Longitudinal Resonating Mode Inertial Mass Sensing Systems

Background of the Invention

[0001] The subject invention provides improved means to measure mass collected on a sample collection surface in real time. A resonant structure is used as the "scale" to determine the mass in real time. The invention employs a membrane, or collection substrate, on the end of a resonant structure resonating in the longitudinal direction. A structure resonating in the longitudinal mode offers a considerably higher resonant frequency than the same structure in the bending mode. The higher the resonant frequency, the more resolution in the frequency of oscillation is available to determine the mass of the collection surface or membrane. The present invention implements this attribute in connection with such a structure.

Description of Related Art

[0002] Aspects of the invention include improvement over known devices in terms of the materials, mounting, driving, and sensing methods of the resonant structure, tube, or resonator.

[0003] The subject resonant structures are typically driven in longitudinal resonance by one of at least two different excitation methods disclosed. One such means is a voice coil with magnet; another is a piezoelectric excitation method utilizing a piezoelectric "motor" to drive the system into resonance. Neither of these methods relies on the magnetorestrictive qualities of the resonant structure. The Q of the materials disclosed herein is among the highest of all currently available materials.

Brief Summary of the Inventive Art

[0004] Those with ordinary skill in the art of the design of Inertial Mass sensors are invited to recall that the relative sensitivity to mass detection of subject invention inertial mass sensors is a function of the fundamental resonant frequency of the resonator. The greater the resonant frequency, the greater the sensitivity. The ability to accurately measure the mass collected, or lost, where the change in mass as delta-m, at the collection means is indicated by a shift in the resonant frequency.

[0005] Mechanical resonators in oscillation will have a small jitter in instantaneous resonant frequency, defined as delta-f, where this jitter is generally a function of the mechanical Resonant Q of the system where the frequency jitter divided by the oscillation frequency or delta-f over f (df/f) and is roughly equivalent to inverse of the value Q for the system. The higher the Q the lower the frequency jitter will be. One material with the lowest jitter, and highest Q, will be an amorphous structure such as fused quartz, which is exactly why these materials are used to make the crystals used in computers. A 2.66 GHz computer, for example, uses a 2.66 GHz crystal, which refers to the crystal clock used to clock the microprocessor that allows the computer to run.

[0006] As taught herein, resonant frequency is measured by measuring the frequency at a chosen sampling rate and averaging that frequency over N measurements which permits a reduction in the RMS jitter of the frequency which results in a more accurate determination of the resonant frequency, and therefore the measured mass of the collection surface or media which is a subject of this invention.

[0007] Advantageously, the highest frequency mode of oscillation of a resonant structure is in the longitudinal mode along the long axis, which is simultaneously the stiffest axis. Uniquqe drive structures are described to driving a resonant structure in this mode.

[0008] The stability and resolution of the resonant frequency of oscillation, which in practice is always some net aggregate of frequencies (because several eigenmodes of oscillation are excited by the driving impulse or mechanical impulse) is dependent upon the mechanical resonant Q of the system.

[0009] Generally, the higher the Q of the system and the more pure the drive AND resulting excitation of the resonator in the target mode of resonant oscillation the more accurately the resonant frequency of oscillation can be determined. For systems with a high mechanical Q and low frequency drift or jitter, also referred to as delta-frequency, the more accurately and repeatability the actual collected mass can be determined. Key to the subject teachings are techniques to maintain very high mechanical resonant Q of the entire system and therefore the resolution of mass change or detection of the mass at the collection means or filter.

[0010] Advantages of nodal clamping and the significant improvements of the mechanical resonant Q that result are taught herein. This teaching includes stiffening the filter collection means to minimize losses from conformal or ductile dampening materials, and introduces general fabrication practices to minimize internal and external frictional dampening that tend to lower the mechanical resonant Q.

[0011] The subject devices utilize a half wave resonant structure, where the wavelength of the first mode of resonance describes half the wavelength of the resonant structure.

Brief Description of the Drawings

[0012] The subject half wave resonant structure is constructed using a center clamped nodal point wherein the resonant structure is clamped in the middle of the tube (or more precisely, the center of mass, which is typically the middle of a uniform structure) instead of at one end. This structure is illustrated in FIG. 5 illustrating where both ends are allowed to longitudinally oscillate (from conservation of energy) with a neutral nodal point at the center of mass 4 along the axis of the tube when only one half of the tube is mechanically, piezoelectrically, or magnetically driven into resonance utilizing feedback control or self resonant circuits. Node 4 is a region of substantially no longitudinal motion and whereupon being clamped, there is minimal energy loss and minimal change of the resonant Q of the tube or resonator.

Utilizing this clamping method, the amplitude of the longitudinal motion at the clamp, or nodal point, is zero. It is possible to clamp the resonant structure at any one of the nodes described in a free-free normal mode for uniform beams. In this case one could clamp the resonant structure at any of the nodes existing at 0.132, 0.224, 0.5, 0.776, and 0.868 units of length (where 0.5 refers to clamping in the middle as described herein) for the first three modes of resonance.

Detailed Description of the Invention

FIG. 5 is a schematic representation of the subject half-wave resonant structure. Note the “knife edge” at 4 that creates a center node clamp to the resonant structure, the upper part at 5 (which, for illustration purposes, will be called the mass collection end) and the lower part at 6. The resonant structure has a total length of A * 2 (twice the length of A, could also be the center of mass whereby the dimensions would not be as shown) and is clamped A units below the base 3, or is node clamped at 0.5 units of length as shown previously above. It is important to note that center clamping is most commonly accomplished at the center of mass but can be at any of the nodes mentioned above.

[0013] The “knife edge” at 4 in FIG. 5 could be an elastic member, such as an O-Ring as well as a washer welded or shrink fit to the resonant structure at 4. Of course an O-

Ring is elastomeric and could damp the system, which is not desirable. Even though the node point dissipates zero energy we teach that using anything but a rigid support only tends to decrease system Q.

[0014] Additionally, the use of elastomeric elements in any part of the support structure would serve to reduce system Q. Accordingly; rigid materials for construction are more preferred, even for seals.

[0015] Center clamping, also defined as center-of-mass clamping, does not restrict the location of the clamp. The center clamp is typically nearly equal to the thickness of the resonant structure or thinner. The use of a center clamp, with two opposing free motion anti-nodes at the distal ends, allows the drive means or coil to be located along the length at one distal end of the clamped node and the sensing means, optical, magnetic, or sensing coils to be located at the opposite distal end of the clamped node.

[0016] The drive could also be a piezo electric device “piezo motor”, shown as item 30 in Fig. 1a, at the nodal point driving and supporting the two distal ends. The location of the sense and drive coils can be easily reversed with no adverse effects. Nodes are described as the location of zero amplitude of a resonant structure and are considered mounting locations that dissipate the minimal amount of energy and have the least effect on the mechanical resonant Q of the system. Anti-nodes of this resonant structure are at the distal ends of the tubes where a collection means or filter structure or test mass is mounted and where the maximum amount of longitudinal motion is located.

Methods Of Use

[0017] Typically, velocity sensitive transducers, such as hall sensors, optical sensors, moving magnets or moving coils, provide optimal signals when located at the anti-nodes; likewise, any collection means or filter structure or test mass to be measured when mounted at the anti-nodes provide the largest excursion in resonant frequency for a given change in mass.

[0018] Of course, the subject devices are not restricted to collecting any particular type of mass on filters. It could very well be the mass of diesel particulate collected on a filter as well as the number of insects landing on a surface to even how much material was deposited in a CVD process.

[0019] FIG. 1 is a section view of the basic construction of one embodiment of the subject patent. Note that all the figures Fig. 1a, Fig. 1b, and Fig. 1c share common numbering so the similar items have the same number. In these figures a removable filter 2 mounted to the upper side of the resonator 3 at 1. The flange 10, for the node clamp, at 12, shown clamping the resonator tube securely between the upper base 4 and lower base 6. Again, nodes are described as the location of zero amplitude of a resonant structure.

[0020] In Fig. 1, Fig. 1b, and Fig. 1c the drive coil is located at 17 within an optional iron, Permalloy, or ferromagnetic core 14 mounted in the base structure 6 on Fig. 1c and mounted in the top structure 4 in Fig.1. The location of the sense and drive coils can be easily reversed with no adverse effects if care is used in providing adequate isolation and elimination of spurious electromagnetic fields.

[0021] Various drive schemes to cause resonance are disclosed. The first three use a coil and magnet assembly where the field generated in the coil repeals and attracts the magnet and a circuit is driven to cause the system to be in resonance. The first three utilize various sensing methods to close the loop to attain resonance and measure the resonant frequency in order to infer the mass of the collection means.

[0022] Fig. 1 shows the drive coil 17 and ferromagnetic core 14 fully capturing the magnet 15. This arrangement yields a very efficient drive arrangement because the system is in a push pull drive field where the magnetic lines of flux are concentrated through the magnet 14.

[0023] Fig. 1b shows the drive coil 17 and ferromagnetic core 14 in close proximity to the face of the magnet 15. This arrangement has the magnetic gap shown in one of the many locations available. This is not the most efficient drive arrangement because the magnetic lines of flux are not concentrated through the magnet 14 but is easy to assemble because the magnet is not captured as it is in Fig. 1.

[0024] In Fig. 1c the drive coil 17 and ferromagnetic core 14 are in close proximity to edge of the magnet 15 at 1/3 the thickness of the magnet. This arrangement has the magnetic gap shown at the geometric center with a uniform gap width all around. The gap width can be different in the radial dimension compared to the axial dimension. This, again, is not the most efficient drive arrangement because the magnetic lines of flux are not concentrated through the magnet 14 but is easy to assemble because the magnet is not captured as it is in Fig. 1.

Method Of Manufacture

[0025] In Fig. 1a a “piezo motor” is used where the piezoelectric properties of a quartz structure cut in the axis that results in the lowest thermo elastic modulus of elasticity to maintain a near zero temperature coefficient of frequency. One configuration is a 5-degree X Cut crystal to attain the desired characteristics. In this scheme one can drive and measure the resonance by picking off the signals as well as injecting the control signals at 31 and 32.

[0026] Referring to Fig. 2 the structure of the resonator with the collection means or filter structure or test mass or filter 2 is secured to the upper side of the resonator 3 at 1 and the node clamp at 12 leaving the lower end of the resonator at 9. With this basic structure the inventive idea illustrates various ways to drive and sense this resonant system longitudinally. It is important to realize that when the invention refers to the resonators at 3 and 9 that the readers do not consider they are separate structures. They are intimately connected. Driving structure 3, by conservation of momentum, dictates that structure 9 respond in an equal and opposite fashion. The drive coil, or drive means, located at 3 or 9. can have the sense coil, or sensing means, located at 9 or 3 and can put both on the same side in yet another configuration. When utilizing a sensing means that is sensitive to spurious magnetic fields a means to prevent or minimize electromagnetic interference may be utilized to result in the highest mechanical resonant Q of the system.

[0027] The sense coil may be replaced with other sensing means such as an optical or hall type sensors as illustrated in FIG. 3 where a small magnet or optical target 18 is shown in close proximity to a hall sensor or optical sensor19.

[0028] Referring to Fig. 2a the similarities to Fig. 2 can be seen but note the magnets of Fig.2 are missing from Fig. 2a. This is because Fig 2a depicts the use of a “quartz motor” 30 drive where the measurement and control leads to 31 and 32 is provided.

[0029] Referring in more detail to FIG. 3 an alternate method of sensing the resonance of the resonator 3 using magnet or grating at 18 with the associated hall sensor or optical sensor at 19 is shown. Other sensing means based on principles of astigmatic focal spot sensing, speckle metrology pattern, emission Doppler frequency shift, or interferometric (an Interferometer is an optical measuring tape if you will) can provide feedback signal using a compact, low-power laser diode or LED. These optical techniques take advantage of the quality of the single frequency laser diodes short wavelength or small focal spot to provide a large signal for a slight dimensional change in movement or length at a bandwidth much greater than the longitudinal oscillation frequency mode of the inventions subject resonant structures that are therefore unaffected by changing magnetic fields emanating from the drive coil. Velocity detectors using a small magnet or magnetized section of the tube and a stationary voice coil can alternatively be employed to determine the resonant motion of the resonator. This mode of sensing will utilize first derivative signal because the velocity of the resonant structure within the coil is the first derivative of position. It is important to realize moving coil detectors do not determine position, they determine velocity. The advantage is that the first derivative of a sinusoidal function is an identical sinusoidal function shifted 90 degrees out of phase and thus coherent phase locking techniques will work for tracking frequency. This is handy because it is frequency that indicates the mass, not the absolute phase. All of these detection signals can be utilized in a simple phase locked loop or negative loop feedback system to change the drive frequency towards the mechanical resonance of the system. Unlike classical ultrasonic driver applications, detailed in much of the prior art, the optimal design of the inventions entire system is towards a high mechanical and electrical resonant Q to provide the greatest frequency stability of the drive and electrical sense signal for a given collected mass. This is because most of the prior art describing ultrasonic resonator applications do not require that they be able to lock on to a particular frequency with low jitter because they have lots of power and simply want to weld plastic, clean teeth, or atomize liquids. As such almost none of the prior art needs to deal with the issues detailed herein.

[0030] One may replace the drive coil assembly 17 of Fig. 1b or Fig. 1c with a voice coil assembly similar to high-end speaker assemblies to drive the system into resonance. Just as well, another approach provides a flat face type coil drive assembly that has a high flux area for the gap to increase efficiency.

[0031] Alternatively, when the structure similar to Fig. 1 is driven by a coil 17 magnetism theory dictates that the drive coil acts as a variable reluctance core that depends on the phase of the strain waves passing through it. The slight changes in coercivity induced by the strain waves being off and on resonance will cause a slight back EMF to be generated in the coil 17. This back EMF can be detected as an impedance and be used simultaneously as a sense coil AND drive coil in a self-excited resonant circuit that minimizes drive coil impedance which thereby causes the electrical drive frequency to match the mechanical resonant frequency of the resonator. This back EMF is an oscillating electrical function that has a phase relationship to the drive current waveform. As the drive current waveform approaches the mechanical resonant frequency, from a lower frequency, the back EMF waveform phase with respect to the drive waveform will lag. The back EMF waveform will be equal to zero at the exact mechanical resonant frequency and the back EMF waveform will lead when the drive waveform frequency is greater than the mechanical resonant frequency. This phase detection can be locked by using a PLL (phase locked loop) to servo the drive frequency to maintain a zero phase lag between the back EMF waveform and the drive current waveform. This point of operation, with zero phase lag, is one of the most efficient, with the lowest drive impedance in the coil and the highest mechanical (and electrical) resonant Q in the circuit.

Using the "Piezo Motor", as shown in Fig. 1a and the resonator detailed if Fig. 2a, as the "drive coil", will allow another inventive aspect to measure the phase of the voltage instead the phase of the impedance in a very similar manner to accomplish the same task as just described. Advances in DSP design and performance as well as significant decreases in cost a digital solution to accomplish precise control may be invoked.

[0032] Another variant is described as an appropriately shaped (glass blown or fused quartz structure) with an electrodeposited layer of magnetostrictive material deposited on the outside of the structure, such as depositing the layer over the resonant structure shown in Fig. 2. This electrodeposited layer of magnetostrictive material will have a very low energy of coupling, but sufficiently high mechanical resonant Q resulting in a design such that the loss in drive energy is more than offset by the decrease in frictional losses from this electrodeposited layer of magnetostrictive material. The high mechanical resonant Q is a result of the intimate contact of the thin deposited metal magnetostrictive film upon a thin walled quartz resonator. The collection media or filter holder may also be fabricated integrally from a bonded quartz geometry and support stipple structure (similar to vacuum chucks in the semiconductor industry) as well as diamond frit material to maintain a very high mechanical resonant Q.

[0033] A preferred implementation involves driving the resonant structure longitudinally utilizing a voice coil and magnet drive means. The primary advantage of this approach is that the resonant structure does not have to be fabricated out of a low Q magneto restrictive material. This embodiment will allow selecting materials with high Q factors, where the Q relates to the energy loss per cycle of resonance. Some alloys of nickel based alloys; Bulk Solidified Amorphous Alloys, Liquid metal, Ni Span C, Ni Span D, titanium, glass, sapphire, ruby, crystalline quartz, fused quartz, and quartz alloys are known to exhibit extremely high Q factors and are a good choice for this inventive idea.

[0034] It is generally desirable to select a material with the highest Q for the inertial microbalance. Referring to FIG. 1b a section view of the basic construction of another embodiment of the subject invention is with a removable filter 2 mounted to the upper side of the resonator 3 at 1.

[0035] The clamping washer 10 for the node clamp at 12 is shown clamping the resonator tube securely between the upper base 4, clamping washer 10, and lower base 6. Nodes are described as the location of zero amplitude of a resonant structure. The drive coil 17 is located in close proximity to the magnet 15, which is securely mounted to the resonator at 9. It should be noted the design of the coil magnet drive system may be designed similar to a voice coil in a speaker or a flat arrangement similar to a flat solenoid coil design common in the art. Note that 14 that acts as an iron or ferromagnetic field focusing means (flux concentrator) mounted in the lower base structure 6. The sense means is located at 15 allowing detection of the resonance of the upper resonator 3. Alternatively, it is possible to incorporate an ultrasonic velocity transformer in the tube end to maximize longitudinal amplitude at the distal anti-node end 3. The sensing means can also be optical as detailed previously in FIG. 3.

[0036] Various advantages that may be realized in accordance with the subject methods and devices variously include, but are not limited to:

(1) The energy transmitted to the support by the resonant structure is minimized thereby increasing the “Virtual Q” where the “Q” can be considered as a measure of inverse of the energy loss per cycle of resonance. Designing the resonant structure to utilize a center clamped mode allows for magnetic separation of the drive coil from the sense coil, thereby minimizing magnetic cross talk that reduces the “Virtual Q” of the system. The “Virtual Q” is reduced by reducing the magnetic cross talk that comes about when the energy to drive the coil is picked up by the sense coil. In one embodiment the invention teaches that utilizing an alternating current drive to cause a pure sinusoidally changing MAGNETIC field in order to excite only the first fundamental frequency without including the harmonics is paramount in obtaining the highest system Q. There are digital methods, using DSP (Digital signal processors) to drive a coil, with appropriate electrical modifications such as adding resistors, capacitors, and/or inductors, to obtain a pure sinusoidally changing magnetic field in the piezo motor, the magnetostrictive tube or voice coil drive that may not require inputting a pure sinusoidally changing drive current typical of analog circuitry.

(2) Utilizing a center clamped mode provides a convenient geometry to introduce a variety of sensing methods other than utilizing a hall sensor or a sense coil. A hall sensor can be added to replace the sense coil. An optical grating, or any similar surface, can be affixed to the resonant structure and corresponding optical measuring methods may be utilized to affect the sensing portion of the system. The benefits of utilizing an optical sensing method with a coil drive system is that the spurious magnetic energy generally does not interfere with most optical sensing methods and the measurement will not decrease the Q of the system because no energy is induced into typical optical sensing systems.

[0037] Further improvements relate to methods of manufacture of the collection media. Optimally, the ideal collection means or filter, shown in Fig.1 as item 2, would be constructed of deposited amorphous diamond on a film deposition form that is subsequently dissolved away leaving a very high stiffness 100 to 200 micron thick support structure with resonances above the range of 10,000 to 100,000 of Hz. This technology improvement is most similar to improvements in high quality tweeter domes used in high-end audio equipment that are designed to have a high resonant frequency of the internal structure. Utilizing this design philosophy will have the a very low impact in the overall mechanical resonant Q of the entire system so that the fundamental mode of oscillation does not excite high order modes of oscillation of the collection means or filter and therefore the entire system.

[0038] The use of non-organic materials in the entire assembly minimizes the frictional dampening characteristics associated with many plastic and cross-linked polymer derived materials one might use for the filter collection means, or filter holder. A benefit of a diamond structure is it can be manufactured to exacting specifications where it can behave much like a Teflon filter media having a collection efficiency of 99.99% at 0.1 microns AND can be run as a heating element as well to burn off the particulate much like a self cleaning oven. In this configuration a re-usable filter collection means is made where the heating capabilities of the deposited amorphous diamond structure is utilized to burn off the particulate or the collected sample. Additionally, ozone can be utilized to clean the remaining particulates that are not removed by heating alone, that are composed of carbon or hydrocarbon particulates, that are susceptible to free oxygen radical that will convert to carbon dioxide, carbon monoxide, and water in the presence of ozone.

[0039] Still more subject improvements relate to methods of removing particulate from the collection media. The method is to provide a corona discharge system or ultraviolet light ozone generation system and automatically or manually draw the ozone through the collection means, or filter or media to rid the media of contamination of the light carbon and hydrocarbon particulate contamination. The injection of ozone flow can be from any direction. Upon exposure to ozone, light carbon is converted directly to carbon dioxide, carbon monoxide, and water vapor thereby allowing the media to be utilized again without having to manually change the media.

[0040] Utilizing such an approach offers the ability to determine the percentage of mass that is pure carbon. This may be particularly advantageous in us in two exemplary applications: in diesel compliance testing as well as inhalation toxicology studies.
The subject method is to collect the carbon bearing particulate, just as one would in a normal collection event, and record the mass of the resultant collection event. Then, one would flood the system with ozone and thereby convert the particulates composed of carbon or hydrocarbon particulates susceptible to free oxygen radical that will convert to carbon dioxide, carbon monoxide, and water and then read the mass at the end of the cleaning cycle. The remaining mass could be conjectured to be elements non-carbon material such as asbestos from a nearby burning building

Variations

[0041] It is contemplated that any optional feature of the inventive variations described may be set forth and claimed independently, or in combination with any one or more of the features described herein. Reference to a singular item, includes the possibility that there is a plurality of the same items present. More specifically, as used herein and in the appended claims, the singular forms "a," "an," "said," and "the" include plural referents unless specifically stated otherwise. In other words, use of the articles allow for "at least one" of the subject item in the description above as well as the claims below. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation.

[0042] Without the use of such exclusive terminology, the term "comprising" in the claims shall allow for the inclusion of any additional element irrespective of whether a given number of elements are enumerated in the claim, or the addition of a feature could be regarded as transforming the nature of an element set forth in the claims. Except as specifically defined herein, all technical and scientific terms used herein are to be given as broad a commonly understood meaning as possible while maintaining claim validity.

[0043] The breadth of the present invention is not to be limited to the examples provided and/or the subject specification, but rather only by the scope of the claim language. Use of the term “invention” herein is not intended to limit the scope of the claims in any manner. Rather it should be recognized that the “invention” includes the many variations explicitly or implicitly described herein, including those variations that would be obvious to one of ordinary skill in the art upon reading the present specification. Further, it is not intended that any section of this specification (e.g., the Summary, Detailed Description, Abstract, Field of the Invention, etc.) be accorded special significance in describing the invention relative to another or the claims. All references cited are incorporated by reference in their entirety. Although the foregoing invention has been described in detail for purposes of clarity of understanding, it is contemplated that certain modifications may be practiced within the scope of the appended claims.

DRAWINGS

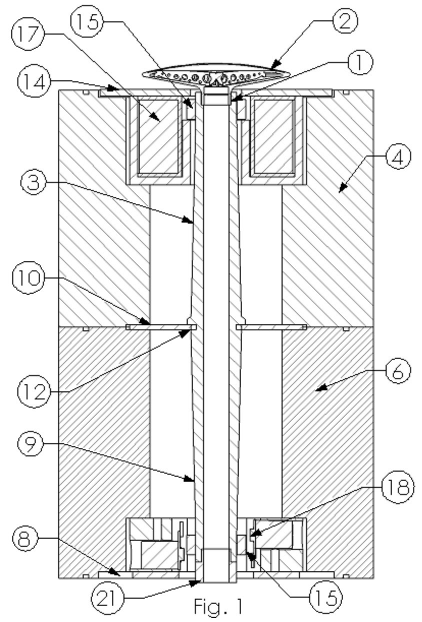

Fig. 1

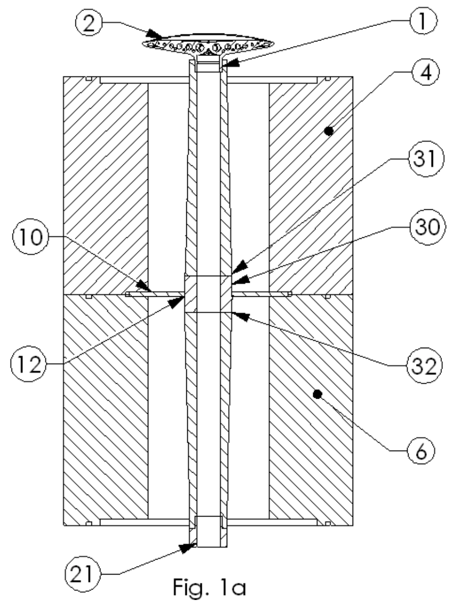

Fig. 1a

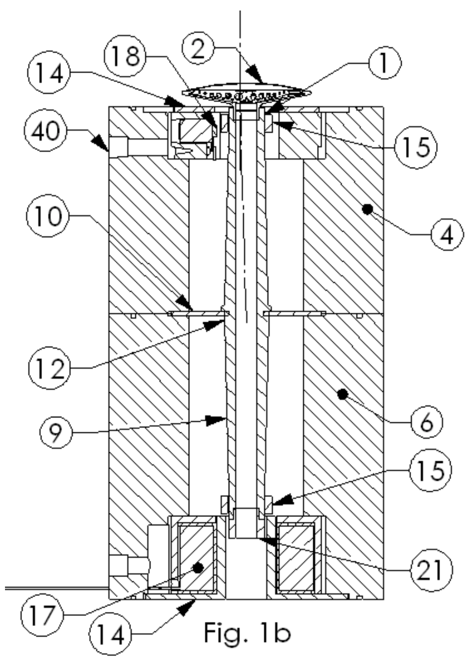

Fig. 1b

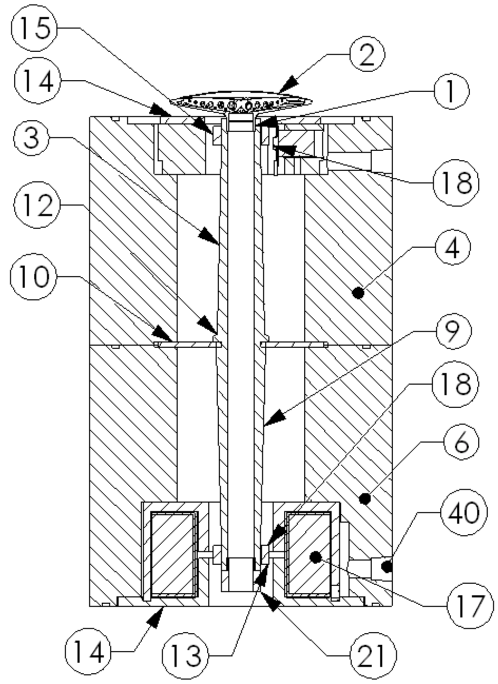

Fig. 1c

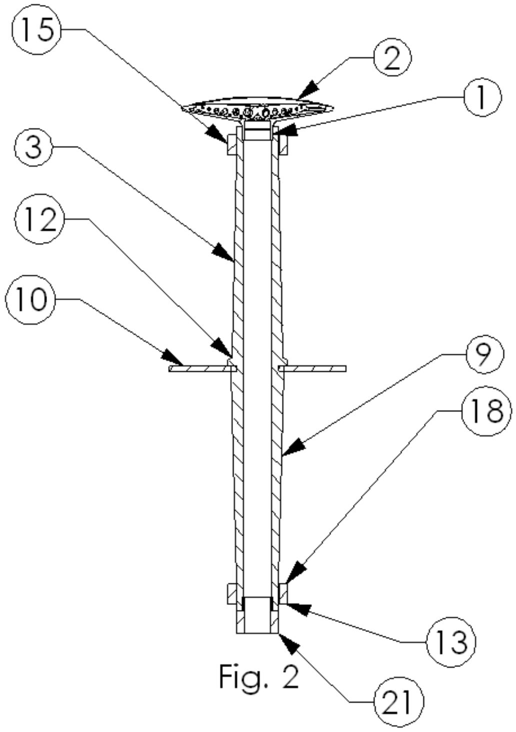

Fig. 2

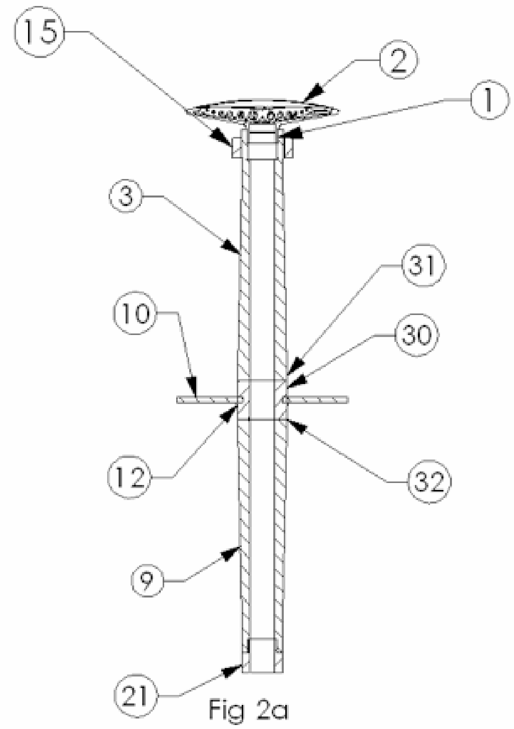

Fig 2a

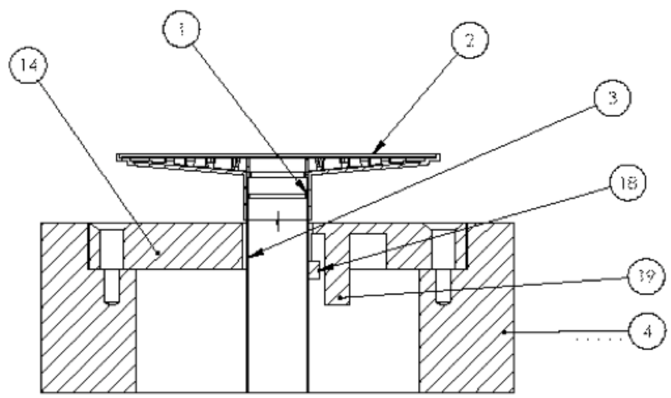

FIG. 3

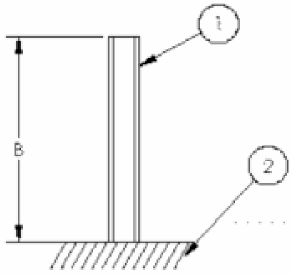

Fig. 4

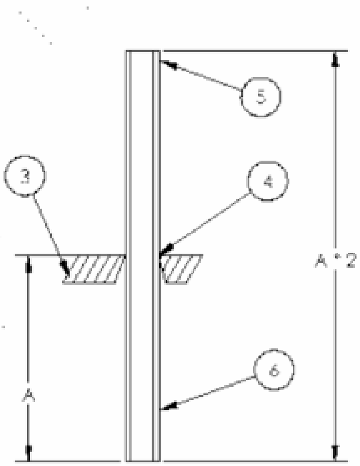

Fig. 5