invention and the prior art attempts to clean such webs using ultrasonics.

Said ultrasonic siren is preferably of a design such that the vibrations emanating therefrom have essentially plane wavefronts of relatively uniform intensity normal to the vibration propagation axis extending between said siren and said reflector. In the embodiment of FIG. 4, the design of reflector 34 and the physical restrictions both on the geometry of the medium and the orientation of the resilient web in the medium are the same as the embodiment of FIG. 3 and will be more particularly discussed in connection with the latter embodiment.

An electrodynamic transducer using a resonant solid essentially cylindrical aluminum bar as the oscillating driver can also be used in the arrangement according to the invention for generating the required large amplitude perturbations of a gas or vapor medium. It can be employed in the arrangement of FIG. 4 in lieu of the acoustic siren and its associated compressed air supply.

Returning to the embodiment of FIG. 3, vibration radiator/amplifier 82 and coupling stub 80 may be of any desired design capable of achieving the functions of transmitting the vibrations generated by the transducer to output radiator 32, amplifying said vibrations, and efficiently coupling them to the liquid medium. Both of these devices are specialized mechanical transformers that increase the particle velocity of the vibrations transmitted through them. These transformers are essentially plain homogeneous metal bodies whose characteristics as vibration amplifiers are defined by the geometry of their design, the magnification produced being a function of their input and output surface areas, and their geometric profile along the vibration propagation axis. Said axis is perpendicular to the plane of the surface defining output radiator 32. Along said axis, the coupling stub and radiator/amplifier are each mechanically resonant at the fundamental vibration frequency of the transducer.

Multiple stage amplification can be utilized if desired to increase the potential gain of the device. However, each successive stage added to the device markedly reduces its transmission efficiency. Dissipation of the vibrational energy into the surrounding structure such as inner housing 68 is avoided by mounting the coupling stub by means of an isolator as shown in the drawings, or at a vibration nodal plane, in a conventional manner. A thin soft metal gasket (not shown) is preferably interposed between the output surface of coupling stub 80 and the input surface of amplifier/radiator 82 to improve the mechanical coupling and prevent damage to the threads of connecting stud 84.

The surface defining output radiator 32 is plane and perpendicular to the vibration propagation axis. The shape thereof can take any number of geometric forms; however, in the embodiment shown in the drawings, a plane rectangular output surface is shown. Large surface areas of web 18 can be uniformly irradiated with this output surface geometry by displacing cleaning head 10 across the web and/or displacing the web past said output radiator.

Reflector 34 is adapted to reflect the high frequency field emanating from output radiator 32 back into the fluid medium. By properly positioning the principal surface 100 of reflector 34 relative to output radiator 32, reflector 34 serves to magnify the amplitude of the periodic perturbations of the fluid medium. Principal surface 100 of reflector 34 is a smooth flat plane surface oriented substantially perpendicular to the vibration propagation axis and parallel to output radiator 32. Said reflector is positioned so that the primary beam of vibrational energy radiated from output radiator 32, or the output radiator of any other embodiment of the high frequency field generating device according to the invention, impinges on the principal reflecting surface thereof. The surface area of principal surface 100 should preferably be large enough to intercept all of this energy. In order to achieve magnification of the periodic perturbations within the liquid medium, reflector 34 is designed and positioned such that the wavefronts reflected from the principal surface 100 of the reflector constitute a secondary source of vibrations which interfere with and have displacement amplitudes that are essentially in phase with the vibrations emanating from output radiator 32. Reinforcement of the vibrations in the fluid medium is developed by this in-phase superposition of the principal and reflected vibration wavefronts, thereby increasing the displacement amplitude of the fluid perturbations. The reflector according to the invention produces amplification of the medium perturbations without requiring any additional energy to be supplied to the system from an outside source.

This amplification is dependent solely on specific mechanical properties of the reflector and its spatial orientation in the system. Preferably a bar of uniform thickness having a smooth flat principal surface 100 oriented substantially perpendicular to the vibration propagation axis, reflector 34 is located with the fluid medium interposed between its principal reflecting surface 100 and the output radiator 32 of the field generating device 26. Two requisites exist in order to generate a field in a fluid medium wherein the incident and reflected vibration displacements are essentially in phase. Firstly, the phase of the vibrations normally incident to the reflector must undergo phase inversion at the fluid/reflector interface when reflected from said reflector principal surface. This phase inversion is produced where the material of said reflector has a characteristic impedance larger than the characteristic impedance of the fluid medium. Said phase inversion in conjunction with the second requisite permits the production of stationary waves or a high standing wave ratio in the fluid. The second requisite is the spacing between the reflector surface **100** and output radiator **32**. In order to produce the stationary or high standing wave ratio field, such spacing must be approximately equal to n multiple half wave lengths of the vibration in the fluid, where n is zero or any integer. For the narrow gap condition (zero half wave lengths plus a small increment), the relative position of the resilient web between the reflector and output radiator is not critical, as where said spacing is less than one twentieth of a wave length. However, where n is an integer, the resilient web should be situated in the region of a vibration displacement antinode for maximum process efficacy.

Two other factors influence the efficiency of reflector **34**. The first of these is the magnitude of the mismatch between the characteristic impedance of the fluid and the reflector. Increasing this mismatch increases the magnitude of the fluid perturbations by maximizing the percentage of the vibrational energy reflected back into the fluid medium. The second factor is the thickness of the reflector in the direction parallel to the vibration propagation axis. For optimum reflection of the normally incident vibrations, this dimension should be equal to an integral number of odd quarter wave lengths of the fundamental vibration in the reflector. Reflector **34** is preferably formed from metal, Tungsten being particularly adapted for this purpose.

The use of reflector **34** in conjunction with the vibration generating means **26** produces displacement amplitudes in the fluid medium that could not otherwise be realized by the generating means alone. However, to insure proper operation of the system, the fluid medium should extend between, and be in contact with output radiator **32** and surface **100** of reflector **34**. Where the fluid medium is liquid, a thin air or vapor film in the treatment zone between the reflector and output radiator of only a few thousandths of an inch in depth can effectively decouple the system and prevent the operation thereof. In the embodiment of FIGS. **1** and **2**, the web may be impregnated with a liquid before reaching the device according to the invention so that it is only necessary to add an additional layer of liquid medium between the web and the output radiator to produce the desired unbroken continuity of the liquid medium. However, care must be taken to insure that the motion of the web and liquid film through the treatment zone is rectilinear, rather than curvilinear, since the latter motion produces forces which may in turn produce a stratified film of air within the treatment zone.

Where web **18** is pervious, as in the case of fabrics and wet press felts, maximum cleaning efficacy is achieved by orienting the web with its surface plane perpendicular to the vibration propagation axis. It is noted that the general constraints and operating parameters described above with regard to liquid mediums would also apply to any other embodiment using any fluid as the medium.

The foregoing arrangement serves to generate in the fluid medium perturbations of large displacement amplitude which serve to develop disjunctive forces between the resilient web and any soil particles mechanically bonded thereto. It has been found that these disjunctive forces are not the cavitational forces usually associated with conventional ultrasonic cleaning devices, but rather, principally those viscous forces generated due to proper use of the selective entrainment characteristics exhibited by particles in a periodically perturbating fluid medium. Said forces are developed by application of the method according to the invention described below.

These viscous forces are produced and sustained by impressing high frequency vibrations on the fluid medium. The propagation of vibrations through the medium, of necessity, produces periodic perturbations of the fluid. The viscous forces generated are due to the relative motion that occurs between the solids and the fluid and are developed in the fluid boundary layers adjacent to the solids. These forces cause a momentum transfer from the fluid to the soil impregnated web, thereby causing the solids to oscillate.

The viscous forces developed on the solids are periodic. However, at any given moment they are not uniformly distributed nor do they have the same magnitude. The resilient web and each contaminant particle on it are all individually subjected to viscous forces. The amplitude of these forces can vary widely and is a function of the kinematic constraints to which the oscillating solids are subject. To understand these constraints and the manner in which they determine the magnitude of the forces that are developed, the essential kinematics of this type of forced vibration are described below.

The motion of the solids oscillating in the medium is also periodic. For a viscous driving force, the displacement amplitude (maximum excursion of any solid oscillating in the medium must always be less than the displacement amplitude of the medium itself. The quotient formed by expressing the displacement amplitude of any solid and the displacement amplitude of the fluid medium as a ratio is termed the entrainment ratio, said ratio being always numerically less than one.

The kinematic constraints that are essential to this process can be readily described by use of an idealized model. The model to be used will describe the motion produced if the solids are small spherical particles; particles whose size and density are in the same range as common fabric soiling agents. In this situation, both the oscillations of the particles and the alternation of the periodic viscous forces acting on them occur at the same frequency as the impressed vibrations.

For those contaminant particles within a size and density range usually encountered in applications of the process according to the invention, the entrainment ratio of any particle driven by a periodic viscous force is a function of the size of the particle, its density, the frequency at which the medium is oscillating and the absolute viscosity of the medium. Thus, for a viscous momentum transfer, the extent to which any of these solid particles will be entrained in the fluid is determined only by specific physical properties of the particles and the medium.

The entrainment ratio is a vector quantity. The relative motion between said particles and the fluid differs in phase as well as magnitude. Particles that are negligibly entrained oscillate essentially in phase with the perturbations of the medium. As the entrainment ratio of said particles increase, the difference in phase between their motion and the motion of the fluid also increases. For the limiting condition in which the entrainment ratio approaches unity, the phase difference between the particle and fluid motion approaches ninety degrees.

In a specific medium that is oscillating at a fixed vibration frequency, differences in entrainment ratios are due solely to variations in the size and density of said particles. Thus, within the limits previously defined the magnitude of the entrainment ratio may be expressed as follows:

$$\left|\frac{\xi p}{\xi f}\right| = \frac{1}{\left[1+\left(\frac{4\pi \rho p^{F} r p^{2}}{9\eta}\right)^{2}\right]^{1/2}}$$

where:

ϵp = displacement of particle in fluid (cm.);
ϵf = displacement of fluid medium (cm.);
ρp = density of particle (gm./cm.^{3});
F = vibration frequency (Hz/sec.);
η = absolute viscosity of fluid (dyne-sec./cm.^{2}); and
r_p = radius of particle (cm.).

The entrainment ratio is inversely proportional both to the density of the particle and to the square of its radius. The product of these two terms is designated the inertial coefficient of the particle.

FIG. 7 shows a semilog plot of entrainment ratio magnitude against particle size for water as the fluid medium at frequencies of 1,000 Hz, 20,000 Hz and 100,000 Hz, and for air as the fluid medium at 1,000 Hz and 100,000 Hz. The plots shown in FIG. 7, assume a particle density of 1 gm/cm^3. As more particularly shown in said figure, entrainment ratio as a function of particle size, and similarly of inertial coefficients, is markedly non-linear; in fact, it is nearly a step function. In other words, the transition from a condition of near total entrainment to that of negligible entrainment occurs within a small range of inertial coefficients. Thus, for a particular set of conditions, particles with inertial coefficients greater than a certain critical value are negligible entrained; those particles having inertial coefficients somewhat lower in value are almost entirely entrained.

As previously noted, the entrainment oration of a particle is also dependent both on the frequency at which the medium is oscillating and on the absolute viscosity of the medium. Particles that are negligibly entrained in a given medium which is oscillating at a specific frequency can be virtually totally entrained by changing either or both of these system variables. Thus, in viscous momentum transfers, the entrainment ratio of particles can be controlled to a certain extent by the proper selection of either the frequency at which the medium is oscillating and/or the viscosity of the medium. Within very wide limits, proper selection of values for these variables will permit particles having inertial coefficients smaller than any specific value to be almost totally entrained, or will permit particles having inertial coefficients larger than any specific value to be negligibly entrained.

The difference between negligible and near total entrainment can be exhibited by two particles of the same material whose radii differ by one order of magnitude.

The technique used in the method and apparatus according to the invention is based on the ability to produce large disjunctive viscous forces between any resilient web and contaminant particles mechanically bonded thereto by selectively entraining the solids in a fluid medium. In order to describe how this principle of "selective entrainment" is applied and used to produce said disjunctive forces between the resilient web and the contaminant particles adhering to it, the relationship between the motions of the solids in the oscillating fluid medium and their associated viscous forces must be described. These process kinetics are first described for the above-described idealized model.

When relative motion exists between a periodically oscillating fluid and particles entrained therein, the periodic viscous forces developed and acting on the freely oscillating particles are strictly defined. Values for the force acting on any given particle can be computed by using either Stokes' Law or a modified form of it. In its simplest form, this force is a function of the radius of the particle, the absolute viscosity of the medium, the frequency at which the medium and the particle are oscillating, and the difference between the displacement of the medium and the displacement of the particle.

Furthermore, in any system undergoing steady state vibrations, a dynamic equilibrium exists. In the case of a particle oscillating under the influence of a viscous driving force, the inertial force of the particle is in dynamic equilibrium with the periodic viscous driving force. Each of these forces varies periodically from zero to a specific maximum value. In other words, the amplitude of the particles' displacement and the amplitude of the periodic viscous force are invariant. This fact is as equally valid for a particle with a small entertainment ratio as for a particle with a large entrainment ratio.

However, if the natural excursions of a particle are restricted, an unbalancing force develops. The amplitude of the periodic viscous force acting on the particle increases because restricting the excursion of the particle increases the difference between the displacement amplitude of the medium and the displacement amplitude of the particle. The viscous force developed on the particle is a direct linear function of the difference between these displacement amplitudes. When the excursions of a particle that would have a naturally high entrainment ratio are restricted to the extent that its entrainment in the fluid becomes negligible, the viscous force acting on it has a substantially larger amplitude. This large force will act on the particle as long as the motion of the particle is restricted. However, if the viscous force acting on the particle is large enough to overcome any bonding force that is restricting the motion of the particle, said bond will be broken and said particle will be freed to oscillate at its natural high entrainment ratio. If this occurs, the viscous force acting on the particle diminishes to its prescribed value.

The motion of a resilient web oscillating under the influence of a periodic viscous driving force is considerably more complex to describe than the motion of the aforementioned particles. However, if the woven web is considered to be a pervious membrance constructed of a large number of small interconnected masses, the volume of each mass defined by the cross-sectional diameter of any constituent thread, and an equivalent inertial coefficient determined for these small web masses, in general, said inertial coefficients would be considerably larger than the inertial coefficients of particles whose size and density are in the range of common soiling agents. Therefore, a combination or combinations of vibration frequency and fluid viscosity can be selected wherein the entrainment ratio of a woven web is far smaller than the entrainment ratio of the contaminant particles adhering to it. The converse of this last statement also exists as a theoretical corollary, and use can be made of it where possible.

Therefore, a combination or combinations of vibration frequency and fluid viscosity can be selected wherein the entrainment ratio of the web is negligible and wherein the entrainment ratio of the contaminants would be substantial, in many cases essentially unity, if they were not mechanically bonded to the web. However, because said contaminants are mechanically bonded to the web and cannot oscillate at their natural entrainment ratio, viscous forces are developed that act directly on the particle/web bond. When the viscous forces so developed are larger than the forces bonding the contaminant particles to the web, dislocation of the contaminants from the web occurs.

Thus, by proper selection of vibration frequency and a fluid of the proper viscosity, viscous forces are applied according to the method of the invention to break the mechanical bond between and separate contaminant particles from any resilient web. Thus, effective cleaning can be achieved. In addition, at the appropriate frequencies, the disjunctive viscous forces are proportional to the displacement amplitude of the oscillating fluid medium, so that improved efficacy in cleaning is achieved with every increase in the ability of the system to increase the displacement amplitude of the fluid medium perturbations.

Turning now to the selection of frequency, as noted above, the actual frequency selected depends on the size and density of the contaminant particles to be removed from the web, and the physical structure of the web itself. In the embodiments wherein a liquid medium is utilized, most applications of the arrangement according to the invention will be in the range of 20,000 Hz to 60,000 Hz. As a practical matter, the upper frequency is on the order of 100,000 Hz. The lowest available frequency depends, in large measure, both on the size and density of the contaminants and on the physical structure of the web being cleaned. As the selected frequency at which the system is intended to operate is reduced, a point is reached at which the entrainment ratio of the web begins to become appreciable. Any further reduction of the operating frequency below this point would cause a reduction in the magnitude of the disjunctive viscous forces, thereby reducing the efficacy of the cleaning. Further, as the frequency is reduced into the audible range, the intensity of the vibrations being produced would bring discomfort to personnel in the vicinity as well as produce possible physical damage to their hearing. However, with proper shielding a practical lower frequency limit is on the order of 1,000 Hz.

In the embodiment of FIG. 4, wherein an ultrasonic siren or an electrodynamic transducer is utilized to generate the vibratory field and a gaseous or vaporous medium is interposed between the siren or the transducer output radiator and the reflector, with proper shielding, a frequency range between approximately 500 Hz and 40,000 Hz represents the practical operating limits thereof.

In addition to the previously discussed periodic viscous forces, and those forces due to a direct momentum exchange between the perturbating fluid and the soiled resilient web, the apparatus according to the invention also serves to generate in the fluid medium substantially directional, ponderomotive forces. Among said ponderomotive forces are Bjorkness, Oseen, acoustic radiation pressure and acoustic streaming. These forces serve to accelerate the displacement of dislocated particles from the region of the resilient web, thereby insuring that said contaminants are carried off the web with the removal of the liquid medium. Said forces also serve to assist in the dislocation of the particles from the web.

Referring again to FIGS. 1 and 2, the liquid deposited by liquid medium application assembly **28** is removed from the traveling web **18** by vacuum assembly **30** along with the particles separated from the web and entrained in said liquid. Said vacuum assembly includes a vacuum manifold **102** disposed with the opening thereof in facing relationship with the upper surface of web **18**. The vacuum manifold is connected through conduit **104** to a vacuum mechanism (not shown) which provides the vacuum pressure necessary to suction up the liquid and dirt particles and which receives such dirt particles.

Referring now to FIGS. **5** and **6**, two alternate embodiments of the resilient web cleaning device according to the invention are disclosed. Like reference numerals are utilized in FIGS. **1**, **2**, **5** and **6** where like elements are present. In the embodiment of FIG. **5**, the liquid medium is sliced off by a fluid slice assembly **110**, rather than being suctioned off by a vacuum assembly as in the embodiment of FIGS. **1** and **2**. The web is passed about a guide roller **112** and a stream of fluid, preferably air or water is directed from nozzle **114** so as to strike the surface of web **18** on a tangent thereto. This fluid stream is carried past the web and carries with it substantially all of the liquid medium deposited by liquid medium application assembly **28** and the particles entrained therein. A conduit **116** is connected to a source of fluid under pressure to provide the fluid slice.

In the embodiment of FIG. **5**, the reflector **34** is mounted on a reflector support assembly **120** which includes a ball screw adjustment mechanisms **122** for longitudinally displacing reflector **34** toward and away from output radiator **32** in order to control the spacing therebetween. An isolation device **126** is provided to decouple reflector **34** from support assembly **120** to prevent the transmission of vibrations. In the embodiment shown in FIG. **5**, said isolation means takes the form of four relatively thin quarter wave length long legs. A layer of material having a much lower characteristic impedance than the reflector may also be used as an isolation device. Similar adjustment devices may be applied to the reflector of the other embodiments of the device according to the invention.

In the embodiment of FIG. 6, cleaning head **130** differs from cleaning head **10** in that both the vacuum assembly and liquid medium application assembly are dispensed with. Rather, web **18** passes around guide rollers **132** and **134** in the direction of arrow **136** and passes through a bath of liquid **138** retained within container **140**. In all other respects the resilient web cleaning apparatus according to the invention remains unchanged.

By means of the foregoing resilient web cleaning devices, extremely rapid high-level cleaning can be achieved solely by the action of chemically non-reactive mediums. However, if desired, small amounts of suitable chemical cleaning agents can be added to the fluid medium to further enhance the cleaning process. The resilient web cleaning apparatus according to the invention serves to produce extremely large amplitude fluid perturbations at the proper frequency necessary to produce viscous forces of sufficient magnitude to break the bonds between the particles and the webs to be cleaned. Unlike the known ultrasonic cleaning devices, it is these viscous forces, rather than the conventional cavitational effects which primarily effect the highly efficient cleaning produced by the arrangement according to the invention.

It will thus be seen that the objects set forth above, among those made apparent from the preceding description, are efficiently attained and, since certain changes may be made in the above constructions without departing from the spirit and scope of the invention, it is intended that all matter contained in the above description or shown in the accompanying drawings shall be interpreted as illustrative and not in a limiting sense.

It is also to be understood that the following claims are intended to cover all of the generic and specific features of the invention herein described, and all statements of the scope of the invention which, as a matter of language, might be said to fall therebetween.

What is claimed is:

1. A device for cleaning particles from a resilient web in a fluid medium comprising generating means operating in a resonant mode having an output radiator disposable adjacent to said web for generating longitudinal vibrations of essentially plane wavefronts adapted to produce periodic perturbations in said fluid medium in the region of an area of said web; and reflecting means having a plane principal surface disposable in facing relation to said generating means output radiator with said web therebetween for reflecting said vibrations back into said fluid medium, said reflecting means principal surface being spaced from said generating means output radiator a distance such that the reflected vibrations are substantially in phase with the vibrations radiated into said fluid medium by said generating means output radiator for the increase in the displacement amplitude of said fluid medium perturbations such that disjunctive forces are produced for the release of said particles from said web into said fluid, said disjunctive forces being primarily due to selective entrainment of the particles and the generation of ponderomotive forces within said fluid medium.

2. A cleaning device as recited in claim 1, wherein said generating means is adapted to generate at its output radiator longitudinal vibrations having a fundamental frequency or frequency range lying between 500 Hz and 100,000 Hz.

3. A cleaning device as recited in claim 1, wherein said generator means is adapted to generate at its output radiator longitudinal vibrations having a fundamental frequency or range of frequencies selected coordinately with the viscosity of said fluid medium for the release of said particles from said web into said fluid medium.

4. A cleaning device as recited in claim 1, wherein said reflecting means is spaced from said generating means output radiator a distance substantially equal to $n/2$ wave lengths of the fundamental vibration frequency in said fluid medium, where n is zero or an integer, said web being positioned intermediate said generating means output radiator and reflecting means so as to lie substantially at a displacement antinode of the longitudinal vibrations in said fluid medium.

5. A cleaning device as recited in claim 4, wherein said reflecting means is spaced from said generating means output radiator a distance less than one-twentieth wavelength of the fundamental vibration frequency in said fluid medium.

6. A cleaning device as recited in claim 4, wherein said reflecting means comprises an acoustic reflector having a characteristic impedance greater than the characteristic impedance of said fluid medium.

7. A cleaning device as recited in claim 1, wherein said reflecting means is spaced from said generating means output radiator a distance selected so that the vibrations reflected back into the perturbating fluid medium produce a field having a substantially high standing wave ratio.

8. A cleaning device as recited in claim 1, wherein said reflecting means is of a thickness, as measured along the vibration propagation axis of the longitudinal vibrations radiated from said output radiator, selected so that substantially more of the energy impinging on said reflecting means is reflected therefrom than is transmitted therethrough.

9. A cleaning device as recited in claim 8, wherein said reflecting means is of a thickness substantially equal to $m/4$ wavelengths of the fundamental vibration frequency in the reflecting means as measured along the vibration propagation axis of the longitudinal vibrations radiated from said output radiator, where m is an odd integer.

10. A cleaning device as recited in claim 1, wherein said reflector means has a planar principal surface facing said web and said output radiator is defined by a planar surface extending substantially parallel to and overlapped by the planar principal surface of said reflecting means.

11. A cleaning device as recited in claim 1, wherein said generating means includes electro-acoustic transducer means for the vibration of said generating means output radiator in a longitudinal direction along a vibration propagation axis extending between said output radiator and said reflecting means.

12. A cleaning device as recited in claim 11, wherein said output radiator is defined by a planar surface extending substantially parallel to and overlapped by said reflecting means principal surface and normal to said vibration propagation axis.

13. A cleaning device as recited in claim 11, wherein said generating means includes at least one mechanical transmission line amplifier for increasing the vibration displacement amplitude of said generating means output radiator.

14. A cleaning device as recited in claim 1, wherein said fluid medium is a liquid, said generating means output radiator lying in said liquid medium.

15. A cleaning device as recited in claim 14, wherein said resilient web is carried past a cleaning station intermediate said generating means output radiator and said reflecting means, said device including means for depositing a layer of a liquid medium on said web in advance of its passing said cleaning station; and means for removing at least a portion of said deposited liquid medium and particles entrained therein from said web after the passage thereof past said cleaning station.

16. A cleaning device as recited in claim 15, wherein said generating means output radiator is disposed on a first side of said web, said liquid depositing means being positioned for depositing said liquid medium layer on said first side of said web, said web being substantially impregnated with a liquid in advance of the depositing of said liquid medium layer thereon, said reflecting means being positioned on a second side of said web opposed to said first side and in engagement with said web and/or said liquids impregnated therein.

17. A cleaning device as recited in claim 15, wherein said liquid and particle removal means includes vacuum means disposed adjacent said web for the suctioning off of at least a portion of said liquid medium and the particles entrained therein.

18. A cleaning device as recited in claim 15, wherein said liquid and particle removal means includes fluid slice means for directing a stream of fluid tangentially across the surface of said web to drive at least a portion of said liquid medium and the particles entrained therein from said web.

19. A cleaning device as recited in claim 15, wherein said generating means output radiator is disposed on a first side of said web, said liquid depositing means being positioned for depositing said liquid medium layer on said first side of said web, said web being permeable to said fluid medium, said reflecting means being positioned on a second side of said web opposed to said first side and in engagement with said web and/or said liquid medium.

20. A cleaning device as recited in claim 15, wherein said liquid and particle removal means includes fluid slice means for directing a stream of fluid through said web to drive at least a portion of said liquid medium and the particles entrained therein from said web.

21. A cleaning device as recited in claim 1, wherein said fluid is a gas or vapor, said generating means including an ultrasonic siren for generating said longitudinal vibrations.

22. A cleaning device as recited in claim 1, wherein said fluid is a gas or vapor, said generating means including an electrodynamic transducer for generating said longitudinal vibrations.

23. A cleaning device as recited in claim 1, including means for displacing said device relative to said web.

24. A cleaning device as recited in claim 1, including means for displacing said web relative to said cleaning device.

25. A cleaning device as recited in claim 1, wherein said web is permeable to said fluid medium, said fluid medium defining a contiguous path between said generating means output radiator and said reflecting means.

26. A cleaning device as recited in claim 1, wherein said fluid is a liquid and wherein said web, said reflector means and said output radiator all lie in said liquid.

* * * * *