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(71) Applicant: **CAMBRIDGE ENTERPRISE LIMITED**
[GB/GB]; The Old Schools, Trinity Lane, Cambridge,
Cambridgeshire CB2 1TN (GB).

(72) Inventors: **WELLAND, Mark Edward**; Nanoscience
Centre, 11 J J Thomson Avenue, Cambridge, Cambridgeshire
CB3 0FF (GB). **CONSTANTINOU, Peter**; Nanoscience
Centre, 11 J J Thomson Avenue, Cambridge, Cambridgeshire
CB3 0FF (GB). **GANNEY, Ian James**; Nanoscience
Centre, 11 J J Thomson Avenue, Cambridge, Cambridgeshire
CB3 0FF (GB).

(74) Agent: **MARKS CLERK LLP**; 62-68 Hills Road, Cambridge,
Cambridgeshire CB2 1LA (GB).

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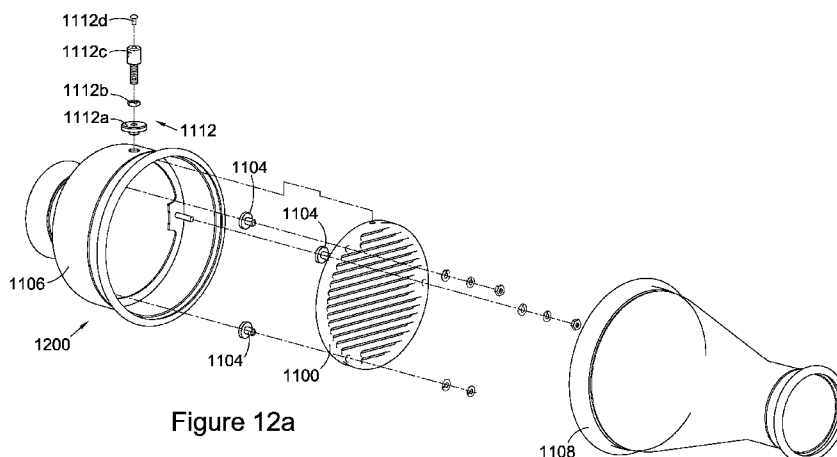


Figure 12a

(57) Abstract: We describe a method of monitoring the performance of an engine, the method comprising: providing a gas flow from a gaseous output of an engine to be monitored; sensing an electrical charge on particulates in said gas flow using a particulate charge sensor, to provide a sensed charge signal; and processing a waveform said sensed charge signal to determine a performance metric of said engine.

Sensing Methods and Apparatus

FIELD

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This invention relates to methods of monitoring the performance of engines, in particular but not exclusively gas turbine engines of aircraft; and also to related sensing systems and sensors.

10 BACKGROUND

General background prior art relating to particle sensing can be found in WO2011/151462, WO2010/088049, EP2,256,472A, US2013/0247648 A1, US2007/0137177 A1, US2006/0090540 A1, RU2474806 A, RU2310180 C1 and
15 US2010/0206042 A1. More particularly, we have previously described a volcanic ash sensor for an aircraft in WO2013/017894. This described a 'Christmas tree' type sensor having a generally conical shape with a surface which is stepped or ribbed in order to provide a turbulent air flow. The aim was to increase the probability of charged particle capture, in particular by flow separation in the air flow over the device. In broad
20 terms the aim was for particles to be trapped in the gullies, swirl around and attach to the metal. Figure 2 shows an example of the sensor 100 described in WO'894, comprising a cone-shaped copper coil 106a on a metal support 106b.

Volcanic ash can damage aircraft engines and lead to engine failure/stall. Figures 1a
25 and 1b show example SEM images of volcanic ash from Eyjafjallajokull (Iceland) and Montserrat (West Indies) respectively. Measurements of the 2010 Eyjafjallajokull eruption indicate that the volcanic ash particle size is less than 300µm. Measured in Germany the ash cloud particle size distribution was bimodal with peaks at 300nm and 2µm; this is typical.

30

The inventors have carried out extensive testing of a range of different configurations of volcanic ash sensor under a range of different conditions. In doing so that have learnt that, although there is a particular need for sensing volcanic ash, the sensing systems investigated also have other potential applications.

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SUMMARY

According to a first approach there is therefore provided a method of monitoring the performance of an engine, the method comprising: providing a gas flow from a gaseous output of an engine to be monitored; sensing an electrical charge on particulates in said gas flow using a particulate charge sensor, to provide a sensed charge signal; and processing a waveform of said sensed charge signal to determine a performance metric of said engine.

Research carried out by the inventors has demonstrated that it is possible to analyse the sensed charged signal (which may be represented by either a current or a voltage), to determine information which relates to characteristics of the particulates in the gas flow. This in turn can be used to provide information which is diagnostic of performance of an engine, in particular of the gas turbine engine of an aircraft. Thus embodiments of the method can be used to gather data, for example statistical data, on engine performance for diagnostic and/or maintenance purposes.

The analysis of the sensed charged signal may be performed online or offline, locally or remotely – for example in the case of an aircraft data may be analysed in real time to monitor engine performance and/or locally stored for later analysis, and/or combined with a database of performance data from the same or other engines, and/or transmitted, for example to a remote station for storage/analysis.

Embodiments of the method are particularly advantageous for monitoring the performance of an aircraft engine because of the substantial cost associated with maintenance of such engines. The maintenance cycle of a gas turbine on an aircraft may require, for example, certain maintenance steps at 5,000, 10,000 and 15,000 miles, but the intervals are determined with a substantial built in safety margin. In reality the need for maintenance can vary substantially depending upon the operating conditions of the aircraft – for example if an aircraft flies to locations with a high concentration of sand, such as North Africa or the Middle East, then the maintenance cycle should be short compared, say, with an aircraft which generally flies within northern Europe. Embodiments of the above described method of engine performance monitoring can thus offer benefits to both safety margin and cost effectiveness.

Embodiments of the method are not limited to use with gas turbine engines and may also be applied, for example, to an internal combustion engine such as a diesel engine. Some embodiments of the method monitor a gas flow derived from an exhaust of the engine. This is a convenient location to monitor, inter alia, combustion of the engine fuel by monitoring particulates in the exhaust. For example such an approach may be employed to determine how efficiently the fuel is being burnt and/or to indicate when there is inefficient burning taking place. Optionally information of this type may be provided as feedback to a user of the engine (e.g. pilot/driver) in substantially real time. Additionally or alternatively such information may be employed to provide an output signal indicating whether/when the engine needs servicing. In embodiments of the method the particulates in the gas flow which are monitored may include one or more of: carbon, carbon species, partially burnt fuel, carbon-rich hydrocarbons and the like.

In a gas turbine engine it may not be practical to monitor a final exhaust output from the engine and, instead, the output from an intermediate combustion stage of the engine may be employed, for example to provide the similar feedback/warning data to that previously described. Depending upon the configuration of the engine, an air bleed duct or line from a compressor of the engine may provide a suitable gas flow. In some preferred implementations of the method the sensing is performed at a location in the gas flow where there is some limitation on the temperature and/or pressure of the gas flow, for example after a pressure-regulating valve.

In embodiments of the method the waveform is processed to determine a change in a spectrum of the sensed charge signal over time. Optionally the waveform may be processed in more than one way to provide more than one parameter representing the signal. Multiple parameters may then be combined to provide an output, for example indicating one or more characteristics of particulates in the monitored gas flow. Thus signal processing applied to the waveform may include, but is not limited to: determining a mean value of the waveform, determining an integrated value of the waveform, determining an integrated absolute value, determining a polarity (sign) of the waveform, determining a standard deviation of the waveform, and determining other statistical parameters of the waveform. These values may be determined at intervals or as running values, for example using a sliding window. Waveform characterising parameters, such as those described, may be determined in either or both of the time

domain and the frequency domain, in the latter case for example performing a Fourier transform on a digitised version of the waveform. Optionally pre-processing such as filtering may be applied.

5 Experimental work by the inventors has shown that different types of particulate within a gas flow give rise to different types of waveform albeit generally noisy. Additionally or alternatively to the previously described approaches, embodiments of the method may apply one or more classifiers to the waveform to distinguish different types of particulates and/or different types of engine performance such as efficient/inefficient
10 performance. The skilled person will be aware that there are many different types of classifier which may be employed. Embodiments of the method may employ either supervised or unsupervised learning to distinguish between different types of waveform; examples of suitable techniques include, but are not limited to: Bayesian techniques, for example a Bayesian classifier; a support vector machine; an artificial
15 neural network (supervised or unsupervised); and various principle component analysis and expectation-maximisation techniques.

It has also been observed experimentally that a 'burstiness' of the sensed charge signal varies depending upon the sensed particulates. Thus still further additionally or
20 alternatively a parameter representing a degree of burstiness of the waveform may be determined and used to distinguish between particulate types/engine operation regimes/maintenance requirements. In broad terms such a burstiness parameter may be responsive to a correlation between characteristics of the waveform over time. More particularly embodiments of the method may perform a correlation, more
25 particularly an auto-correlation on time or frequency domain data representing the waveform. Suitable frequency domain data may be derived from a time-frequency transform such as a Fourier, wavelet or similar transform.

In a related approach there is provided a method of sensing particulates in an air flow
30 within an aircraft, the method comprising: monitoring particulates in said air flow using a charge sensing system to provide a sensed charge signal responsive to said particulates; and processing a waveform of said sensed charge signal to discriminate between different types of particulates and/or a background signal responsive to said waveform.

In embodiments of the above described methods of particulate sensing/engine performance monitoring, optionally the charge collection device comprises more than one electrode in the gas flow, thereby providing more than one waveform for analysis. In such a case the two or more waveforms may be processed, for example as previously described, either separately or in combination. In addition the waveforms and/or parameters derived therefrom may be compared with or combined with one another, for example to provide one or more differential signals or parameters. Again these one or more differential signals/parameters may be analysed according to any of the previously described techniques.

Where used, the background signal in such methods (and in later described methods) may comprise a signal or information representing the response of the sensing system when little or substantially no ash and/or other pollutant is present. Additionally or alternatively however the background signal may comprise a signal or information representing the response of the sensing system to ash or a particular type of ash and/or to one or more specific or general classes of pollutant(s). In the latter case these may be represented by data characterising the ash or particular type of ash and/or one or more specific or general classes of pollutant(s). Here the term "pollutant" is used generally to refer to a substance other than a target substance of the sensing system (recognising that a pollutant in one application of the system may be a target in another application of the system).

In a further related approach there is provided a system for monitoring the performance of an engine, the system comprising: a gas inlet providing a gas flow from a gaseous output of an engine to be monitored; a particulate charge sensor to sense an electrical charge on particulates in said gas flow to provide a sensed charge signal; and a processor to process a waveform of said sensed charge signal to determine a performance metric of said engine.

There is still further provided a sensing system for an aircraft, the system comprising: a particulate charge sensor, the particulate charge sensor comprising: an electrically conducting particulate charge collection device, an electrically insulating support for mounting said collection device in an air duct, and a charge sensing system having an input electrically coupled to said particulate charge collection device, wherein said charge sensing system is configured to determine a level of charge on said particulate

charge collection device to determine the presence of particulates in said air duct; and a processor to process a waveform of a charge sensing signal from said charge sensing system of said particulate charge sensor to discriminate between different types of particulates and/or a background signal.

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The processor may comprise analogue and/or digital circuitry and/or a general purpose computing system or digital signal processor operating under control of stored processor control code.

10 In a still further approach there is provided a particulate analysis system, the system comprising: a particulate charge sensor, the particulate charge sensor comprising: an electrically conducting particulate charge collection device, an electrically insulating support for mounting said collection device in a duct, and a charge sensing system having an input electrically coupled to said particulate charge collection device, wherein
15 said charge sensing system is configured to determine a level of charge on said particulate charge collection device to determine the presence of particulates in said air flow; and a signal processor, coupled to an output of said charge sensing system of said particulate sensor, wherein said signal processor, is configured to analyse a time-series charge signature and/or charge polarity from said particulate sensor to
20 discriminate between different types of particle providing charge to said particulate charge collection device.

As previously mentioned, it has been experimentally established that different types of particulate result in different polarities of charge on the charge sensor (with respect to
25 ground). Thus embodiments of the methods/systems we describe may advantageously determine a sign or polarity of the sensed charge. In embodiments this may be sufficient, by itself, to provide valuable diagnostic information. The skilled person will appreciate that there are many different ways in which a signal polarity may be measured including, for example, determining an average or weighted average of a
30 signal. Where the charge sensor has multiple electrodes or plates an average or weighted average of a differential signal between the electrodes/ plates may be determined.

In a particular approach, there is therefore provided a volcanic ash sensor for an
35 aircraft, the sensor comprising: an electrically conducting ash charge collection device;

an electrically insulating support for mounting said collection device in an air duct; and a charge measurement system having an input electrically coupled to said ash charge collection device; wherein said charge measurement system is configured to determine a level of charge on said ash charge collection device to determine the presence of volcanic ash in said air flow; and wherein a surface of said ash charge collection device has a plurality of ribs, steps, and/or openings; further comprising an ash charging electrode for mounting upstream of said ash charge collection device in said air flow, and a particle charging electrical power supply coupled to said ash charging electrode to apply a voltage to said charging electrode charging said ash; and wherein said electrically conducting ash charge collection device comprises a pair of separate adjacent collection electrodes, wherein said charge measurement system is configured to determine a differential said level of charge on said pair of collection electrodes to determine the presence of volcanic ash in said air flow; further comprising a signal processor, coupled to an output of said charge sensing system of said particulate sensor, configured to analyse charge measurements from said pair of electrodes dependent on a value of $\frac{S_+ - S_-}{S_+ + S_-}$ where S_+ is a charge measurement from a first of said electrodes and S_- is a charge measurement from a second of said electrodes.

A corresponding sensor may be used for particulate sensing for engine performance monitoring instead for volcanic ash sensing.

Possible sensor configurations

A preferred particulate sensor comprises an electrically conductive mesh or grid, mounted on an insulating support in the gas/air flow: A comparison of different sensor topologies, including cone, ring, rod, and mesh topologies, indicated that a mesh or grid topology was significantly more sensitive than the others. In one preferred embodiment the mesh or grid comprises a metal plate bearing a plurality of apertures, particularly slots, preferably with chamfered front edges. This provides a robust sensor and the thickness of the plate provides some interaction length for the charged particles with the sensor. To reduce the risk of resonance in the air flow, mechanical asymmetry and/or one or more cross-members may be added. Preferably the mesh or

grid is located in a flared region of the gas/air duct, to reduce the back pressure and maintain a good flow, and extends substantially completely across the duct.

5 In embodiments the sensor electronics is configured to detect a signal on the conductive mesh or grid from charged particulates in the gas/air flow. Thus preferably the sensor electronics comprises an electrometer – though the skilled person will appreciate that equivalently a current from and/or voltage on the sensor may additionally or alternatively be measured. Preferably an input to the electrometer includes an over-voltage protection circuit, and preferably also a current spike
10 protection circuit. Preferably the sensor electronics provides a variable (controllable) gain; in embodiments the gain of the sensor electronics is extremely high, for example greater than 10^8 , 10^9 or 10^{10} , in embodiments around 10^{11} (that is 10^{-11} coulombs charge would provide a one volt output). Preferably the sensor is coupled to the electrometer by capacitance compensated-cable to reduce the effect of cable
15 movement and vibration. Where vibration is a significant issue the signal processing electronics may include a vibration sensing element such as an accelerometer and a circuit or signal processing arranged to compensate for or substantially null out the vibration by subtracting a component of the vibration from the sensed signal. In embodiments the sensor electronics includes a low pass filter stage, in particular with a
20 cut-off (corner) frequency of less than 5 kilohertz, 3 kilohertz, 2 kilohertz or 1 kilohertz. Optionally the bandwidth of the sensor electronics is variable (controllable) so that it may be adjusted depending upon the target substance to be detected for example ash or aerosol. The skilled person will appreciate that signal processing for the sensor may be performed in the analogue and/or digital domain and/or by a programmed signal
25 processor such as a digital signal processor.

In some preferred embodiments of the sensor the sign of the charge on the electrically conducted mesh/grid is determined: The polarity of the detected signal may be used to distinguish the physical and/or chemical nature of detected particulates.

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In embodiments the grid/mesh may be divided into two and combined with an electrostatic particle deflection stage to selectively sense positively charged and negatively charged particles within the same air flow. The electrostatic particle deflection stage may comprise, for example, a pair of parallel plates across which a
35 high voltage is applied (typically greater than 0.5 KV). Each of the two portions of the

grid/mesh may be connected to a respective input stage of the sensor electronics or a common set of sensor electronics may be time multiplexed to detect the signal on each portion (half) of the grid/mesh. Optionally a particle charging stage may also be incorporated upstream of the sensor (and deflector), but in practise this has not been found to be necessary. Where used such a charging stage may comprise, for example, a mesh connected to a high voltage (greater than 0.5 KV) source or a grid of conductors in which alternate conductors are respectively connected to either a high voltage supply or ground/0V.

There are many places in which a particulate sensor as described above may be located in an aircraft. However in some preferred arrangements the particulate sensor is located in an air bleed duct or line from a compressor stage of an engine of the aircraft, in particular following a pressure-regulating shut off valve as this provides some restrictions on the environmental limits the sensor must tolerate. Such a pressure-regulating shut off valve (PRSOV) may, for example, be a nacelle PRSOV. Using the air bleed duct or line from a compressor stage of the engine facilitates monitoring volcanic ash entering the engine; in a particularly preferred approach the sensor is located in such an air bleed duct or line supplying air to an air conditioning unit of the aircraft. This further facilitates the sensor detecting aerosols which may end up in the cabin giving rise to a problem, for example a smell, which would need investigation. A particularly preferred location for the sensor is in a location designed for an ozone converter of the aircraft as this typically provides the foregoing advantages and, importantly in addition, locating the sensor here generally results in little or no change in back pressure in the air bleed line. In embodiments, therefore, the sensor may be located in a wing of the aircraft.

In embodiments the sensor electronics comprises a front end coupled to the sensor and an interface to a system data bus of the aircraft; optionally some or all of the signal processing may therefore be performed remotely from the front end, for example by an existing processing system in the aircraft. Additionally or alternatively the sensor may provide a signal on the system data bus for a cockpit display system of the aircraft. Any standard interface may be employed to connect the sensor to the aircraft data bus, for example an ARINC (Aeronautical Radio, Incorporated) standard such as ARINC 429 or ARINC 664.7.

The particulate sensing is preferably used for the aircraft on which the sensing system is mounted but the system may additionally or alternatively be employed for collecting data from aircraft in flight, so that this data can be stored/analysed elsewhere.

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BRIEF DESCRIPTION OF THE DRAWINGS

These and other aspects of the system will now be further described, by way of example only, with reference to the accompanying figures in which:

10

Figures 1a and 1b show SEM images of volcanic ash from Eyjafjallajokull (Iceland) and Montserrat (West Indies) respectively;

Figure 2 shows an embodiment of a 'Christmas tree' – type volcanic ash sensor;

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Figure 3a and 3b show an end view and a vertical cross section view respectively of a particulate sensor according to one example;

Figure 4 shows a schematic diagram of experimental apparatus used to evaluate alternative sensor topologies;

20

Figures 5a to 5d show examples of alternative sensor topologies;

Figures 6a to 6e show signal waveforms from, respectively, a mesh sensor, a rod sensor, a cone sensor, a bauble sensor, and a wedge-shaped sensor;

25

Figure 7 shows a detected charge – collected mass relationship for a plurality of different measurements made with a plurality of different sensor topologies;

30

Figures 8a and 8b show a sensor output signal (upper curve) and cumulative mass flow past the sensor (lower curve) for respective first and second aerosols (DF PLUS and BBTC100);

Figures 9a and 9b show detected charge against calculated mass flowing past the sensor for the first and second aerosols of Figure 8, for cone, ring, rod and mesh sensor topologies;

5 Figures 10a and 10b illustrate comparative sensitivities of different sensor topologies rated relative to a mesh sensor (sensitivity of mesh: sensitivity of other topology) for the aerosols of Figure 8, and a comparison of sensor sensitivity to different aerosol compositions for different sensor topologies;

10 Figures 11a and 11b show, respectively, a computer aided design drawing and a photograph of a sensor grid for use in a gas turbine bleed line;

15 Figures 12a and 12b show, respectively, an exploded view and a closed view of the sensor of Figure 11, in a housing, for insertion into an air bleed duct or line from a gas turbine;

20 Figures 13a and 13b show, respectively, a location of the sensor of Figures 11 and 12 in an air bleed duct or line (the inset photograph shows a low pressure prototype), and example output signals from a sensor of the type shown in Figures 11 and 12 located as illustrated in Figure 13a;

25 Figure 14 shows example pressure, temperature and mass flow rate curves for an Embraer E190 aircraft from take-off, to a cruise altitude of just under 40,000 feet, then landing, where the curves illustrate parameters of the air bleed duct or line at a location following the nacelle shutoff valve of the aircraft;

30 Figures 15a to 15d show, respectively, a schematic illustration of a particulate sensor including an electro static deflector stage, a diagram illustrating the operating principle of the arrangement of Figure 15a, a graph illustrating the operation of a sensor of the type illustrated in Figure 15a, and a photograph of a sensor of the type illustrated in Figure 15a showing volcanic ash deposited on the positive plate of the deflector stage;

35 Figure 16 shows an example of a particulate sensor including a particulate charging stage;

Figure 17 illustrates example sensor electronics for a particulate sensor according to an example implementation;

5 Figures 18a and 18b show, respectively, an integration window for the sensor signal processing system of Figure 17, and an example “traffic light” display indicating the presence of detected particulates;

10 Figures 19a and 19b show first and second examples of sensed charge waveforms for volcanic ash from the Montserrat volcano;

 Figures 20a and 20b show first and second examples of a sensed charge waveform of de-icing fluid (DF-PLUS aerosol);

15 Figures 21a and 21b show first and second examples of sensed charge waveforms of compressor wash (BBTC100);

 Figures 22a and 22b shows first and second examples of sensed charge waveforms of oil (BP Turbo oil); and

20 Figures 23a and 23b show an embodiment of a system for monitoring the performance of an engine/analysing particulate type, and a variant of the system with a split particulate charge sensor.

25 DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

30 Referring now to figures 3a and 3b, these show a mesh/grid topology particulate sensor 300 according to an example of the device. The sensor is mounted within a duct 302, for example in part of the bleed air pipework of an aircraft, supported by a ring-shaped, electrically insulating mount 304 fabricated, for example, from nylon. An electrical connection 306 is provided to a metal mesh 308 which preferably extends across all or substantially all of duct 302. In a test embodiment mesh 308 was fabricated from woven stainless steel wire.

Figure 4 shows a test rig 400 used for comparative testing of different sensor topologies. Broadly speaking the test rig comprises a plurality of segments of stainless steel tubing connected together to form a wind tunnel. The wind tunnel is driven by a fan 402 provided with a filter 404 on the output side to inhibit release of particles. The apparatus is provided with a port 406 for an anemometer (preferably with a computer inter face or data logging) and a sensor module region 410 to accommodate a sensor under test, such as grid sensor 300. A particle dispensing module 420 is provided at an inlet 408 of the apparatus such that aerated particles are dispersed into the air flow entering the tunnel – thus the inlet 408 may comprise an open-ended section of tubing 408a.

Figure 4 illustrates a dispenser module 420 for volcanic ash particulates comprising a Drechsel jar arrangement provided with a connection 422 to a pressurised air supply 424, preferably at relatively low pressure, for example less than 10psi. The aerated ash particles 426 are provided via tubing 428 to the air inlet of apparatus 400. The apparatus of Figure 4 can also be used for testing aerosol particulates. A dispenser dual module for dispensing fine aerosols may comprise a “air gun” of the type typically used for spray painting; this typically operates at a pressure of order 50psi.

Preferably the metal tubing of the apparatus is grounded to avoid static charge building up, and preferably the sensor module region is mounted on a separate support or table 412 to other parts of the apparatus, to reduce vibration.

Not all of the particulates which enter the rig pass through the sensor because of interaction and accretion of particles within the rig. Thus preferably the apparatus incorporates a module for measuring the mass of solid or aerosol particulates flowing past the sensor. In the case of solid particulates a filter may be located downstream of the sensor and the changing mass of the filter used to measure the mass flow rate of particulates past the sensor. In the case of aerosols a quartz crystal micro balance may be located in the flow of the sensor module; the mass flow rate can then be determined from the thickness of the deposited aerosol on the QCM crystal, knowing the density of the aerosol.

The sensor module 410 is connected to sensor electronics comprising an electrometer (described later) which measures the movement of charge as a result of the particles moving past (and/or colliding with) the sensor.

- 5 It is assumed that the detected mass is proportional to the detected charge, and it then follows that:

$$\dot{m}(t) \propto i(t)$$

- 10 Where $\dot{m}(t)$ is the instantaneous mass flow rate and $i(t)$ is the detected instantaneous current. The mass is related to the integral of this signal over the period of which the mass is dispensed:

$$m = \alpha \int_{t_0}^{t_1} i(t) dt$$

- 15 where t_0 is the time the dispersion of the mass starts, t_1 is the time the dispersion of the mass stops and α is a proportionality constant relating the mass to the integral. By calculating the integral α can be determined by taking the ratio of the measured mass to that of the calculated integral:

$$\alpha = \frac{m_{meas}}{\int_{t_0}^{t_1} i(t) dt}$$

where m_{meas} is the measured mass.

- 20 α is a characteristic of the type of sensor and substance under investigation, and can be determined for different sensors and particulates. It can be used to compare different sensors. However, errors arise from the mass measurement techniques, the accretion of particles on the wind tunnel walls and different particle sizes and shapes.
- 25 For this reason multiple measurements are taken to take an approximate average.

Six different sensor topologies were investigated: the Christmas tree or cone topology of Figure 2, the mesh/grid topology of Figure 3, and the four additional topologies illustrated in Figure 5. These latter comprised, respectively, a rod-shaped sensor, a

ring-shaped sensor, a “bauble” sensor, and a range of different wedge-shaped sensors. Thus Figure 5a shows a rod-shaped metal sensor 500 and Figure 5b a ring-shaped metal sensor 502 (other elements like to those of Figure 3 are indicated by like reference numerals). The bauble shaped sensor of Figure 5c comprised a plurality of

5 conductive fins defining a rounded, in particular generally spherical overall shape. Various different wedge-shaped sensors were also fabricated, two of which are illustrated in Figure 5d. These potentially offer less intrusion to the air flow than a mesh sensor and provide a longer conductive path through the sensor, but potentially suffer from poor spatial sensitivity which may give rise to inaccuracies if the air flow is not

10 uniform across the duct. Optionally therefore multiple sensors may be arranged at angular intervals circumferentially within the air duct, for example three sensors at 120 degrees separation. The signals from these sensors may then be combined by signal processing.

15 The performance of these various different sensor topologies was compared in multiple experiments (the results of any particular experiment show considerable scatter). Examples of the signals from the different topology sensors are shown in Figures 6a to 6e. These show a voltage output from the electrometer electronics when the sensors were tested with volcanic ash from the Montserrat volcano (the apparent differences in

20 polarity of the signals are an artefact of the electronic amplification employed – the detected signals had the same polarity). Thus Figures 6a to 6e show recorded voltage profiles from, respectively, the mesh sensor of Figure 3, the rod sensor of Figure 5, the cone sensor of Figure 2, the bauble sensor of Figure 5 (lower trace, compared with the mesh sensor, upper trace), and a wedge sensor of the type shown in Figure 5 (upper

25 trace; the lower trace shows the mesh sensor, for comparison). From these figures it can be seen that the mesh sensor arrangement of Figure 3 performs better than the bauble sensor and the wedge sensor, although it is more difficult to draw clear conclusions from the single examples of Figures 6a to 6c.

30 Multiple signals were measured for each sensor topology and the signals were evaluated by calculating the detected charge from the integral of the measured signal, which represents the current generated in response to the particulate mass passing the sensor. The mass flow can be determined as previously described. This enables a mass-charge relationship to be determined for a measurement, and Figure 7 illustrates

35 a plurality of charge-mass measurements for a range of different sensor topologies and

particulates, comparing rod, cone and mesh sensor geometries. The results of Figure 7 show that the cone sensor is slightly more sensitive than the rod sensor and that the mesh sensor is much more sensitive than either of these, albeit there is a substantial spread in the results. (The spread results from a range of uncontrolled parameters including the environmental humidity, the dispensing method, the collection of particles in the filter, interaction of particles with the test rig, non-uniformity of particle size and other effects).

A similar analysis was performed on a range of different aerosols. Aerosols tested included a de-icing fluid (DF PLUS, comprising monopropylene glycol), a cleaning fluid (compressor wash BBTC100; soapy) turbine oil (BP Turbo Oil 2380), and a second compressor wash (Turco 5884; an aromatic hydro carbon mixture used to clean the jet engine gas path).

Figures 8a and 8b show the response to de-icing fluid and compressor wash fluid aerosols respectively, showing the sensor signal in the upper curve and a quartz crystal micro balance signal measuring the mass flow in the lower curve. Although the curves of Figures 8a and 8b show an output voltage of the same polarity, these signals were taken from different amplification stages one comprising a signal inversion and thus the detected charge of the aerosols of Figures 8a and 8b are of opposite polarity.

The detected charge polarity of an aerosol or particulate flow past a sensor can help to distinguish one type of particulate from another. The ability of different sensor topologies to distinguish signal polarity was investigated and outline results are shown in the table below. Although not shown in the table, the mesh sensor gave the most distinguishable signal polarity by comparison with the other sensor topologies; all the topologies except for the mesh topology also exhibited substantial stochastic fluctuations in the observed signal:

	Sensor	Cone	Ring	Rod	Mesh
Input polarity	DF PLUS	Negative	Negative	Positive	Negative
	BBTC100	Positive			Positive

Knowing the mass of aerosol which is passed the sensor, and the (integrated) detected charge a charge-mass relationship can be plotted for experimental runs for each of the aerosols and for each of the different sensor topologies. Figures 9a and 9b compare the results for the cone, mesh, rod and ring topologies for de-icing fluid and compressor wash fluid aerosols respectively. It is observed that the collected mass of aerosol is two to three orders of magnitude below the collected mass of volcanic ash in the ash measurements. By fitting a linear relationship with a zero intersect to the data the gradients (α), and hence sensitivity of the different sensor topologies to the aerosols can be compared. The calculated values of the sensor sensitivity (α) are shown below:

Sensor X 10 ⁷	Cone	Ring	Rod	Mesh
DF PLUS	-1.37	-3.70	4.98	-46.2
BBTC100	622	1100	712	3640

By using the sensitivity of the mesh as a reference and using absolute values of the sensitivity (α) the sensor sensitivities to the different fluids can be compared. This is illustrated in Figure 10a, which shows the ratio of the mesh sensor's gradient to that of the other topologies. It can be seen from Figure 10a that the mesh sensor topology is significantly better than the other topologies. Figure 10b shows a ratio of the sensitivity to BBTC100 (wash) to DF-PLUS (de-icer). All the sensors are more sensitive to compressor wash than de-icer, but the mesh sensor exhibits the most uniform response.

The foregoing discussion illustrates the experiments which were performed to compare the various different sensor topologies, and taken collectively, the results of the experiments showed that a mesh/grid topology provides surprising and significant advantages over the other topologies, in particular over the cone topology we have previously described in WO 2013/017894.

Based on these results, a practical embodiment of a mesh/grid sensor topology was developed, as illustrated in Figure 11. Thus Figure 11 shows a sensor grid 1100 comprising a stainless steel metal plate with a plurality of slots 1102. To assist airflow through the grid and inhibit resonance (and thus potential whistling) the leading edges of the grid bars are chamfered. Optionally resonance can be further inhibited by

changing a resonant frequency of the bars by adding a cross bar to provide additional stiffness and/or by changing the illustrated bars to rods. In one embodiment the plate has a thickness of 10mm; the width of a grid bar is 2.5mm and the air space between bars is 5mm; in an example embodiment the plate diameter is approximately 140mm; the plate may be made from grade 316 stainless steel. The plate is provided with insulated mounts 1104, for example comprising ceramic bushes which may be fabricated from Macor (registered trademark). A connection hole is drilled and tapped in the edge of the plate to provide an electrical connection.

Figure 12 illustrates a sensor assembly 1200 including the grid 1100 of Figure 11. The sensor assembly comprises first 1106 and second 1108 duct portions fastened together by a strap 1110 to allow access to the plate 1100 for maintenance. At least the upstream duct portion 1108 is flared so that when the assembly is installed in an aircraft bleed air system the air flow is not substantially impaired. The duct portion 1108 may flare to increase its cross sectional area by a factor of 1.5, 2 or more. An electrical connection assembly 1112 a-d is provided comprising a metal terminal 1112 c which screws into the plate 1100 and an insulated bush 1112a. The terminal assembly 1112 connects to a low triboelectric noise coaxial cable 1302 (Figure 13a) to connect the sensor assembly to the sensor electronics. Preferably the connection is relatively short and the cable is securely fastened to inhibit movement (and hence a detection of noise and vibration).

Figure 13 shows installation of the sensor assembly 1200 in the wing of an aircraft 1300. Location of an ash sensor assembly in the wing is not essential, but is advantageous, facilitating location of a sensor in an air bleed duct or line 1304 from a compressor stage of the engine 1306.

The bleed air system takes compressed air from the aircraft engine and, typically, supplies this to the aircraft air conditioning pack, an airframe de-icing system, cabin, flight compartment and door seal pressurisation systems, and other systems. Broadly speaking air for the sensor may be bled off one of the front fans of an engine, but alternatively air may be bled into the sensor. Two aircraft will be considered, by way of example.

In the Embraer E195 the bleed air pressure and temperature is regulated using a combination of the air from the high pressure ninth stage take off and the low pressure fifth stage take off. Preferably the sensor is located in this bleed after the nacelle shut-off valve, in particular in the manifold within the wing section of the aircraft.

5 Advantageously the sensor is mounted where an ozone converter would otherwise be fitted. In this location the maximum normal operating pressure is around 50psi and the maximum temperature is in the range 230°C – 260°C (depending upon the conditions); the ducting at this location has a three inch diameter. In a Bombardier Q400 aircraft preferably the sensor is similarly located following the nacelle shut-off valve, for
10 example in the P2.2 pipeline (2.5 inch ducting); other pipelines which may be used include P2.7 and P3.0. Again in some preferred embodiments the sensor is mounted where an ozone converter would otherwise be located. In the Bombardier Q400 aircraft the maximum normal operating pressure is around 54psi and the maximum normal operating temperature is around 290°C (depending upon the precise location).

15 Figure 14 shows pressure, temperature, and mass flow rate for both engines (left axis) of an E190 aircraft together with altitude (right hand axis); the parameters are similar for the E195 aircraft. The previously described sensor configuration is suitable for operating in this range of temperatures and pressures. In principle it may even be used in a harsher, unregulated environment, for example before the Nacelle shut-off
20 valve and/or after the precooler. The photo insert in Figure 13a shows a prototype device installed in a preferred location described in the manifold within the wing section; the unit is visible and accessible when the flaps are down.

Figure 13b illustrates test results for a sensor of the type shown in Figures 11 and 12
25 showing the signal from water (A), air only (B), Turco cleaning fluid (C), air only (D), water (E) and air only (F). During the air only sections the system detects the remnants of the injected contaminants; the clipping is due to the large system gain (preferably the sensor electronics includes an adjustable gain stage). Tests of this type validated the practical ruggedized sensor design of Figures 11 and 12.

30 Figure 15 shows a schematic diagram of a particulate sensor 1500 for facilitating distinguishing between positive and negative charged particles. Thus in the arrangement of Figure 15a the sensor stage 1502 comprises a pair of separate mesh or grid sensors 1502a, b and a particular deflection module 1504 upstream of the
35 sensor. In the illustrated example the particle deflector comprises an electro static

deflector, in particular a pair of electrodes 1504a, b, in the example deflector plates, across which is connected a high voltage DC supply 1506. The deflection of particles passing through the deflector stage 1504 depends upon whether the charge of a particle is positive or negative, as explained further below. In alternative approaches magnetic deflection may be employed, using a magnetic field with a component perpendicular to the air flow, which results in particles moving along a circular trajectory whilst in the magnetic field.

In one embodiment the deflector stage comprises a pair of copper plates, one at 5Kv, the other at zero volts. As shown in Figure 15b, a particle moving with velocity u , having mass m and charge q experiences an electrostatic force whilst travelling through the electric field between the plates.

The force will give the particle a velocity u_1 in vacuum when leaving the plates. For a parallel plate configuration, shown below, the time between the plates is Δt is given by:

$$\Delta t = \frac{L_p}{u}$$

where L_p is the length of the plates. u_1 is given by:

$$u_1 = \frac{F_T}{m} \Delta t = \frac{L_p q E}{mu} = \frac{L_p q V}{amu}$$

where a is the separation between plates. V is the applied voltage and E can be given as:

$$E = \frac{V}{a}$$

The deflection D_E is then given by:

$$D_E = \frac{u_1}{u} L_E = L_E \tan \theta = \frac{q L_E L_p V}{ma|u|^2}$$

The small deflection between the plates has a parabolic trajectory. The total deflection, D_P , on exiting the plates is given by:

$$D_p = \frac{qE\Delta t^2}{2m}$$

Thus when a potential is placed across plates 1504a, b charged particles are deflected preferentially towards either mesh 1502a or mesh 1502b, depending upon their charge and the direction of electric field across plates 1504a,b. Each of meshes 1502a,b may have separate sensor electronics, in particular a separate electrometer. A ratio may be calculated of the integral of the signal from one portion of the mesh to the integral of the signal from the other portion of the mesh. Figure 15c shows a box plot of this ratio for different plate voltages; it can be seen that as the applied voltage increases the ratio changes, reflecting increased deflection of the particles. The ratios themselves tend to have a large spread; in the plot whiskers are extreme points, red crosses are outliers, the red line is the median, the blue block represents 75% and 25% percentiles, and the green asterisk represents the mean value. When tested with Montserrat ash (finer than the Icelandic ash), ash was deposited on the positive deflector plate as shown in the photograph of Figure 15d, indicating that these particles are negatively charged. In addition, it appears that only small particles adhere to the plate.

It appears from the measurements that in embodiments of this technique more reliable results are obtained if filtered rather than full spectrum signals are employed when calculating the ratio of integrated signals from the portions of the sensor grids/mesh. The filter applied may be a low pass filter with a band width of less than 10KHz, 5KHz, 2KHz, 1KHz or 0.5KHz.

Figure 16 shows an embodiment of a particulate sensor 1600 similar to that illustrated in Figure 15 but with the addition of a particle charging stage 1602. The charging stage may comprise, for example, a grid or mesh 1604 held at a high voltage, for example 5Kv or a grid 1606 of wires alternately connected to either zero volts or a high voltage such as 5Kv. In principal other geometries may also be employed, for example a cylindrical or tubular geometry. In principal this arrangement can be employed in a similar manner to that previously described with referenced to Figure 15, calculating the same ratio as previously described, but calculating the ratio twice, once when the charging stage is active and once when it is off. The off or inactive state of the

charging stage can then be used to produce a base line reference at ratio with which the ratio when the charging stage is on can be compared. The result of the comparison can be used for improved sensitivity/selectivity of particulate detection.

5 Figure 17 shows a sensor interface electronics 1700 for use with a mesh/grid sensor as previously described. Thus line 1702 may be connected to signal cable 306 of the sensor of Figure 3 or to terminal 1112 of the sensor of Figure 12; a ground connection forms the other input connection. The input stage, stage 1, of the electronics of Figure 17a preferably also incorporates a pair of over-voltage protection diodes 1704a, b,
10 clamping the input to the supply rails. These diodes should have ultra-low leakage. At stage two of the input electronics comprises a damping circuit (R15, R16, C5) to protect the following stage from any current spikes; a capacitor C6 may optionally be employed to compensate for the input capacitance.

15 The third stage of the input electronics comprises an electrometer circuit constructed around an ultra-low input bias current operational amplifier with a high gain resistance feedback network. In embodiments this stage preferably includes a low pass filter with a cut off frequency of less than 500Hz, 400Hz, 300Hz, 200Hz or 100Hz, for example around 75Hz; this may be implemented in the feedback network as shown. Optionally
20 R17 may be left open circuit. Preferably the input to stage 3 is guarded as shown to reduce leakage currents; a trimmer may be included to adjust for any DC output voltage off sets.

Stages 4 and 7 of the interface electronics comprise filter stages. In embodiments
25 stage 4 provides a passive low pass filter stage with a cut off frequency of around 1Kz, and stage 7 provides an active low pass filter stage. In embodiments the cut off frequency is adjustable in the range 15-330Hz. Stages 5 and 8 comprise signal isolation/output stages. As illustrated stage 5 comprises a pair of buffers, one providing an intermediate output (OUTPUT 1); stage 8 provides a second output
30 (OUTPUT 2) following low pass filter stage 7. Stages 5 and 8 comprise voltage follower stages and help to isolate the output of the previous stage from noise. Stage 6 comprises an adjustable gains stage.

The skilled person will appreciate that the voltage and current protection and stages 4 to 8 are optional, and that the electrometer stage 3 may be implemented in many different ways.

- 5 The analogue electronics of Figure 17 may provide an input to further digital signal processing 1710, for example, comprising a processor controlled by stored program code. This digital signal processing may be used, for example, to provide one or more warning/alarm signals to the cockpit indicating the presence of detected ash and/or aerosol. Additionally or alternatively the digital processing may log data collected from
10 the sensor or sensors and/or combine data from other inputs, for example, a satellite based communication system and/or weather data and/or other data which may indicate where a volcanic ash cloud is located or expected.

- The sensor electronics and/or digital signal processor of Figure 17 may communicate
15 with one or more other processing systems on the aircraft, for example, via an aircraft system data bus. Thus, referring back to Figure 13a, the interface electronics 1700, 1710 may communicate over system data bus 1720 with one or more of a telemetry or atmospheric data system 1730, a data logger/maintenance system 1740, and a cockpit display/pilot indicator system 1750.

20

Signal processing applied to, a signal from the sensor may comprise, inter alia, determining a mean, integral over time, integral of an absolute value over time, and standard deviation of a sensor signal, in particular from the equations below:

Mean	$\bar{V} = \frac{\int_0^T V(t)dt}{T}$
Integral	$A = \int_0^T V(t)dt$
Absolute Integral	$A' = \int_0^T V(t) dt$
Standard Deviation	$\sigma = \sqrt{\frac{\int_0^T (V(t) - \bar{V})^2 dt}{T}}$

25

In embodiments such a value may be determined by integrating over time, employing sequential windows onto a data set of length N elements (determined by the sample rate and length of time the data is acquired over). Figure 18a illustrates an example window size defining a set of sequential elements of the acquired data. In
5 embodiments each sequential window overlaps the next by a percentage; the window size may be defined in terms of seconds and the overlap may be defined in terms of percentage of the window size. The example of Figure 18a shows the Nth and Nth+1 windows, each of size 6 elements, indicating the overlap.

10 The skilled person will appreciate that there are many different ways in which sensor signal data may be processed. Figure 18b illustrates an example of a traffic light-type display 1800 with red 1802, amber 1804 and green 1806 indicators, in the illustrated example for each of two sensor channels A, B. In one embodiment an indicator is activated when the integral of the signal from the channel exceeds a threshold value, in
15 the illustrated example adjustable. Conveniently an indicator has hysteresis so that once an indicator is activated it only deactivates when the integral of the signal decreases below a lower limit associated with that indicator.

A system installed in an aircraft including the display of Figure 18b, may be simplified
20 to a single indicator or single indicator per sensor channel showing, for example red/green or red/amber/green in accordance with a level of volcanic ash and/or aerosol and/or any particulate detected by the sensor system.

25 **Engine Management**

Since in embodiments the sensor electronics provides information which is useful for engine performance monitoring and for determining whether/when engine maintenance may be required, the interface electronics/signal processing may additionally or
30 alternatively communicate with one or more engine performance monitoring/management systems (not shown in Figure 13). Data of this type may be logged and/or used, for example in combination with other engine performance management data, and/or transmitted from the aircraft back to a central data logging/processing centre which processes engine-related data from aircraft.

The sensed charged waveform, from a sensor as previously described, is characteristically different depending upon the type of volcanic ash sensed. Thus ash from different volcanos is sufficiently different to enable one volcano to be distinguished from another and, more generally, other different types of particulate can also be distinguished. Thus referring to Figure 19, this shows examples of waveforms of volcanic ash from the Montserrat volcano; Figure 20 shows examples of waveforms of de-icing fluid (aerosol), Figure 21 shows examples of waveforms of compressor wash) aerosol, and Figure 22 shows examples of waveforms of turbo oil (aerosol). Further examples of waveforms (not shown), are characteristic of carbon and other particulates in burnt or partially burnt fuel. In addition as previously described, the average sign (positive or negative) of the sensed charged signal is also characteristic of the chemical nature/composition of the sensed particulates.

The sensed charged waveform may be analysed, using digital signal processing, to identify a signature of the signal and hence to identify one or more types of particulate responsible for the observed waveform. Figure 23a illustrates a signal sensing/engine management system 2300 arranged to perform such analysis.

Thus, referring to Figure 23a, a charged particle sensor 1100, preferably a mesh/grid sensor of the type previously described, provides an input to analogue front end signal processing circuitry, in particular electrometer and signal pre-processing (filtering) circuitry 1700 as previously described. The output from this front end is then digitised by an analogue-to-digital converter 2302, which provides an input to digital signal processor (DSP) 2304, which is coupled to working memory 2306 and stored program memory 2308. The DSP 2304 provides a digital data output 2306 providing data indicating, for example, a level of one or more different types of particulate in the air/gas flow through sensor 1100. In embodiments the data output 2306 is coupled to a data bus of the aircraft for routing to further signal processing and/or pilot information/warning indicator(s).

The program memory 2308 stores processor control code which, in one embodiment, comprises code to apply a (moving) window 2310 to the input data and then to determine one or more of a set of parameters for analysing the data. These parameters may include parameters for/from an average sign of the data, mean value of the data, integral value of the data, integral absolute value of the data, standard

deviation of the data, and a fast Fourier transform (FFT) of the data. These one or more parameters, optionally in conjunction with the raw or filtered data time series waveform data, are provided to a classifier 2314. This classifier may, for example, perform principle component analysis on the one or more parameters from the preceding stage and/or may identify a signature of the digitised waveform in the time and/or frequency domain, for example using a neural network or the like. Embodiments of the signal processing may also perform an autocorrelation on the digitised waveform (in either the time domain or the frequency domain), to identify a degree of burstiness of the waveform. The skilled person will recognise that, optionally, multiple different analysis techniques may be applied and the results may be combined (optionally weighted), for potentially more reliable signal identification/discrimination. The code stored in the ROM 2308 may be provided on a separate physical storage medium, illustratively indicated by disk 2320.

Figure 23b illustrates a variant of the system of Figure 23a in which the sensor and front end signal processing is split into two parallel paths (reference numerals labelled 'a' and 'b' respectively), for use with sensor systems of the type illustrated in Figure 15a. The digital signal processing (not shown) may be either separate or combined. Optionally a combined signal may be generated from a sum and/or difference and/or ratio of the signals from the separate sensor portions 1100a,b.

In embodiments of either variant of the system the classifier 2314 may be adaptive and may, in particular, have the ability to learn to distinguish between signals representing different types of particulate, for example employing a neural network (although the skilled person will be aware that other statistical techniques may also be used). Thus the sensor system may be presented with particulates of different types in order that the classifier learns to distinguish between the different particulates and/or learns to distinguish target particulates from a general background signal.

The particulate data may be used for engine performance management in many ways. For example it may be used to determine a degree of efficiency with which fuel is being burnt. Additionally or alternatively it may be used to determine a cumulative level of particulates sensed by the system, indicative of cumulative potential contamination of an engine. This information may, in turn, be used to provide an indication of potential wear on an engine, and hence may be used to provide information for determining

whether or not maintenance of the engine is needed and/or for predicting an interval to maintenance.

5 Some preferred embodiments of the system described above are employed for monitoring particulates in and/or the performance of a gas turbine engine on an aircraft. In such an arrangement a robust sensor of the type illustrated in Figure 11 is particularly helpful as the sensing environment can be challenging - for example the sensor may have to operate in an exhaust air stream where temperatures may reach perhaps 800°C. However there are other, less challenging locations in which a sensor
10 may be located, and thus other mesh/grid sensor configurations may also be employed. More generally, although experiments have indicated that a mesh/grid sensor topology is particularly efficient, the engine management/particulate analysis techniques we have described are not limited to use with a charged particulate sensor of any particularly topology.

15 The skilled person will recognise that the output data from the system 2300 may be combined or correlated with other engine-related data, for example a time since last maintenance and/or data sensed in real time from the engine. The skilled person will recognise that there is a large quantity of data which is typically collected from a gas turbine engine and the data from the sensor system 2300 may be combined with this
20 other information and used in any convenient manner. For example in an aircraft the engine may be rented to provide 'power by the hour' and information generated by the sensor system 2300 may be used by a renter of an engine to control pricing.

25 Applications of the above described system are not limited to aircraft or to gas turbine engines and may be employed, for example, in an internal combustion engine such as an automotive or industrial petrol or diesel engine. In this context sensor system 2300 may similarly provide particulate level data which may then be combined with other data for improved engine performance management. Such other data, in this context,
30 may comprise for example, gas sensing data such as data from an oxygen sensor, and/or engine temperature data, and/or fuel use data.

No doubt many other effective alternatives will occur to the skilled person. It will be
35 understood that the invention is not limited to the described embodiments and

28

encompasses modifications apparent to those skilled in the art lying within the spirit and scope of the claims appended hereto.

CLAIMS:

1. A method of monitoring the performance of an engine, the method comprising:
providing a gas flow from a gaseous output of an engine to be monitored;
5 sensing an electrical charge on particulates in said gas flow using a particulate charge sensor, to provide a sensed charge signal; and
processing a waveform of said sensed charge signal to determine a performance metric of said engine.
- 10 2. A method as claimed in claim 1, wherein said processing comprises analysing a spectrum of said sensed charge signal to determine a change in said spectrum over time, wherein said performance metric is dependent on said change in said spectrum over time.
- 15 3. A method as claimed in claim 1 or 2 wherein said processing comprises applying a classifier to said waveform to determine said performance metric.
4. A method as claimed in claim 3 wherein said classifier is an adaptive classifier, the method further comprising determining or adapting said classifier to improve said
20 determination of said performance metric.
5. A method as claimed in any preceding claim wherein said processing is configured to distinguish one type of said particulate from another.
- 25 6. A method as claimed in any preceding claim wherein said performance metric is determined responsive to a correlation between characteristics of said waveform over time.
7. A method as claimed in any preceding claim, wherein said performance metric
30 comprises a determination of whether or not a target type of particulates is present above a threshold level.
8. A method as claimed in any one of claims 1 to 7 wherein said engine is a gas turbine engine, and wherein said gaseous output comprises an output from an
35 intermediate combustion stage of said gas turbine.

9. A method as claimed in claim 8 wherein said gas turbine is a jet engine of a jet aircraft, and wherein said sensing of said charge is performed in an air flow between said engine and an air conditioning unit of said jet aircraft.

5

10. A method as claimed in any one of claims 1 to 7 wherein said engine is an internal combustion engine, and wherein said gas flow comprises an exhaust gas flow of said engine.

10

11. A method of sensing particulates in an air flow within an aircraft, the method comprising:

monitoring particulates in said air flow using a charge sensing system to provide a sensed charge signal responsive to said particulates; and

15

processing a waveform of said sensed charge signal to discriminate between different types of particulates and/or a background signal responsive to said waveform.

12. A method as claimed in claim 11 wherein said processing comprises discriminating one or more of volcanic ash, oil, and de-icer from one another and/or from said background signal.

20

13. A method as claimed in claim 11 or 12 wherein said processing comprises analysing a spectrum of said sensed charge signal to determine a change in said spectrum over time, wherein said discrimination is dependent on said change in said spectrum over time.

25

14. A method as claimed in any one of claims 11 to 13 wherein said processing comprises applying a classifier to said waveform to perform said discrimination.

30

15. A method as claimed in claim 14 wherein said classifier is an adaptive classifier, the method further comprising determining or adapting said classifier to improve said discrimination.

35

16. A method as claimed in any one of claims 11 to 15 wherein said performance metric is determined responsive to a correlation between characteristics of said waveform over time.

17. A method as claimed in any one of claims 11 to 16, wherein said discrimination comprises a determination of whether or not a target type of particulates is present above a threshold level.

5

18. A method as claimed in any one of claims 1 to 17 wherein said particulate charge sensor comprises:

an electrically conducting particulate charge collection device;

an electrically insulating support for mounting said collection device in a duct;

10 and

a charge sensing system having an input electrically coupled to said particulate charge collection device;

wherein said charge sensing system is configured to provide said sensed charge signal in response to the level of charge on said charge collection device.

15

19. A method as claimed in claim 18 wherein said charge collection device comprises a conducting mesh or grid.

20. A method as claimed in claim 18 or 19 wherein said particulate charge collection device comprises a pair of charge collection electrodes at different transverse locations in said gas flow, the method further comprising capturing a pair of said waveforms, one from each of said pair of electrodes, and performing said determining/discriminating dependent on said pair of waveforms.

21. A system for monitoring the performance of an engine, the system comprising:
a gas inlet providing a gas flow from a gaseous output of an engine to be monitored;

a particulate charge sensor to sense an electrical charge on particulates in said gas flow to provide a sensed charge signal; and

30

a processor to process a waveform of said sensed charge signal to determine a performance metric of said engine.

22. A sensing system for an aircraft, the system comprising:

a particulate charge sensor, the particulate charge sensor comprising: an

35

electrically conducting particulate charge collection device, an electrically insulating

support for mounting said collection device in an air duct, and a charge sensing system having an input electrically coupled to said particulate charge collection device, wherein said charge sensing system is configured to determine a level of charge on said particulate charge collection device to determine the presence of particulates in said air duct; and

a processor to process a waveform of a charge sensing signal from said charge sensing system of said particulate charge sensor to discriminate between different types of particulates and/or a background signal.

23. A sensing system as claimed in claim 22 wherein said processor is configured to discriminate, from one another and/or from said background signal, one or more of: volcanic ash, oil, de-icer, fuel, and one or more combustion residues.

24. A sensing system as claimed in claim 22 or 23 wherein said particulate charge collection device comprises two electrodes, the sensing system further comprising, upstream of said sensor, a particulate charging system, and an electric field generation system to deflect charges particulates towards one or other of said electrodes; and wherein said processor is configured to process waveforms from both said electrodes to discriminate particulates.

25. A method or system as recited in any preceding claim wherein said processing of said waveform comprises determining a polarity of said sensed charge signal to discriminate between different types of particulate for said performance monitoring/sensing.

26. A method or system as recited in any preceding claim configured to sense said charge using an electrically conducting mesh or grid.

27. A particulate analysis system, the system comprising:
a particulate charge sensor, the particulate charge sensor comprising: an electrically conducting particulate charge collection device, an electrically insulating support for mounting said collection device in a duct, and a charge sensing system having an input electrically coupled to said particulate charge collection device, wherein said charge sensing system is configured to determine a level of charge on said

particulate charge collection device to determine the presence of particulates in said air flow; and

a signal processor, coupled to an output of said charge sensing system of said particulate sensor, wherein said signal processor is configured to analyse a time-series charge signature and/or charge polarity from said particulate sensor to discriminate between different types of particle providing charge to said particulate charge collection device.

28. A particulate analysis system as claimed in claim 27 wherein said analysing comprises determining a frequency spectrum of said time series charge signature.

29. A particulate analysis system as claimed in claim 27 or 28 wherein said analysing comprises identifying a correlation between one or more characteristics of said time series charge signature over time.

30. A volcanic ash sensor for an aircraft, the sensor comprising:
an electrically conducting ash charge collection device;
an electrically insulating support for mounting said collection device in an air duct; and

a charge measurement system having an input electrically coupled to said ash charge collection device;

wherein said charge measurement system is configured to determine a level of charge on said ash charge collection device to determine the presence of volcanic ash in said air flow; and

wherein a surface of said ash charge collection device has a plurality of ribs, steps, and/or openings;

further comprising an ash charging electrode for mounting upstream of said ash charge collection device in said air flow, and a particle charging electrical power supply coupled to said ash charging electrode to apply a voltage to said charging electrode charging said ash; and

wherein said electrically conducting ash charge collection device comprises a pair of separate adjacent collection electrodes, wherein said charge measurement system is configured to determine a differential said level of charge on said pair of collection electrodes to determine the presence of volcanic ash in said air flow;

further comprising a signal processor, coupled to an output of said charge sensing system of said particulate sensor, configured to analyse charge measurements from said pair of electrodes dependent on a value of $\frac{S_+ - S_-}{S_+ + S_-}$ where S_+ is a charge measurement from a first of said electrodes and S_- is a charge measurement from a second of said electrodes.

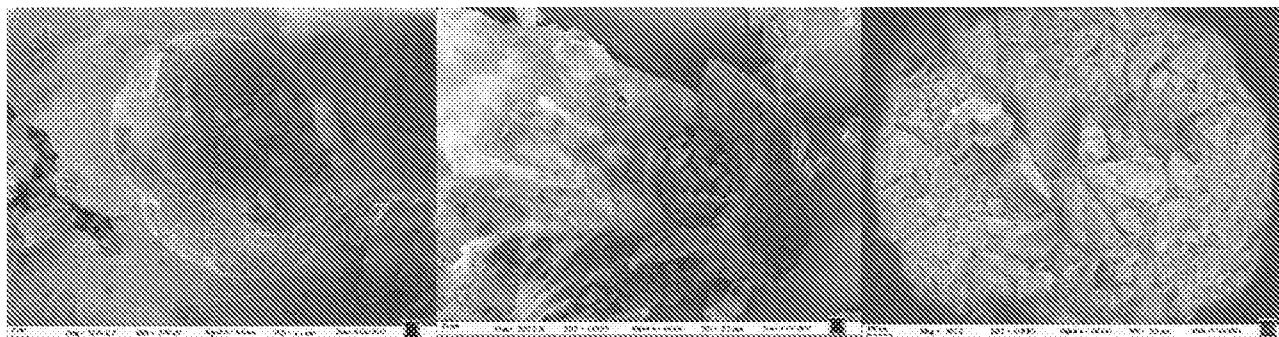


Figure 1a

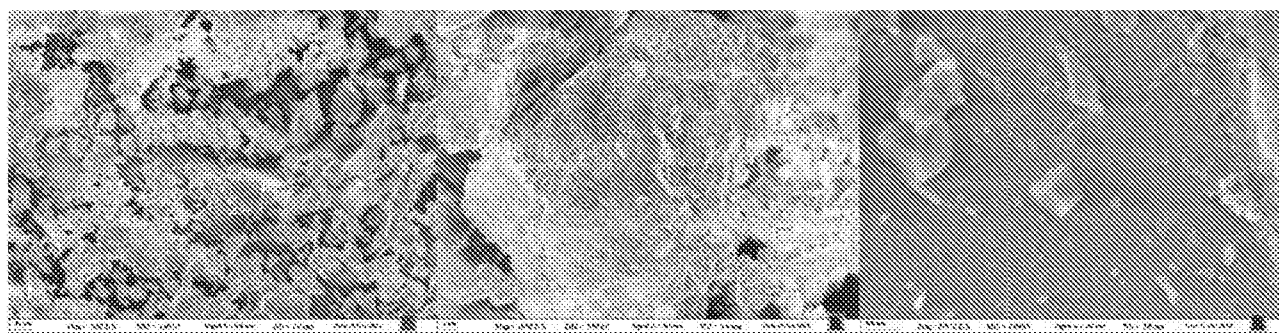


Figure 1b

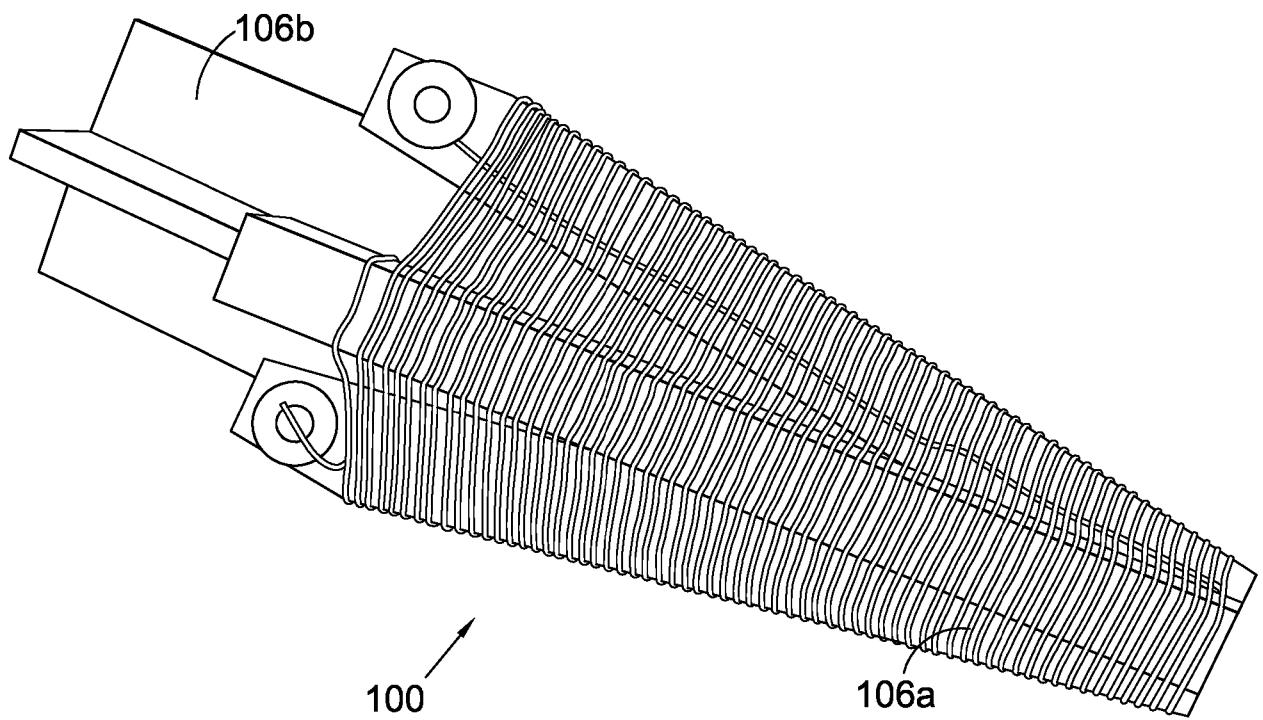


Figure 2

3/24

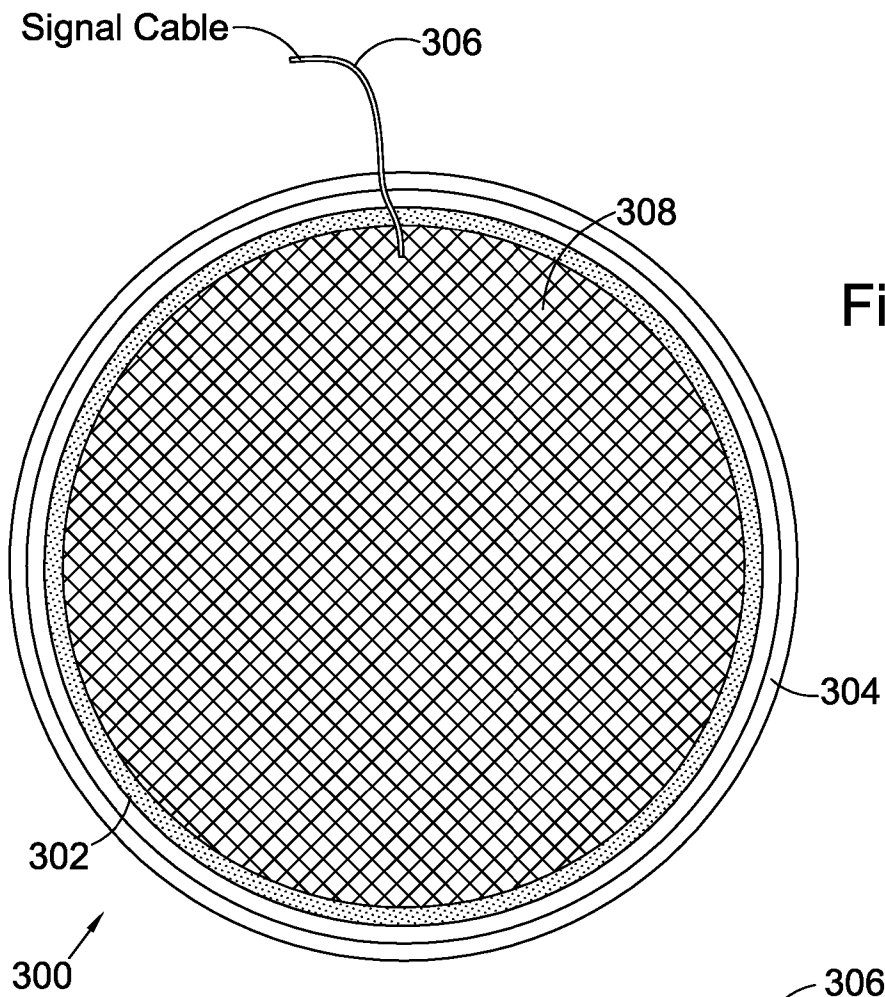


Figure 3a

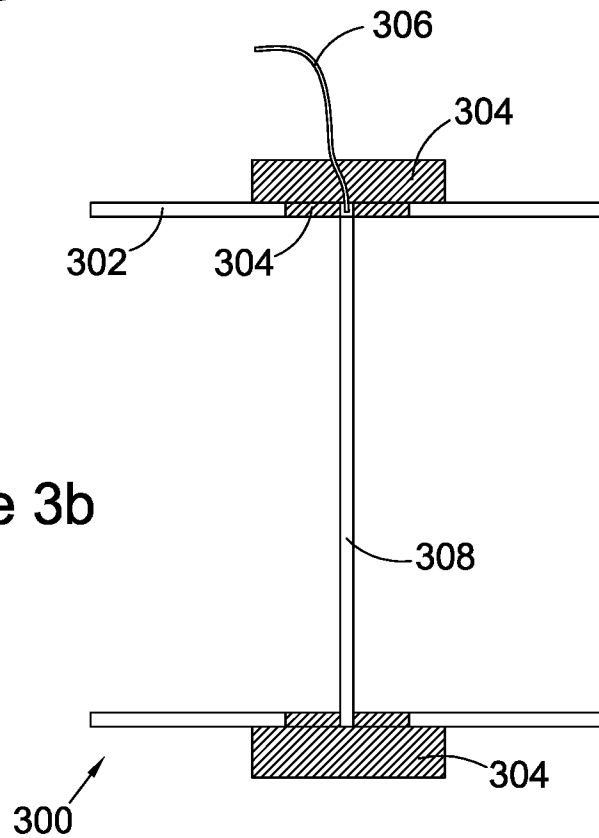


Figure 3b

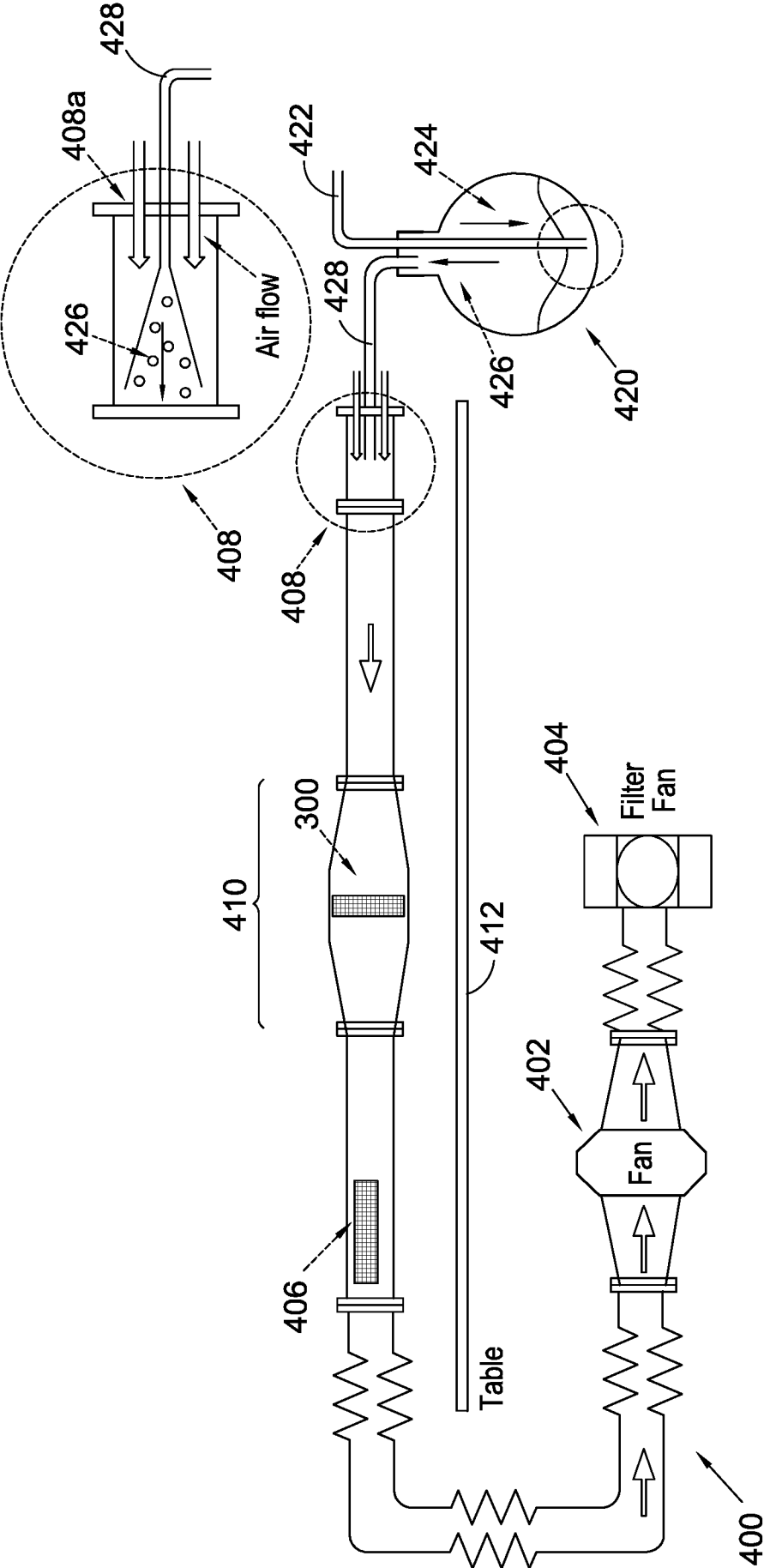


Figure 4

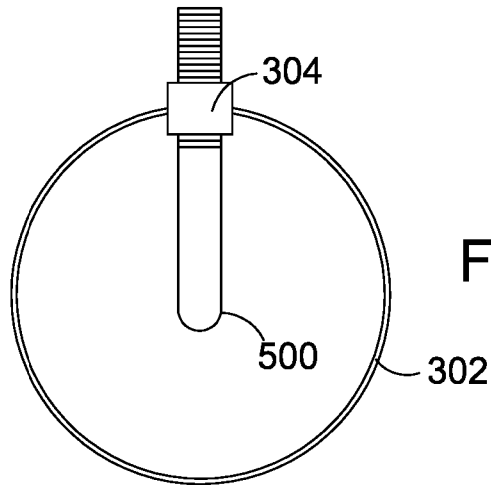


Figure 5a

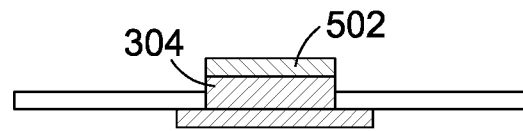
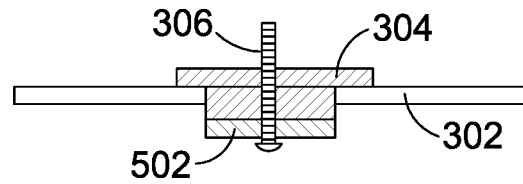
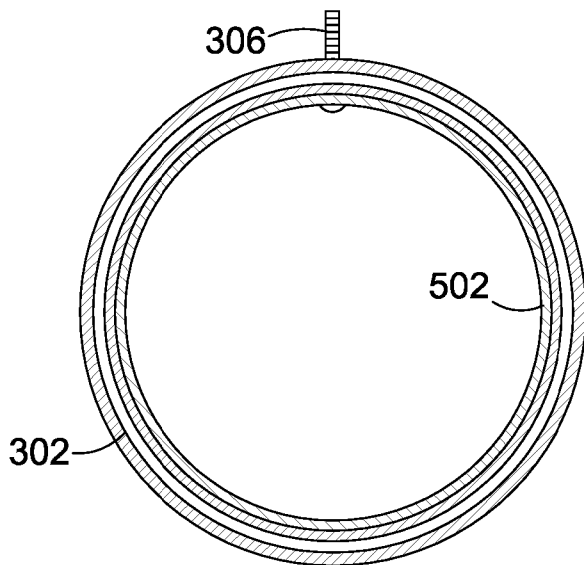


Figure 5b

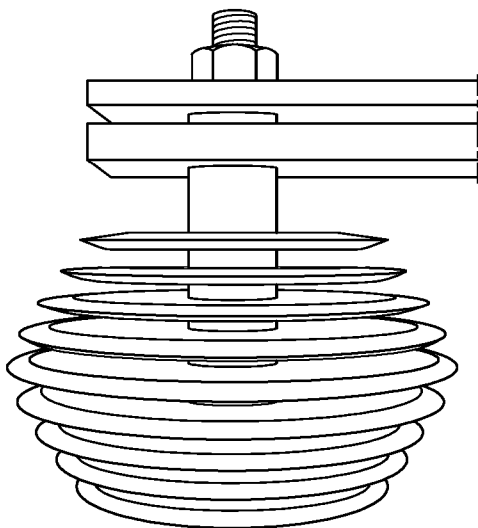


Figure 5c

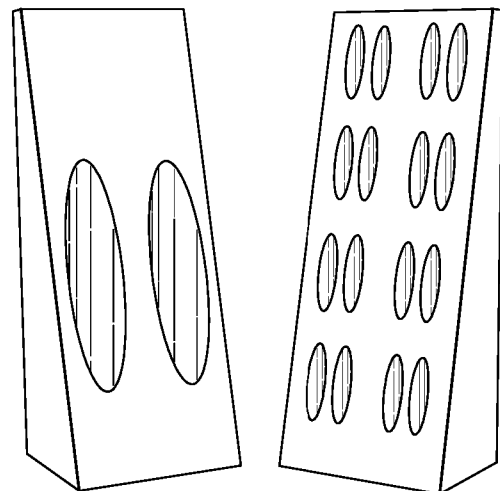


Figure 5d

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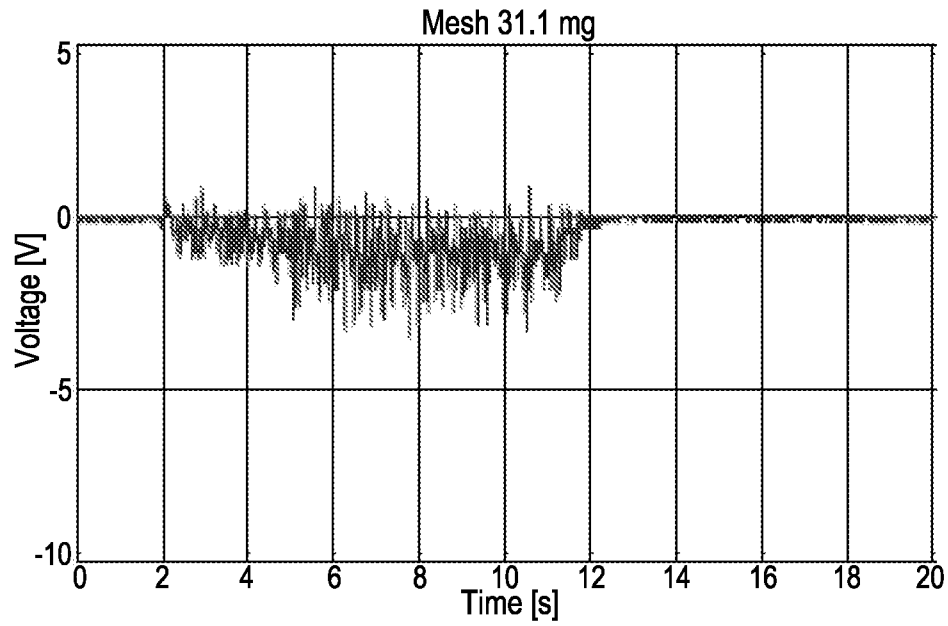


Figure 6a

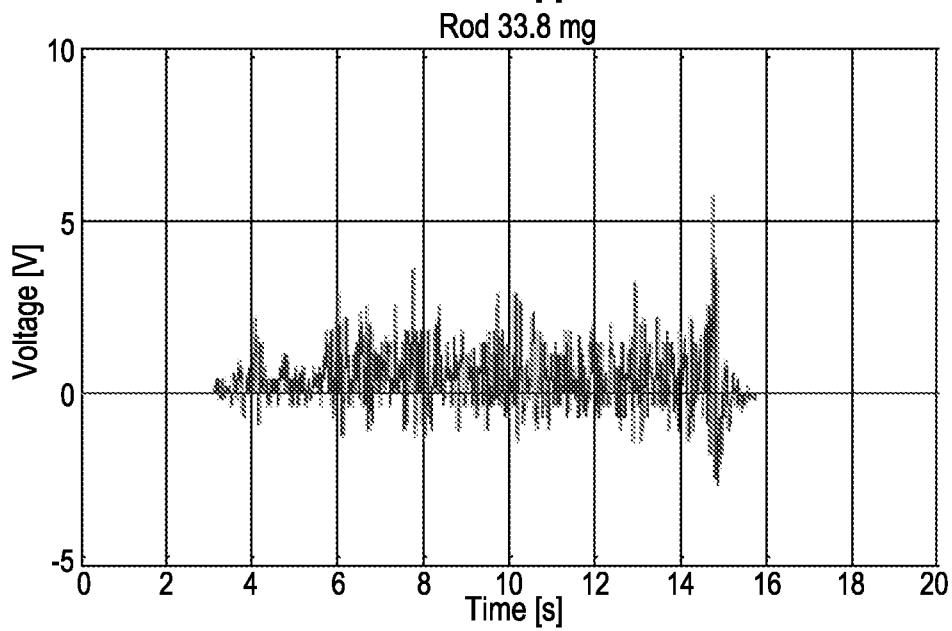


Figure 6b

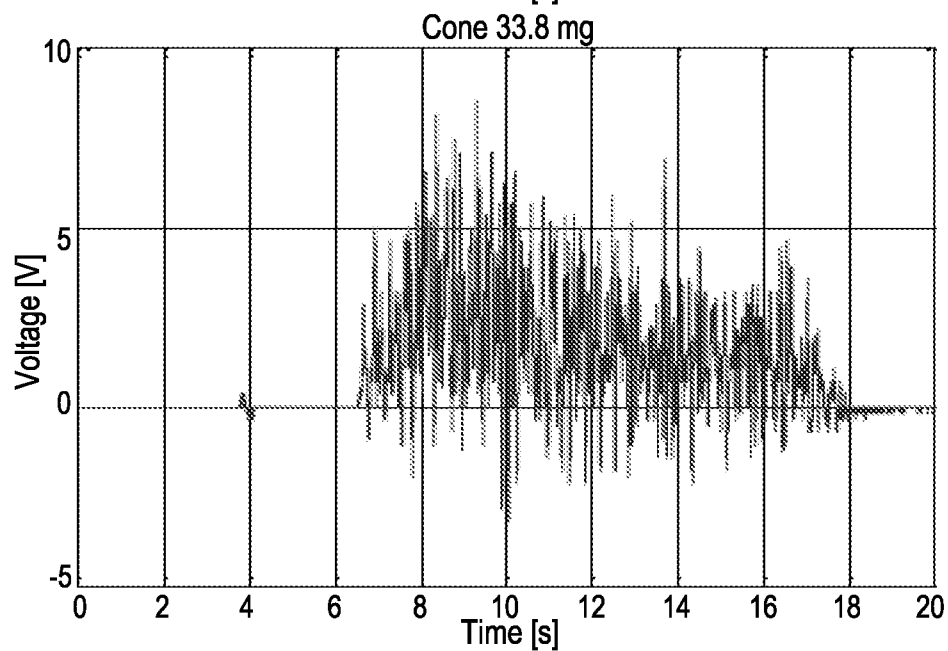


Figure 6c

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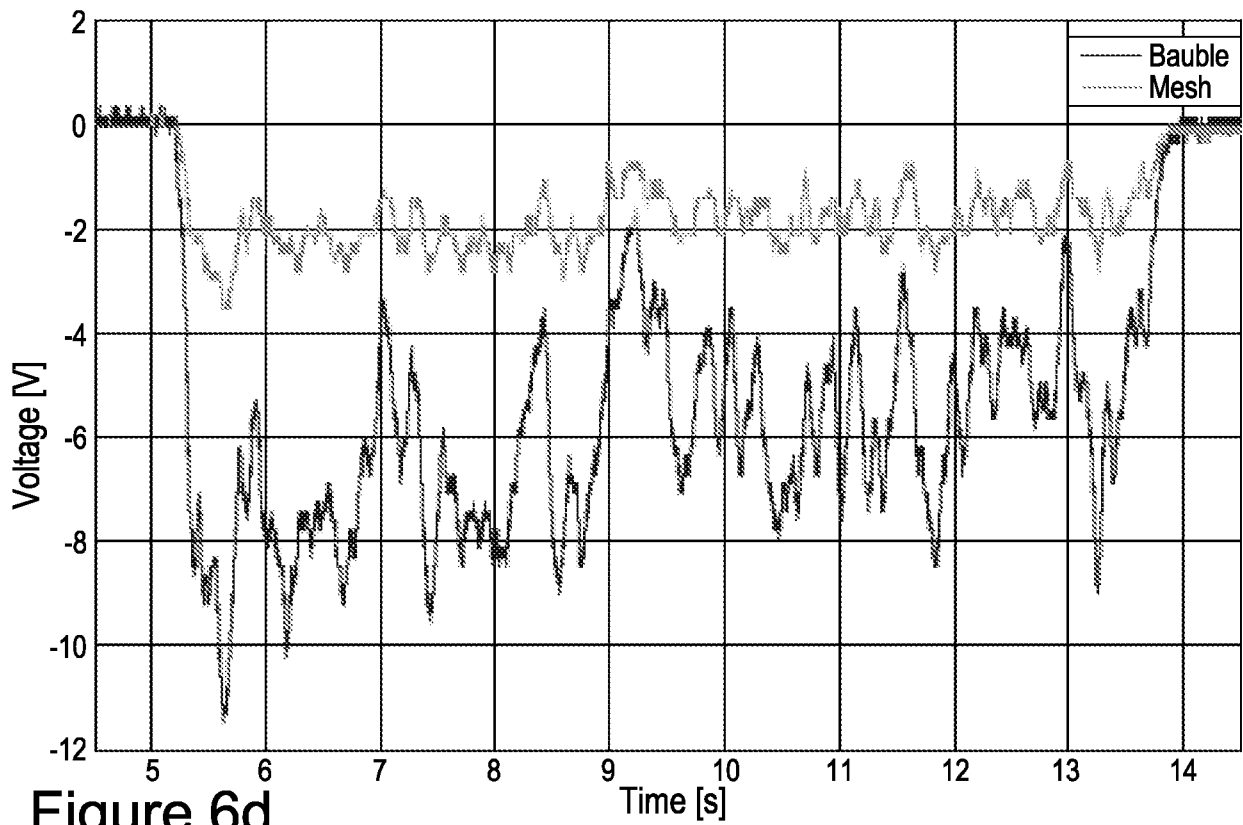


Figure 6d

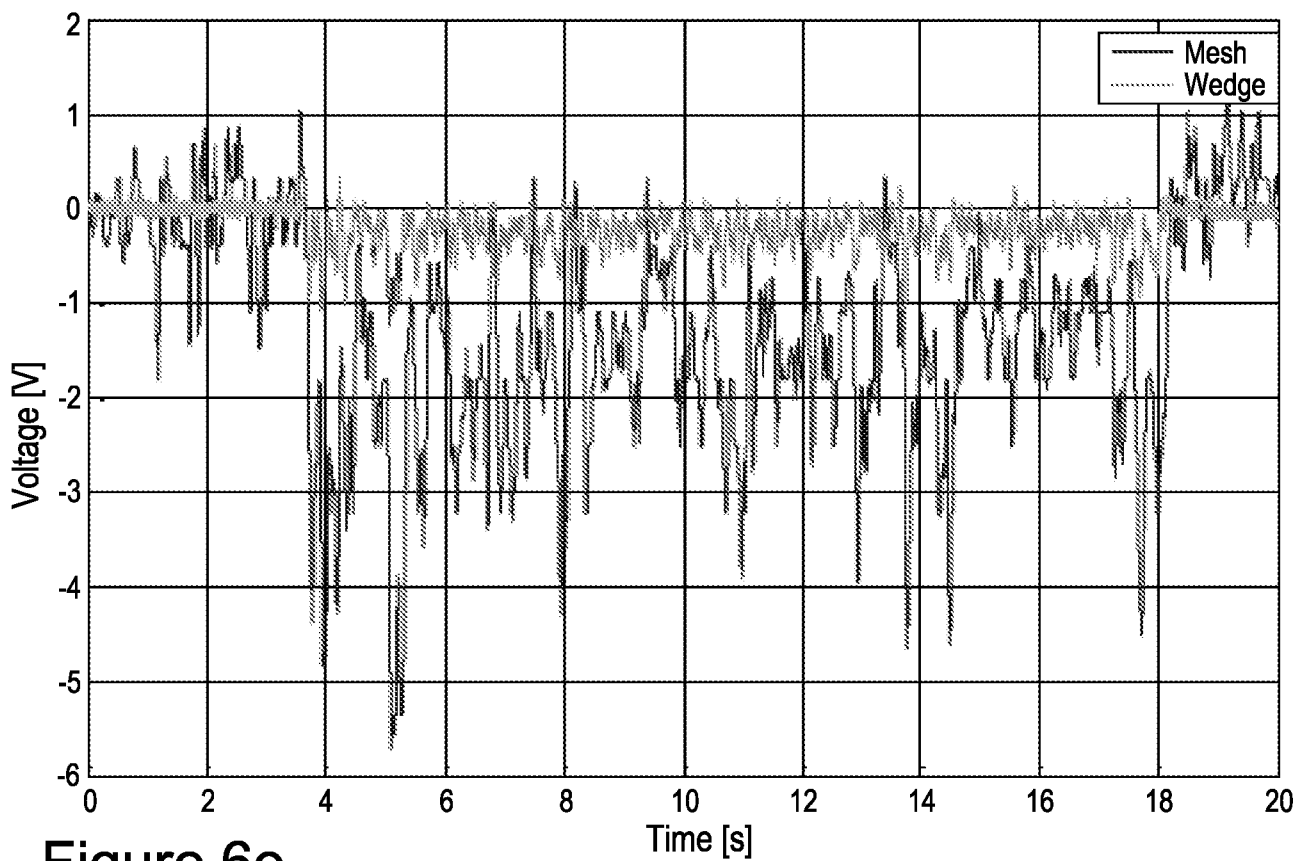


Figure 6e

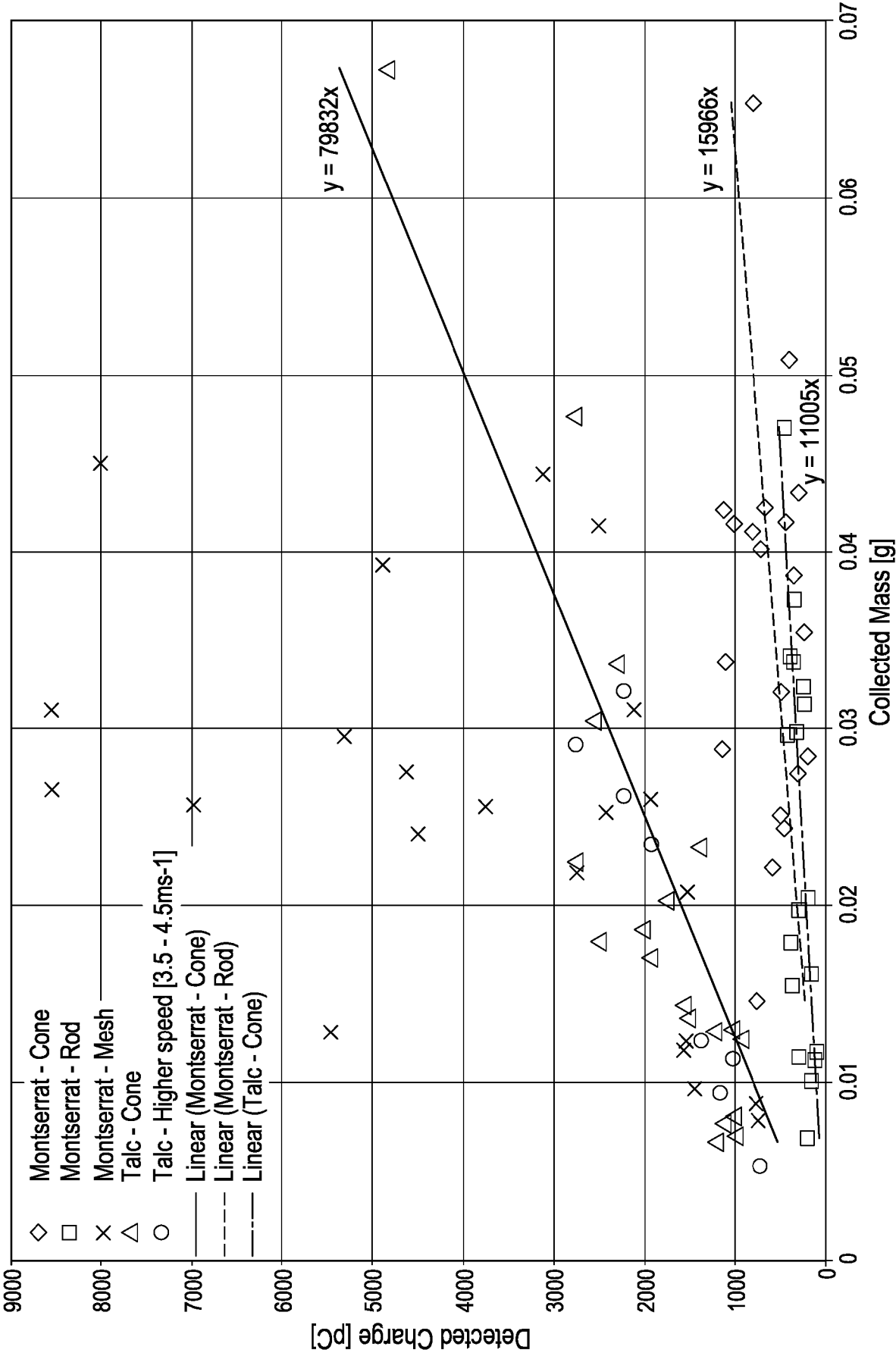


Figure 7

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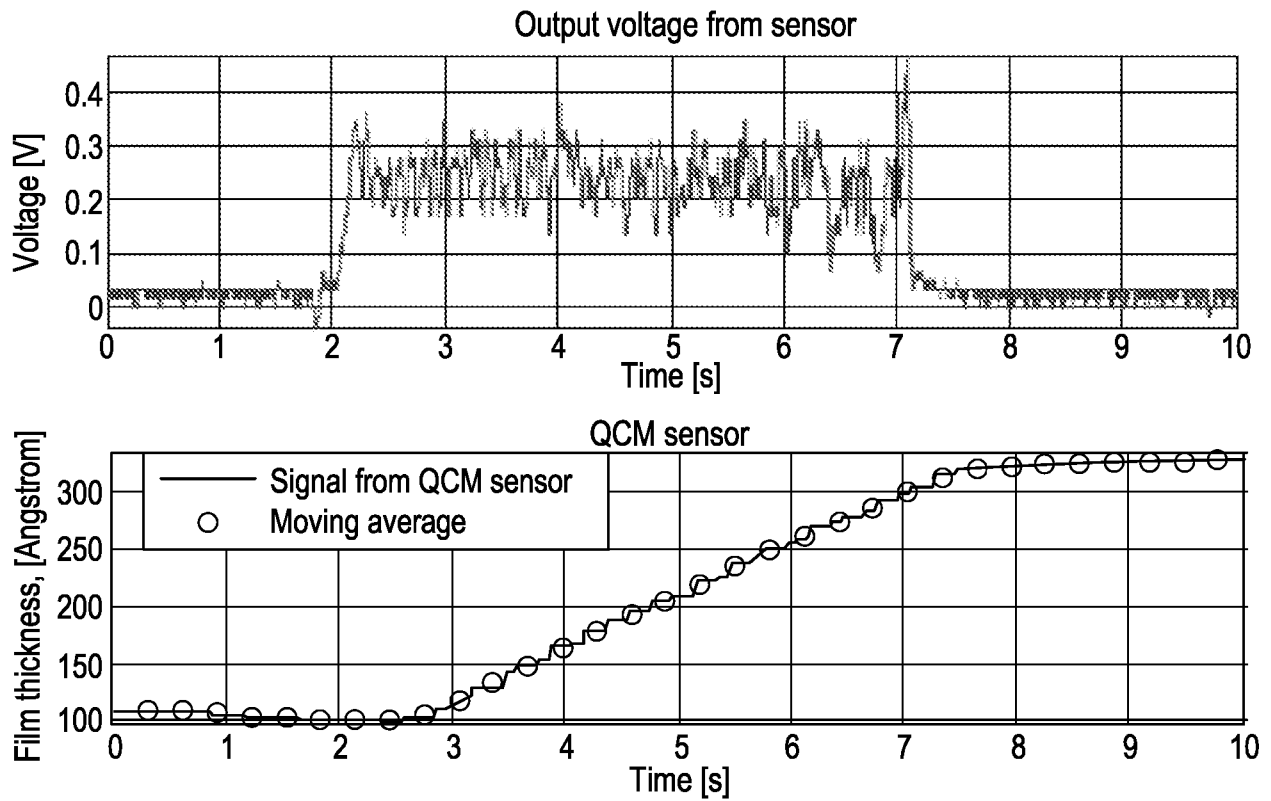


Figure 8a

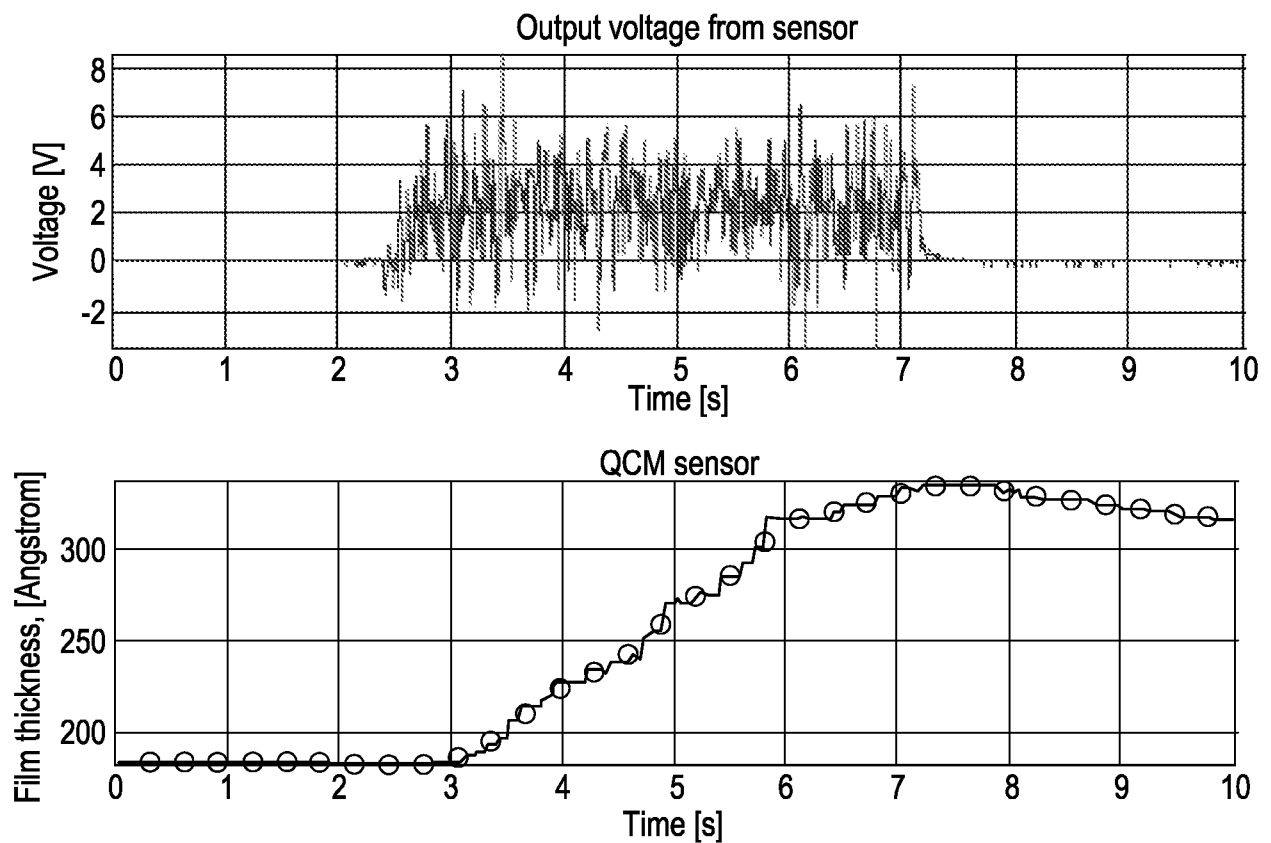


Figure 8b

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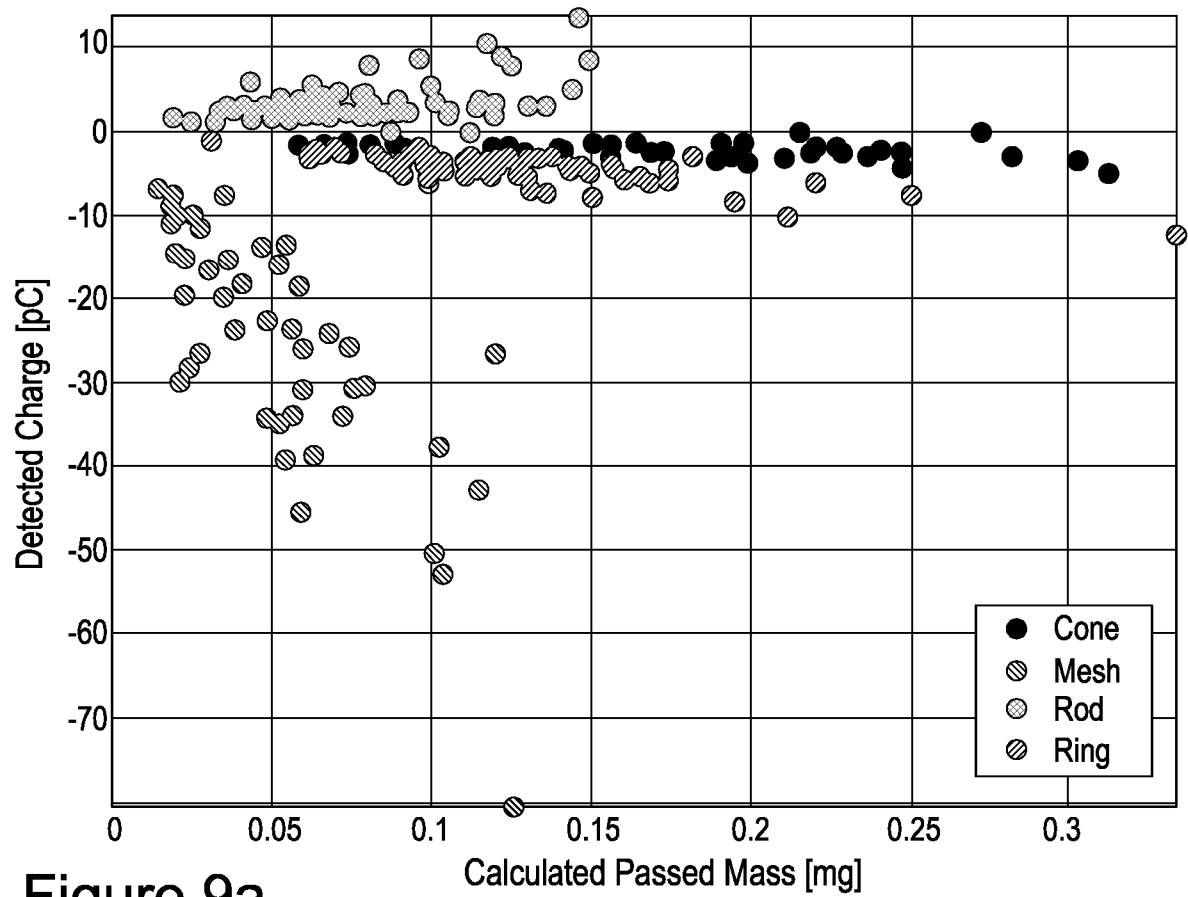


Figure 9a

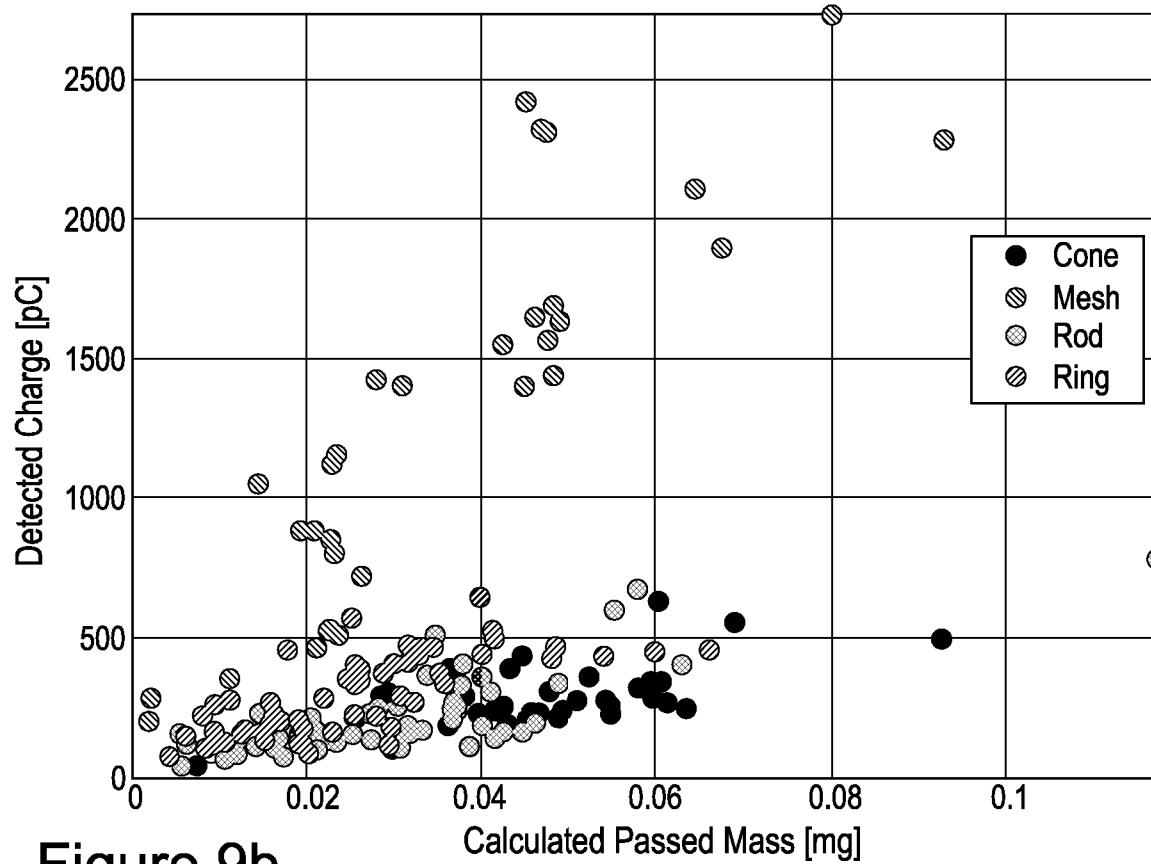


Figure 9b

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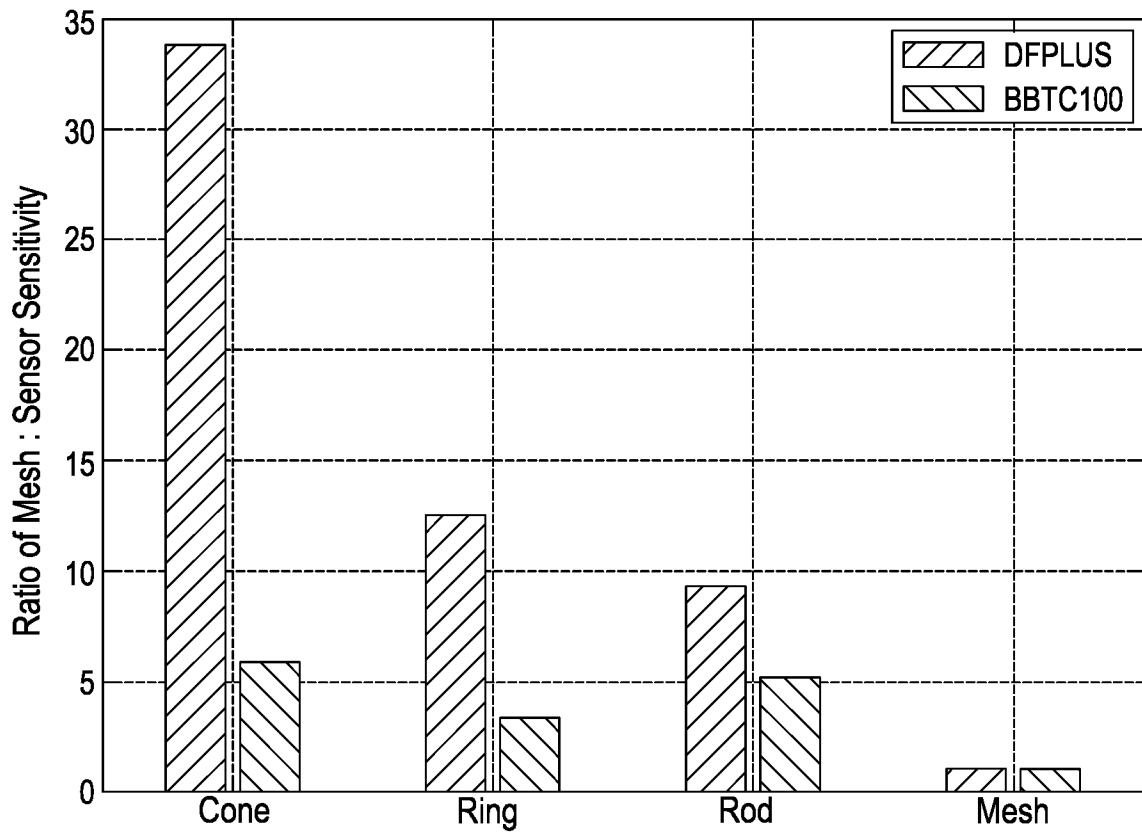


Figure 10a

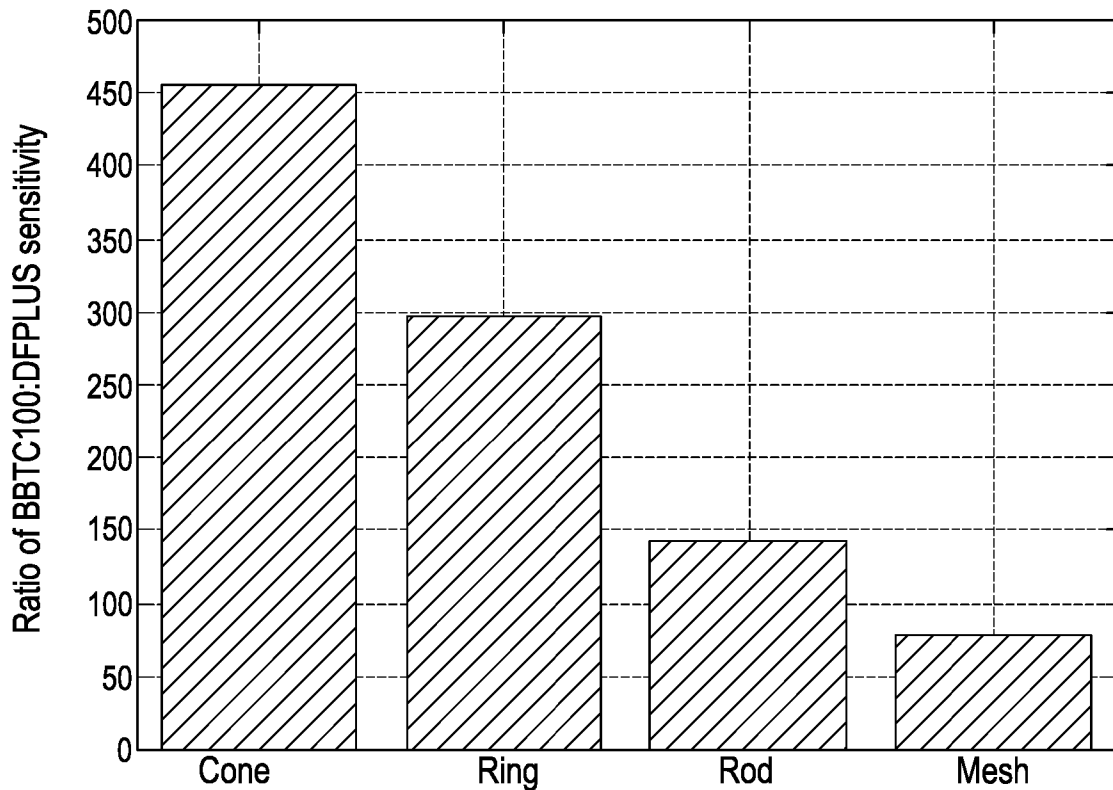


Figure 10b

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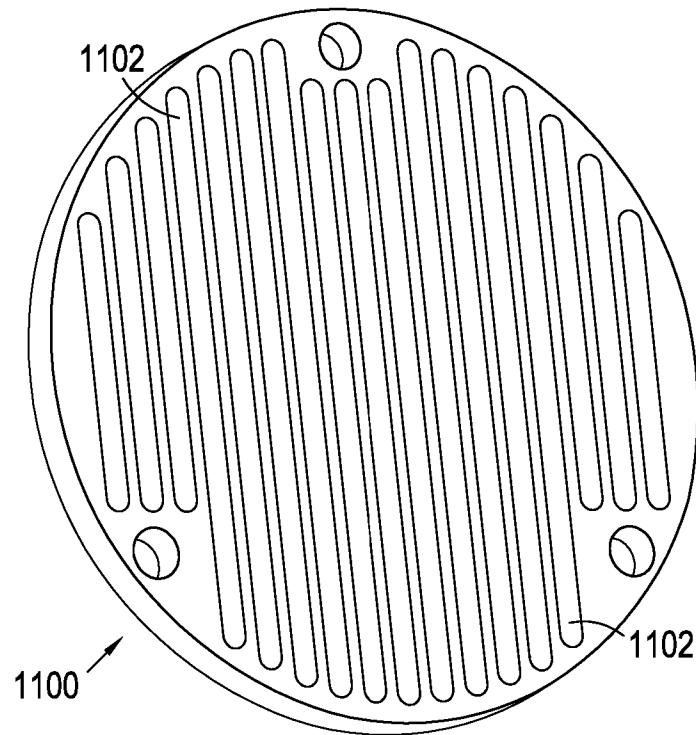


Figure 11a

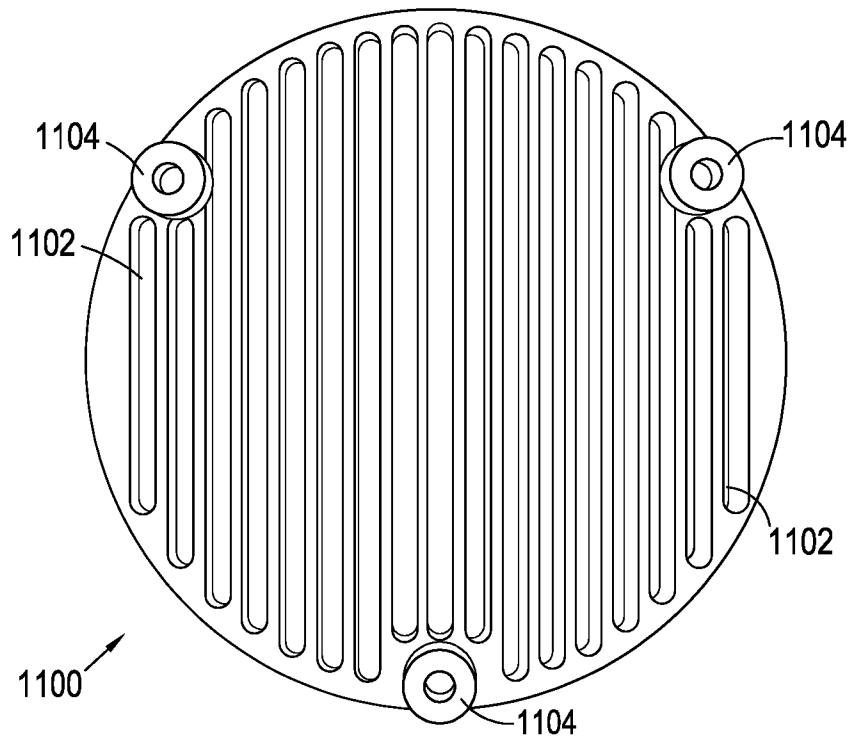
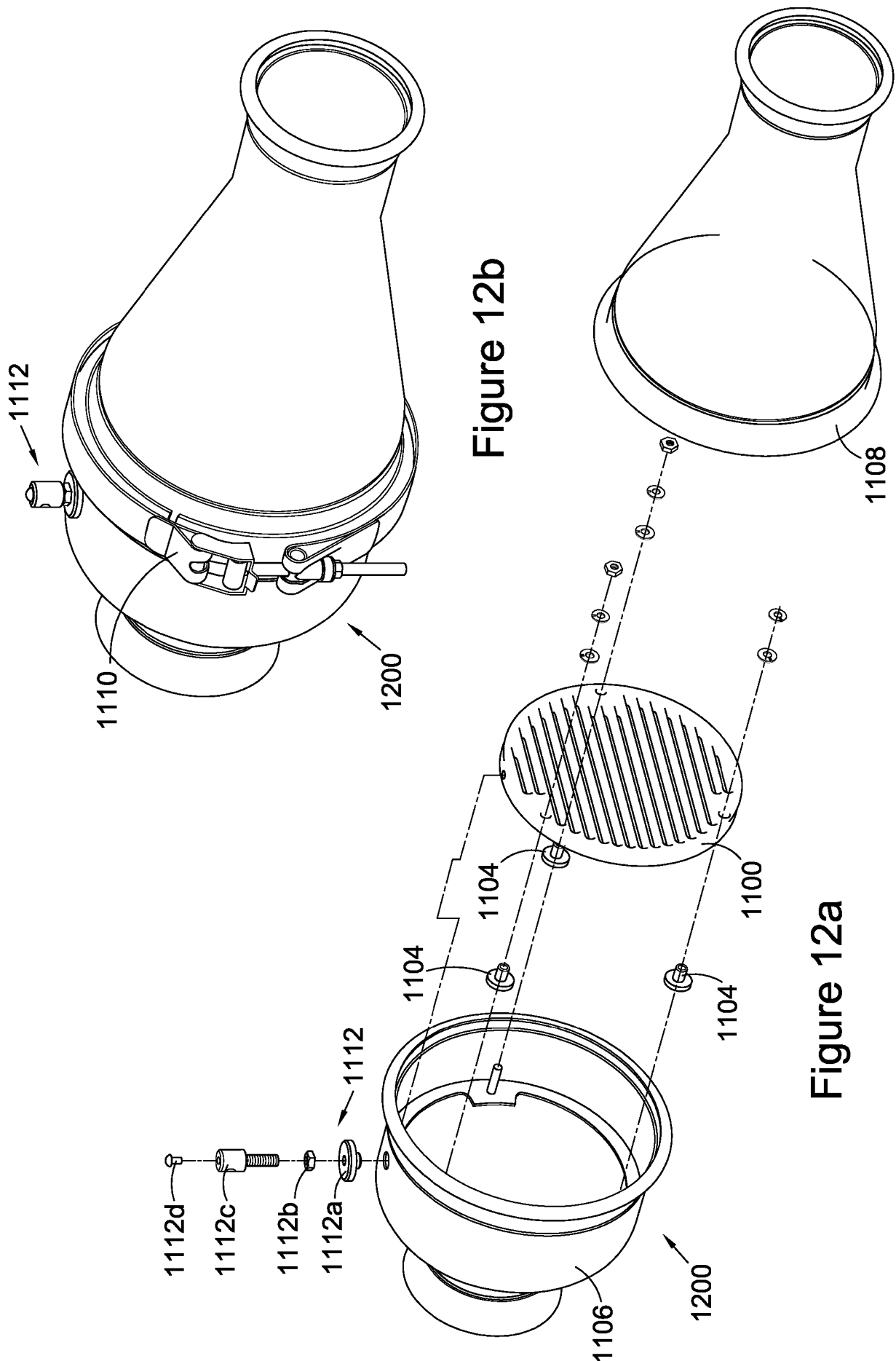


Figure 11b



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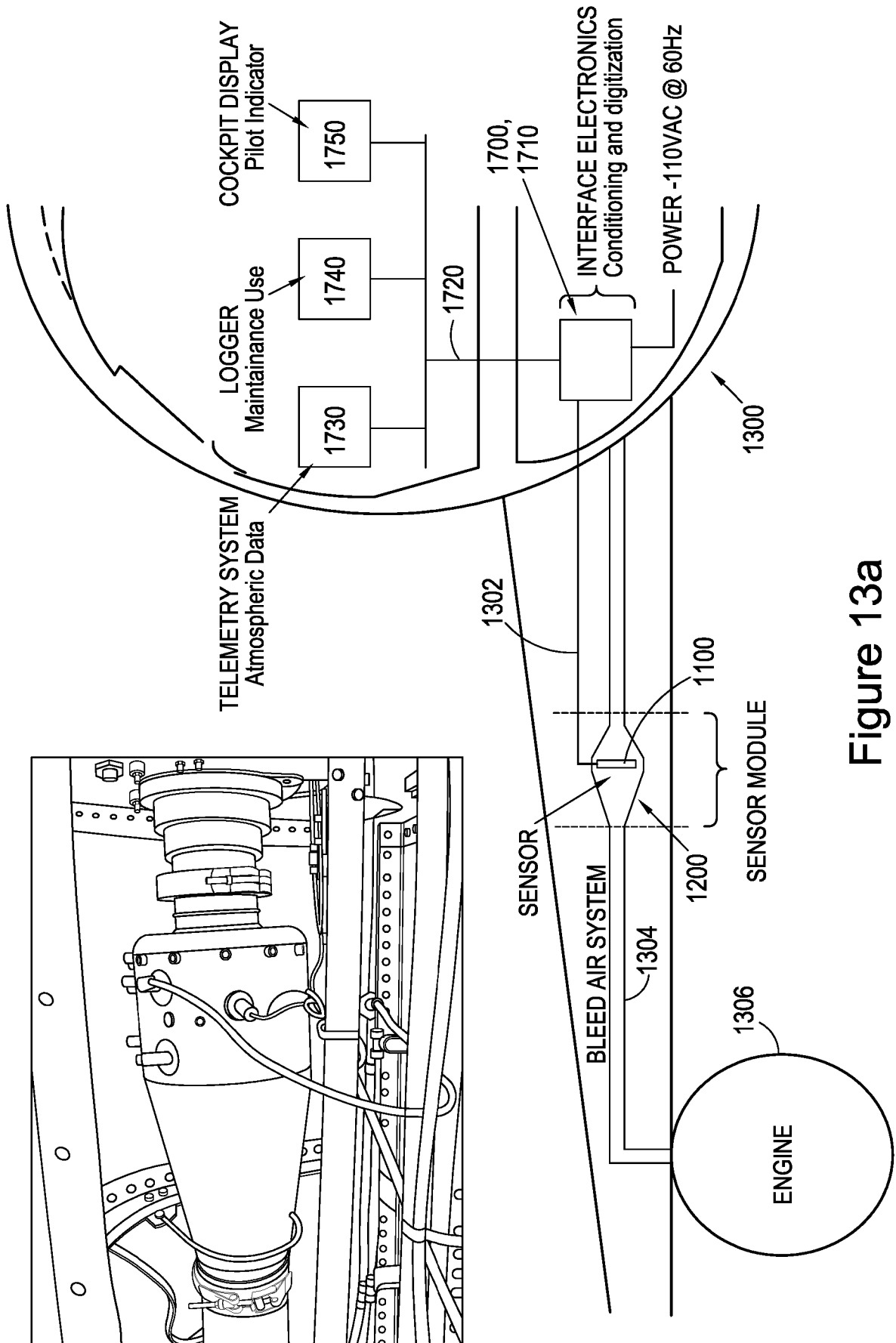


Figure 13a

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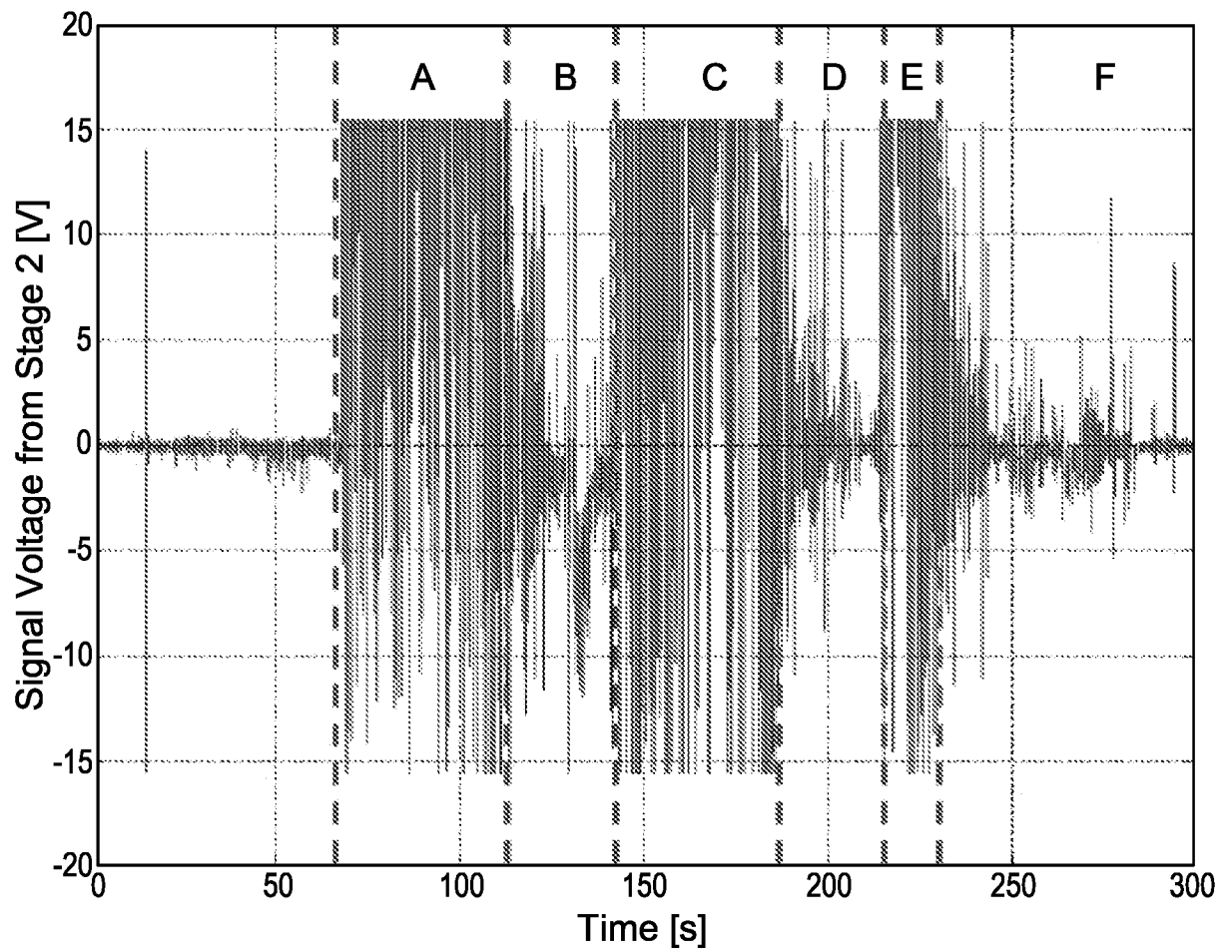


Figure 13b

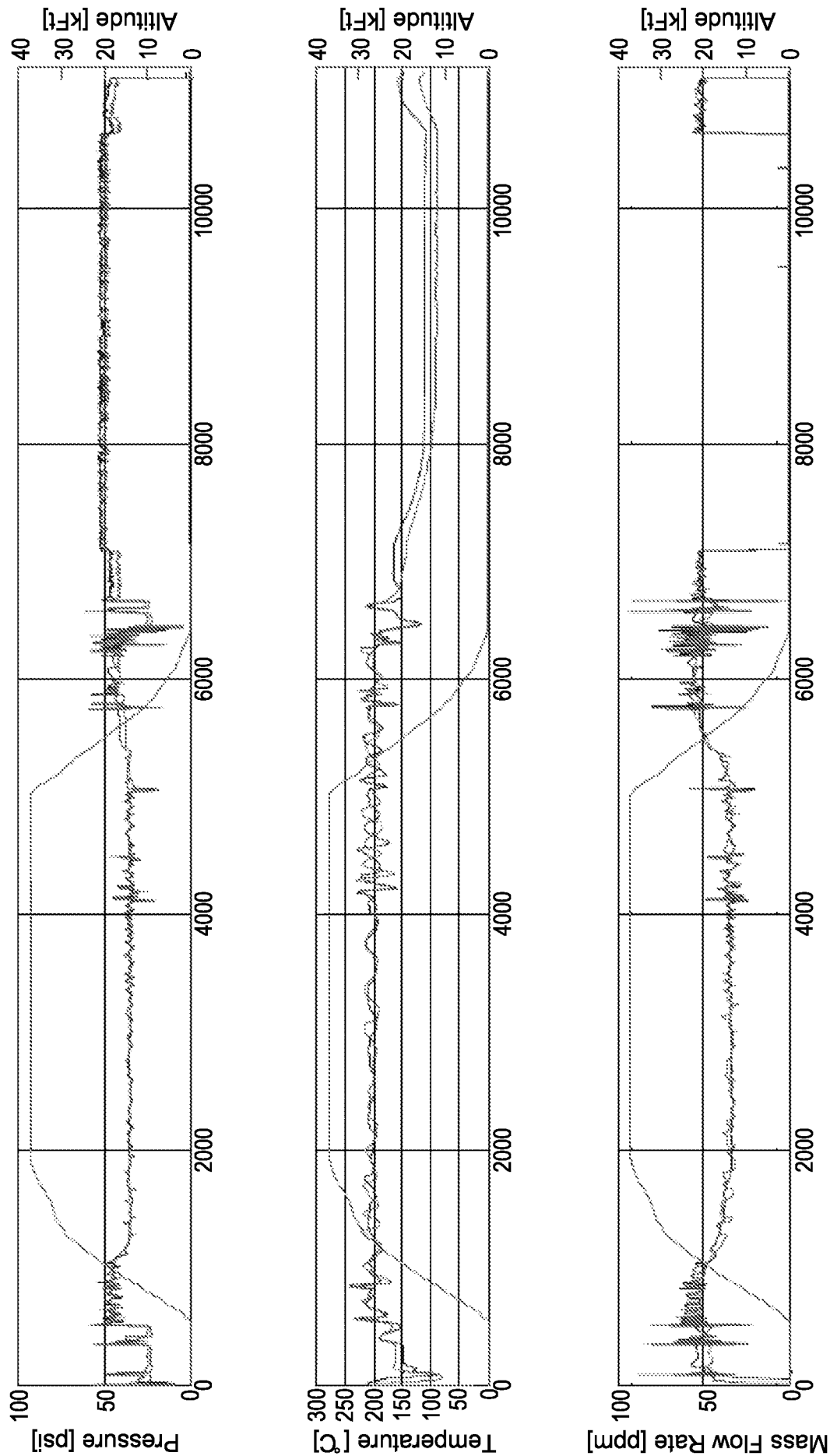
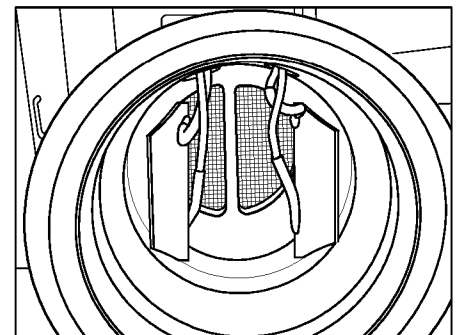
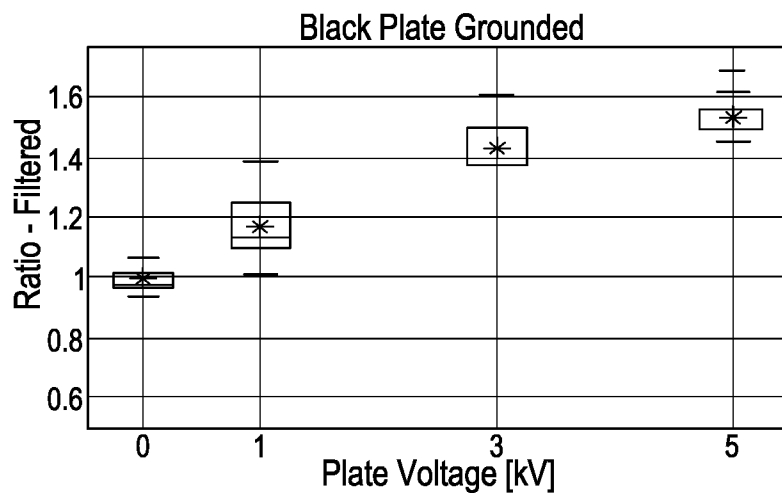
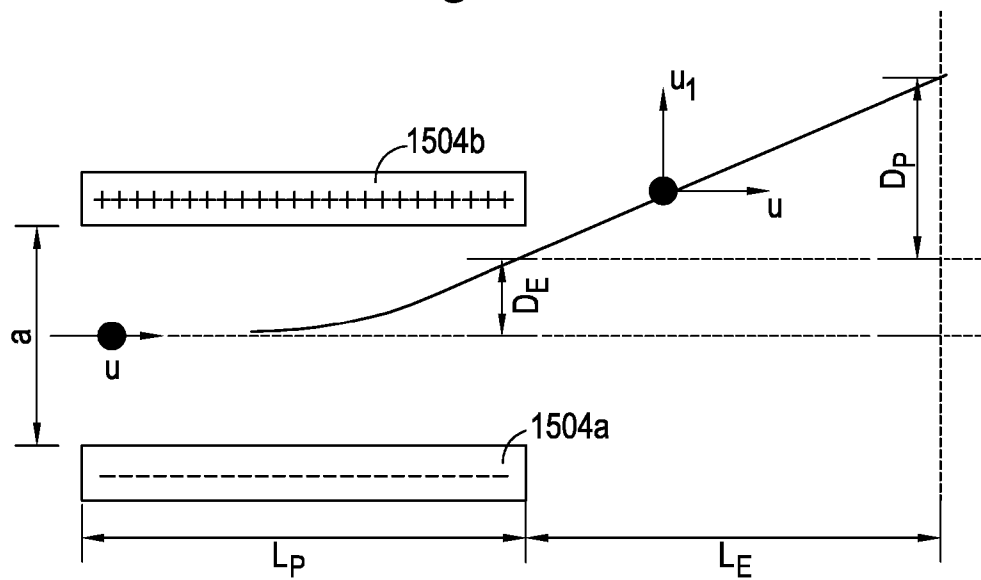
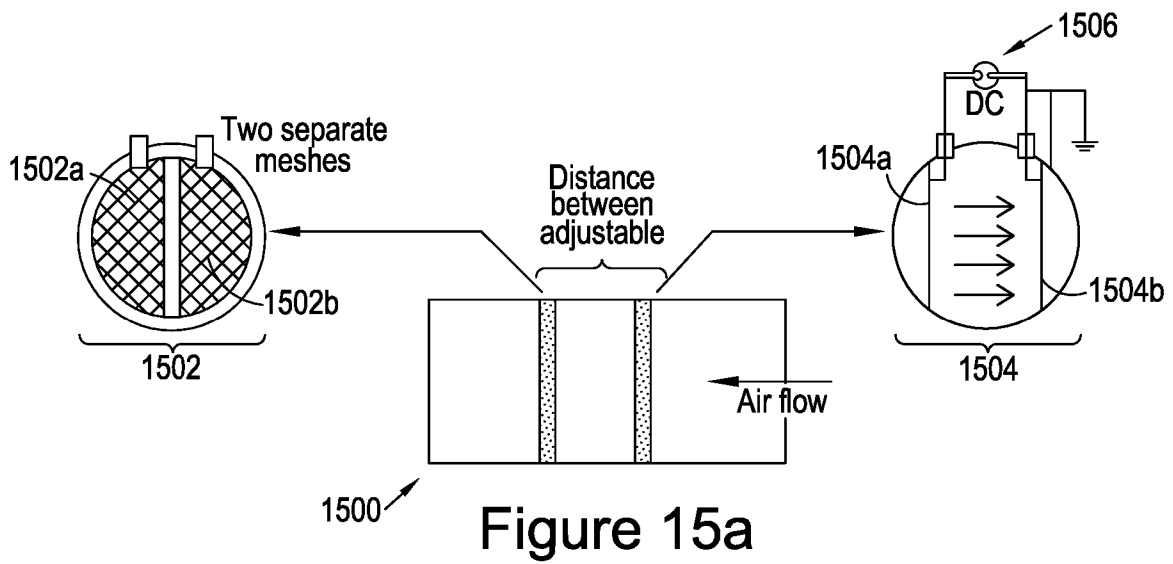


Figure 14

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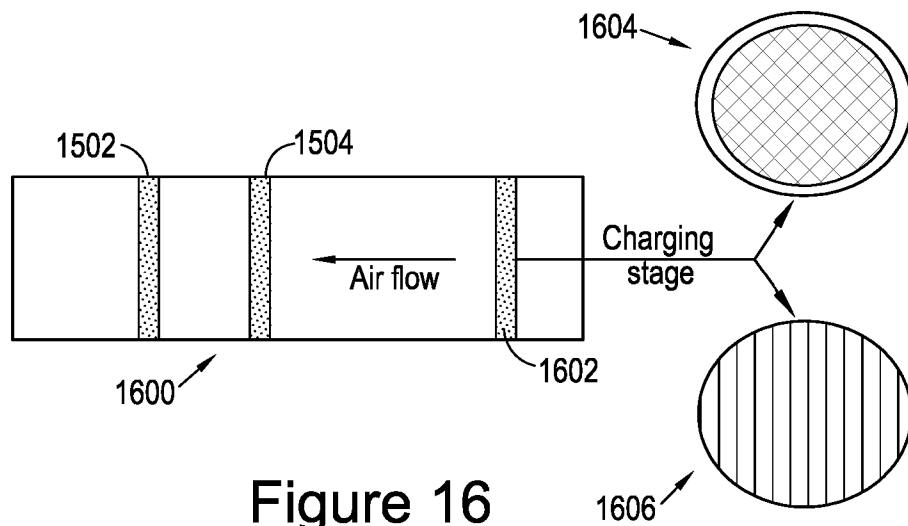


Figure 16

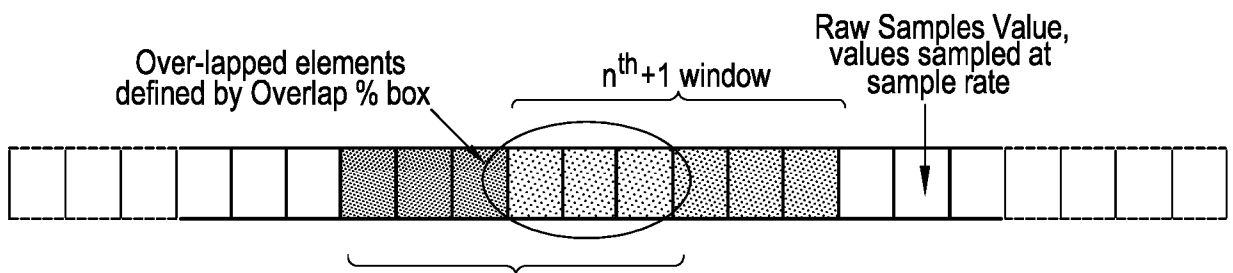


Figure 18a

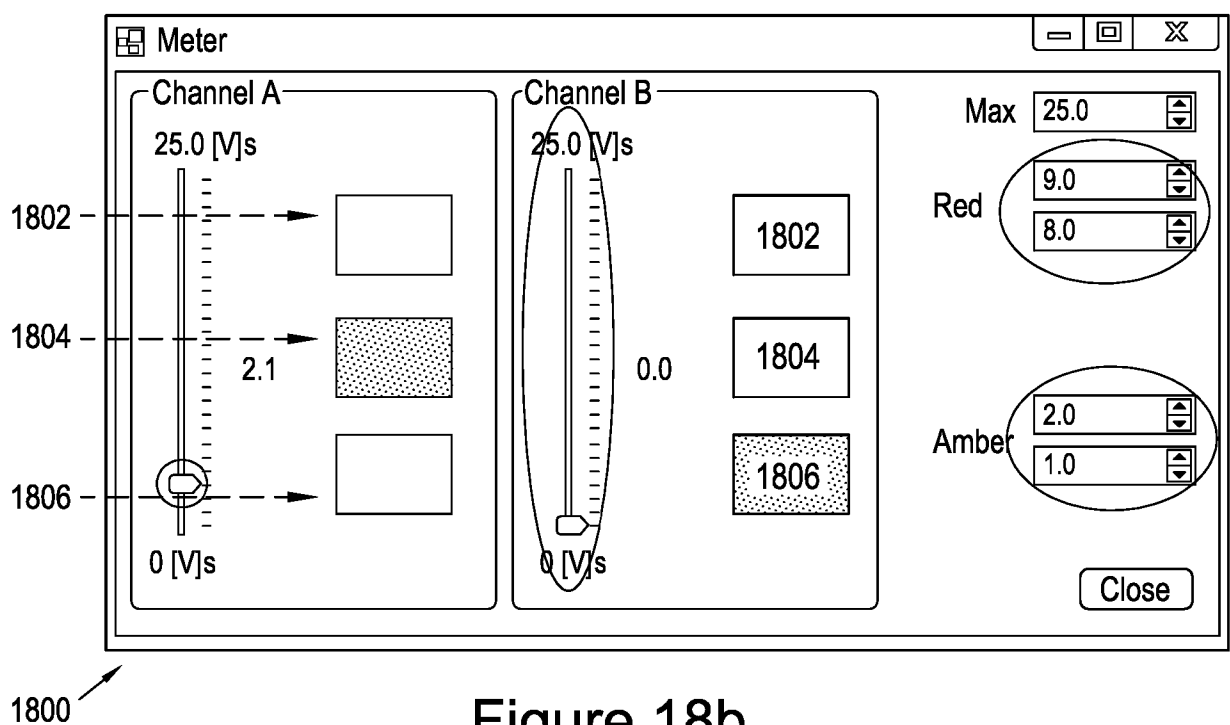


Figure 18b

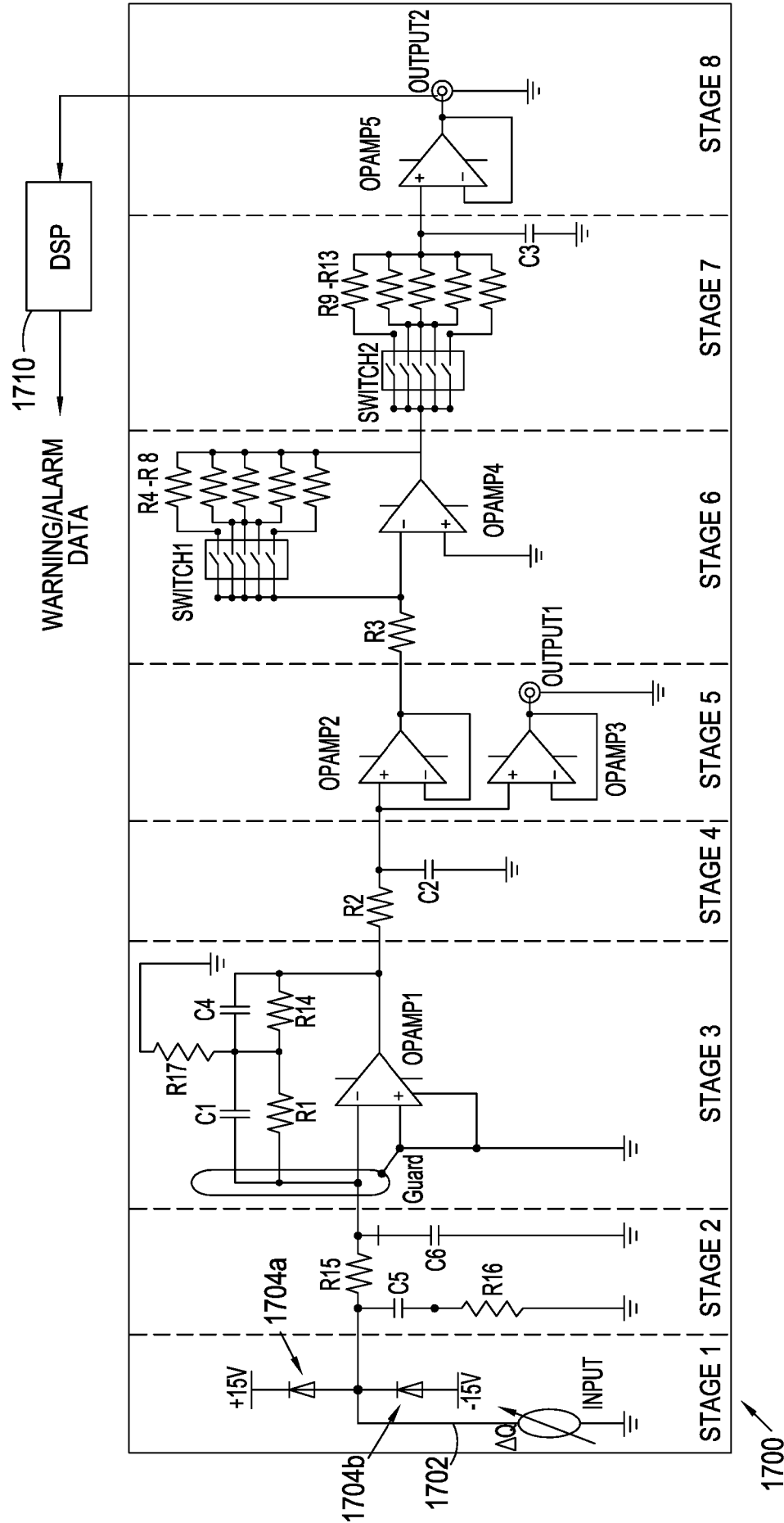


Figure 17

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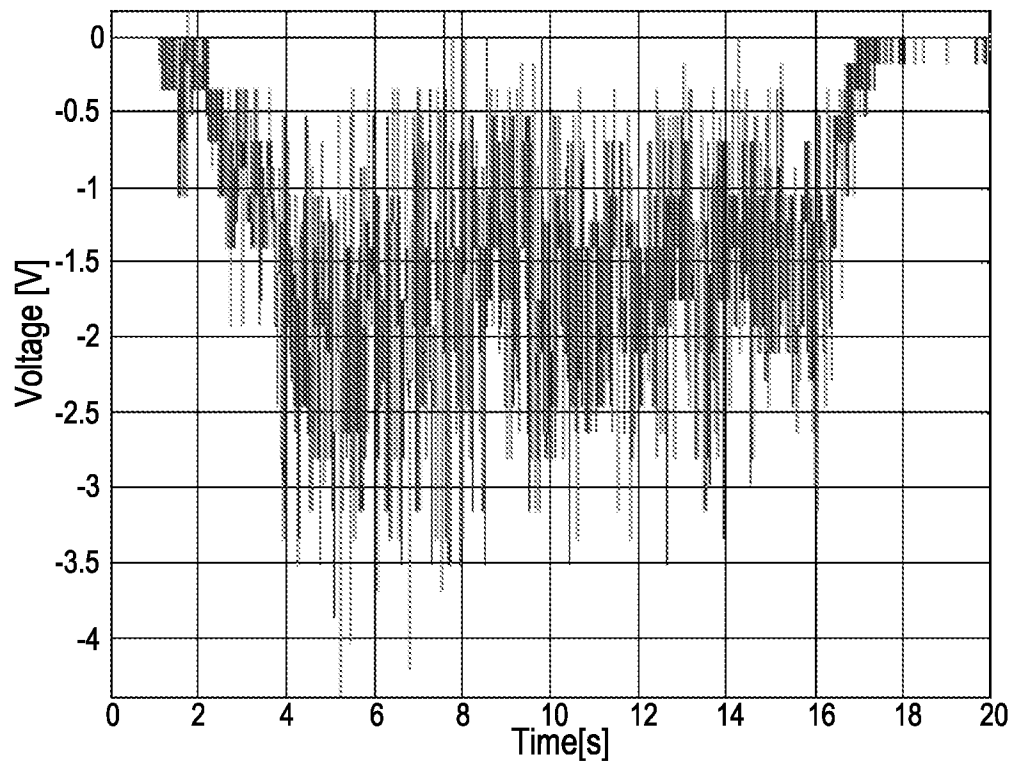


Figure 19a

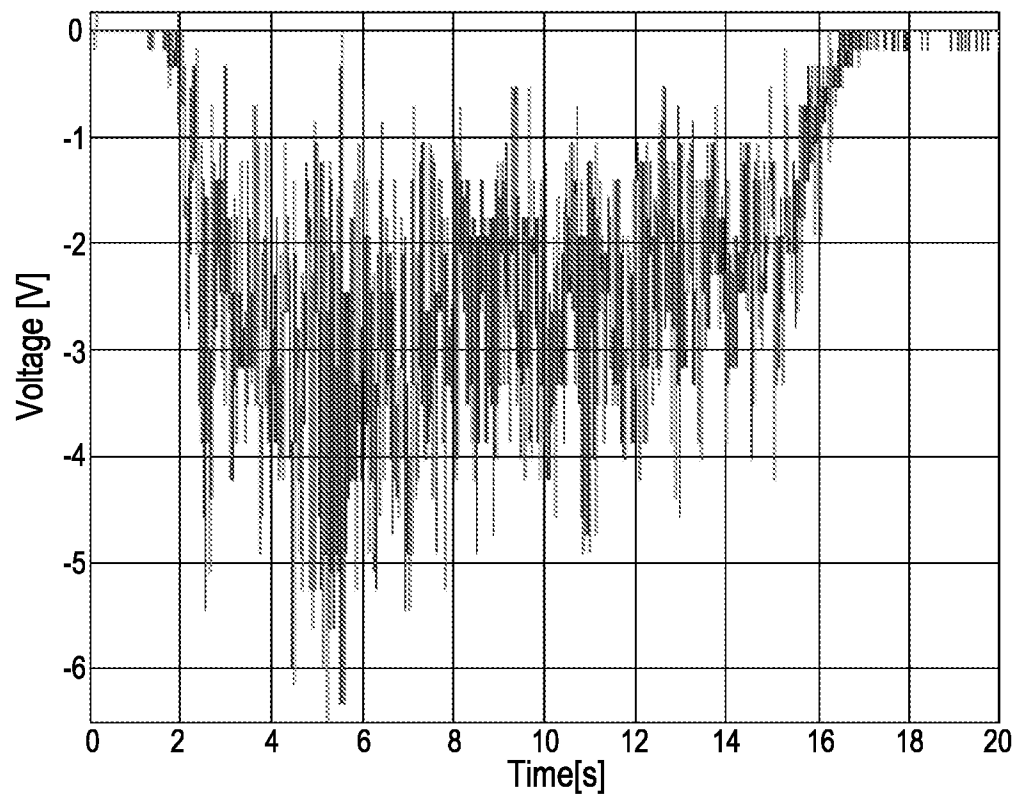


Figure 19b

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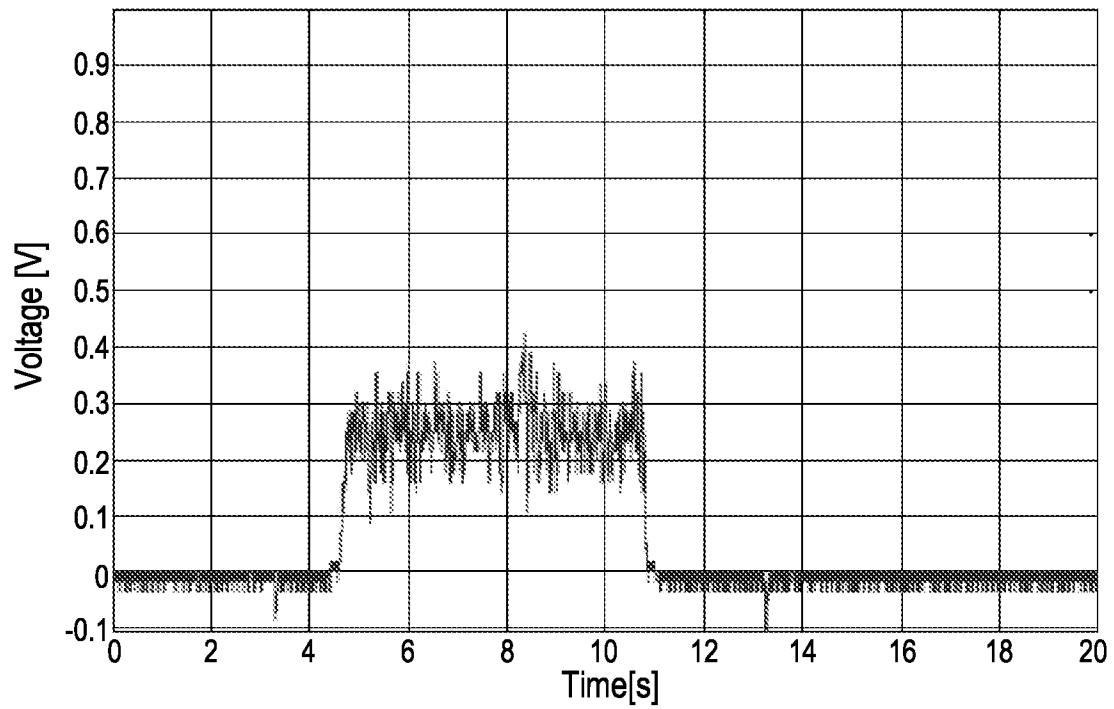


Figure 20a

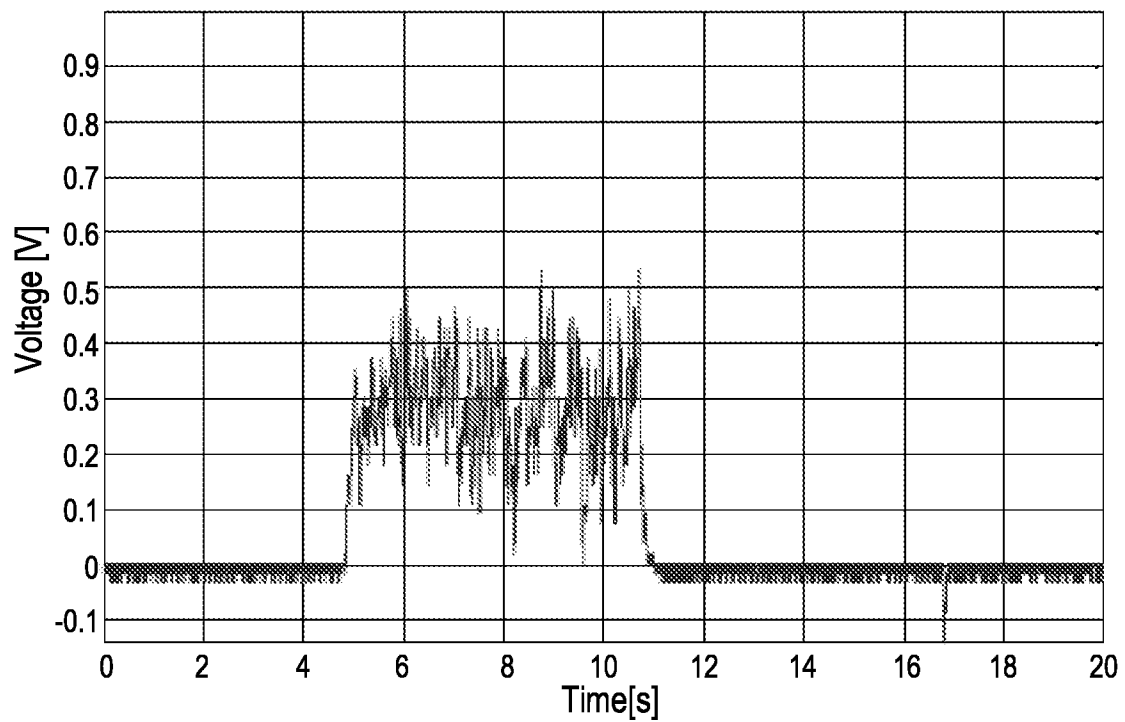


Figure 20b

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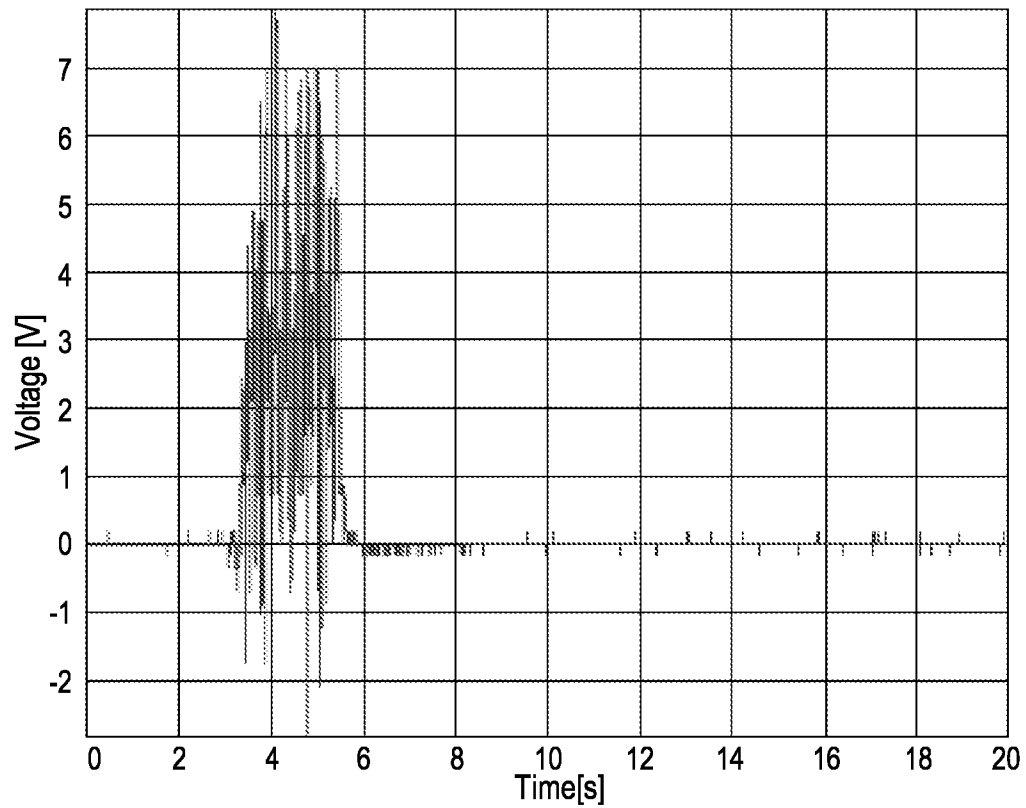


Figure 21a

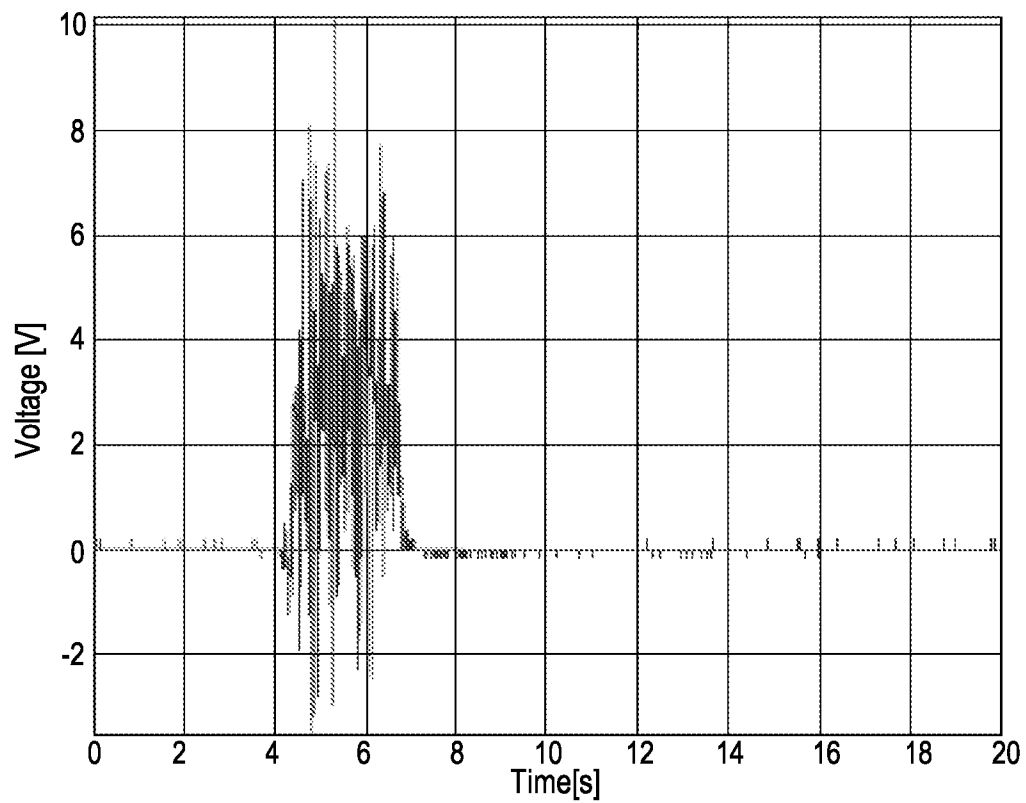


Figure 21b

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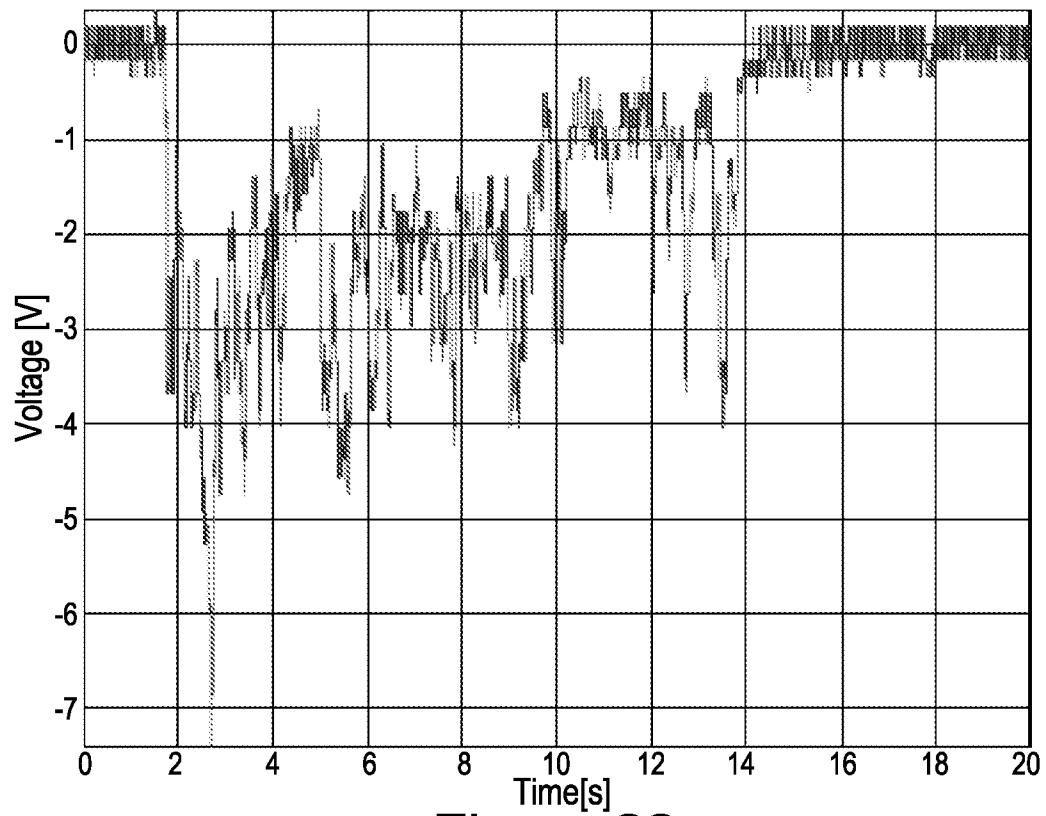


Figure 22a

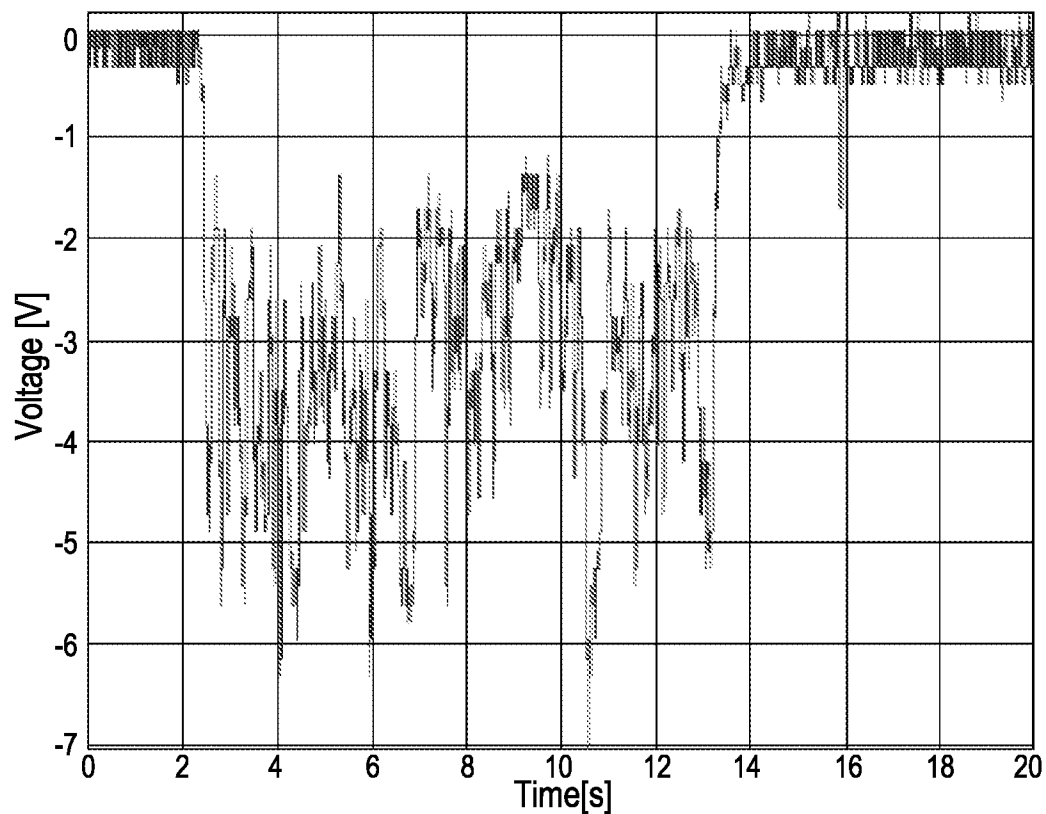


Figure 22b

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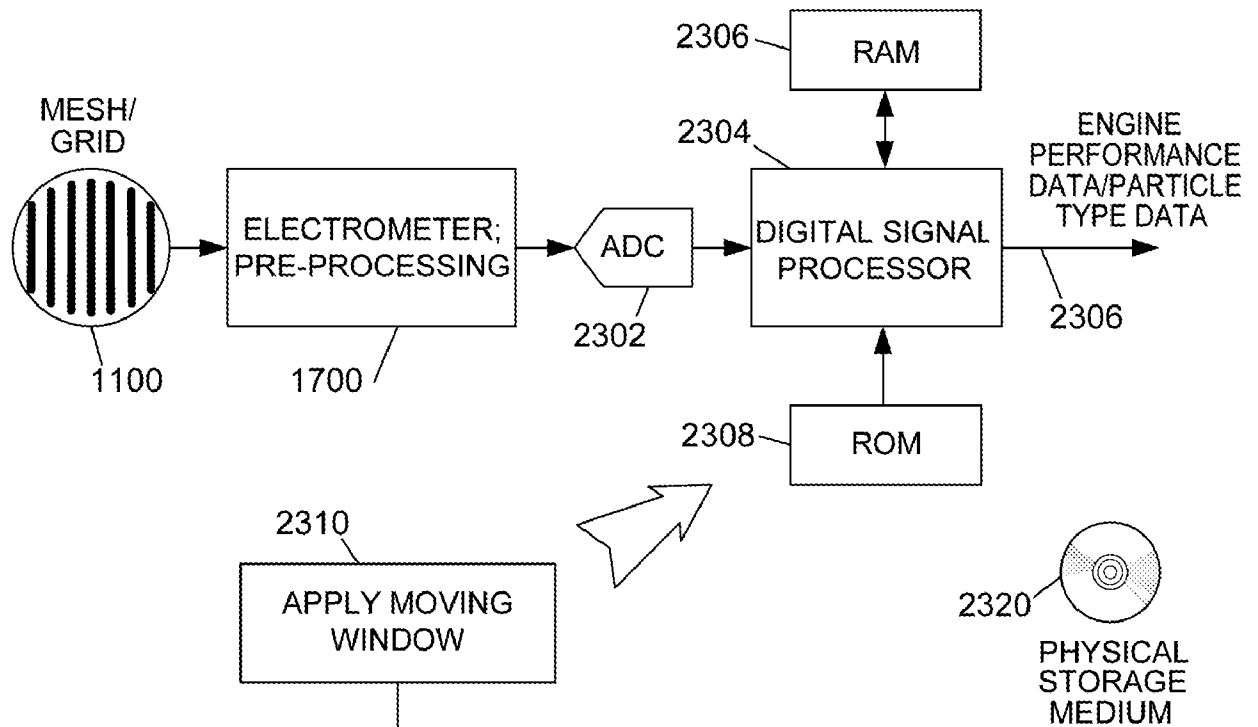


Figure 23a

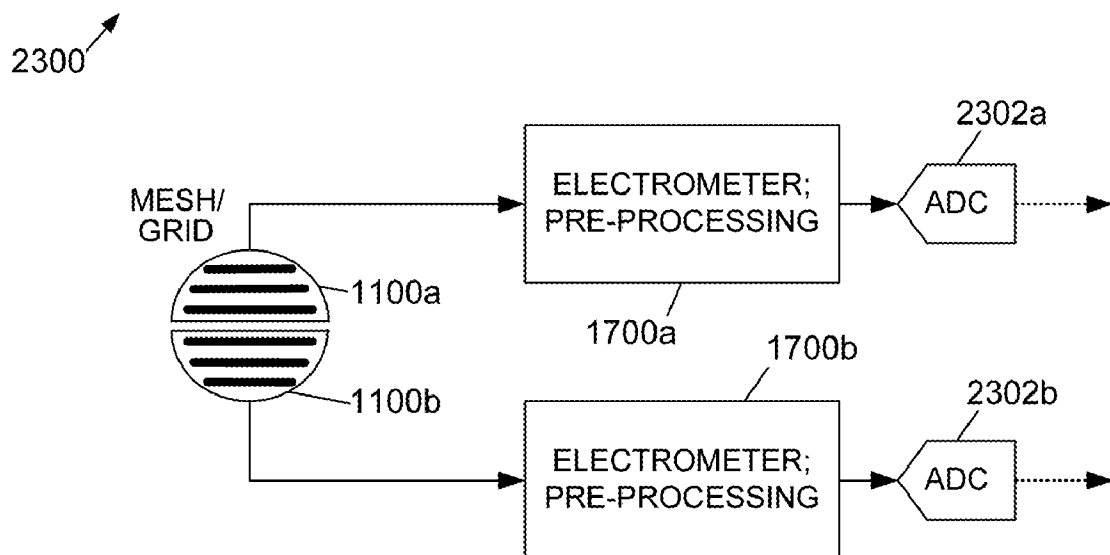


Figure 23b

INTERNATIONAL SEARCH REPORT

International application No

PCT/GB2015/051684

A. CLASSIFICATION OF SUBJECT MATTER

INV. G01M15/10 G01M15/14 G01N15/06
 ADD. G01N15/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G01N G01M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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X	ZHENHUA WEN ET AL: "Electrostatic Monitoring of Gas Path Debris for Aero-engines", IEEE TRANSACTIONS ON RELIABILITY, IEEE SERVICE CENTER, PISCATAWAY, NJ, US, vol. 60, no. 1, 1 March 2011 (2011-03-01), pages 33-40, XP011349017, ISSN: 0018-9529, DOI: 10.1109/TR.2011.2104830	1-19, 21-23, 25-29
Y	the whole document	20,24
A	-----	30
X	US 2012/116649 A1 (STEWART GREGORY E [CA] ET AL) 10 May 2012 (2012-05-10)	1-4, 6-10,21
A	paragraph [0016] - paragraph [0044]; claims 1,3,11,13,18,19; figures 3-5	5,11-20, 22-30
	----- -/-	



Further documents are listed in the continuation of Box C.



See patent family annex.

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Date of the actual completion of the international search

4 September 2015

Date of mailing of the international search report

21/09/2015

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European Patent Office, P.B. 5818 Patentlaan 2
 NL - 2280 HV Rijswijk
 Tel. (+31-70) 340-2040,
 Fax: (+31-70) 340-3016

Authorized officer

Foster, Keir

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2015/051684

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

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A	paragraph [0020] - paragraph [0031]; claims 1-4,9,10,11; figures 2-9	3-5, 11-20, 22-30
X	----- WO 2013/017894 A1 (CAMBRIDGE ENTPR LTD [GB]; WELLAND MARK EDWARD [GB]; AZIZ ATIF [GB]; GA) 7 February 2013 (2013-02-07) cited in the application	30
Y	the whole document	20,24
A	----- US 2010/107737 A1 (KRAFTHEFER BRIAN C [US] ET AL) 6 May 2010 (2010-05-06) paragraph [0046] - paragraph [0049]; figures 8,11 paragraph [0055] - paragraph [0065]; figures 16,17	7,17,19, 26
A	----- WO 84/04390 A1 (BATTELLE DEVELOPMENT CORP [US]) 8 November 1984 (1984-11-08) page 1 - page 4 page 17, paragraph 2 - page 17, paragraph 4; figure 4 -----	19,26

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/GB2015/051684

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