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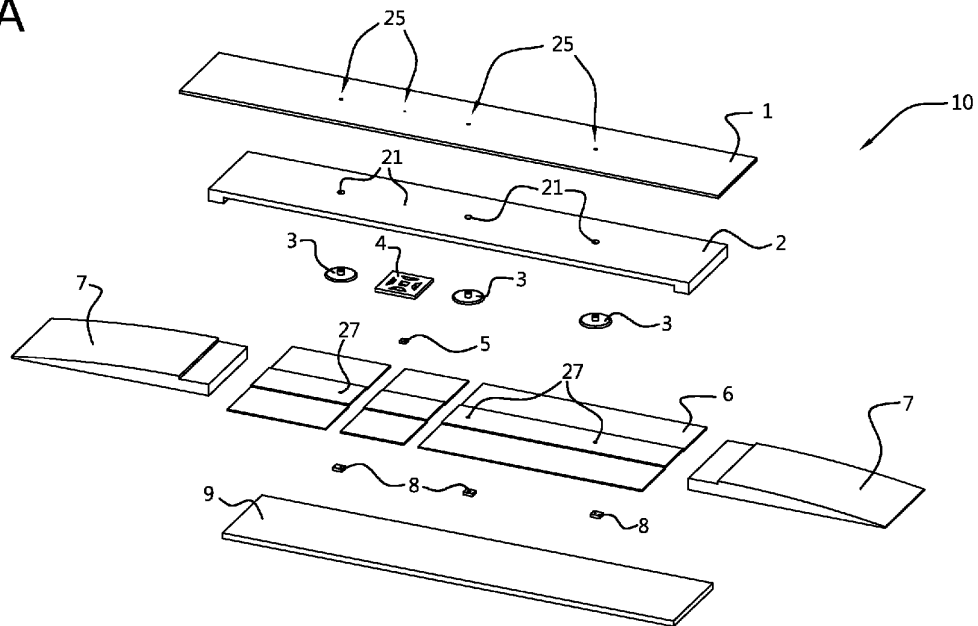
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(54) Title: PRESSURE MEASUREMENT DEVICE

Fig. 1A



(57) Abstract: The invention relates to a pressure measurement device (10) for mounting to a surface. The pressure measurement device (10) comprises a printed circuit board (6), pressure sensors (5, 8) connected to the printed circuit board (6) and a housing (2). The housing (2) covers at least a first side of the printed circuit board (6). The housing (2) comprises ports (21) aligned with the pressure sensors (5, 8). The pressure sensors (5, 8) comprising one or more absolute pressure sensors (5) and one or more microphones (8).

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Pressure measurement device

TECHNICAL FIELD

5 The invention relates to a pressure measurement device for mounting to a surface which may be exposed to air or gas flows.

BACKGROUND

10 Scaled testing of aircraft designs in controlled environments like wind tunnels, and numerical simulations on mathematical models, which form the bulk of the engineering development phases of a design cycle, provide insights into 'ideal' designs. Manufactured parts deviate from these ideal designs which can affect the characteristics of the final product. Hence, it is imperative to perform measurements with the final surfaces to validate the design and manufacturing expectations and understand the true behaviour and performance characteristics of the aircraft. Given the strict safety requirements in aviation and the environments that aircraft operate in, performing measurements through flight-tests is a challenging task.

20 Performing measurements on surfaces rather than in the flow-field provides a valuable and diverse insight into the development of flow over surfaces. Probably the most important parts of any airplane are its lifting surfaces: main wings, canards, and tailplanes. Vital physical quantities of interest to measure on such surfaces exposed to air or gas flows are the steady pressures (also referred to as mean or time-averaged pressures) and unsteady pressure fluctuations. The steady pressures are measured as a time average of low-frequency pressure waves to provide the pressure distribution on the surface due to the flow, from which an integrated force, typically lift, can be obtained. Hence, these steady pressures are also referred to as 'loads'. The unsteady pressure fluctuations can be attributed to hydrodynamic and/ or acoustic waves. Hydrodynamic waves dominate in the regions near a body in a flow. They can arise from turbulent boundary layers, unsteady features such as vortices, or other flow phenomena involving a transfer of mass. Hydrodynamic fluctuations exist in the vicinity or 'near-field' of the source body and die out very quickly over a length scale. The pressure fluctuations existing in the 'far-field' are almost purely due to acoustic waves and are commonly referred to as 'far-field noise'. Hydrodynamic waves can be filtered out to obtain the contribution of acoustic waves to 'near-field noise'.

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Both steady pressures and unsteady pressure fluctuations are omnipresent in aerodynamic situations and are interesting to investigate and understand to be able to improve the performance of the design.

5 A known solution to measure steady pressures from the low-frequency pressure waves is to use pressure belts wrapped around the wing of an aircraft, comprising conventional pressure tubes that may be more than a couple of metres long to cover the chord of the wing and reach the transducers typically located in the cabin. The measured data are hence affected by viscous lag. It is almost impossible to measure high-frequency
10 pressure waves with these conventional tubes. As these belts are usually wrapped around the chord, sensibly, static pressures along the same chord cannot be recorded by belts as each tube can measure data at only one location. These tubes are circular and, unless they have an exterior skin, the surface features undulations, which can affect flow development. Extensive care must be taken to ensure that these long tubes are not
15 pinched or have leaks and remain securely fixed to the surface during flight manoeuvres.

High-frequency analogue pressure sensors are available to measure higher frequency pressure waves. These sensors have heights of around 3mm and are most effective when fixed inside a cavity provided in the airframe. This is because they have the wiring
20 and reference pressure tubes on the opposite side of the sensing element that need space to be routed to a computer without damage. It is therefore difficult to install these sensors into existing structures.

Another solution for measuring high-frequency pressure signals are commercial flight-
25 safe surface microphones that are typically used to record the fluctuations within the audible frequency range. These microphones usually have their sensing elements flush with the supporting packaging and are not located in cavities. The typical large diameter of these microphones makes it hard to achieve high spatial resolutions required for effectively investigating hydrodynamic fluctuations. Moreover, the sensing element itself
30 is large and hence, tends to average out turbulent pressure fluctuations associated with turbulent scales comparable to, or smaller than, their sensing element, irrespectively of how fast they can react.

To install any sensor flush with the original airframe or use the space within an airframe
35 to route cables and wiring, access is required to these spaces, which can often be tight. Hence, installing these sensors on existing airframes is very challenging. Flight testing activities are often performed on special aircraft manufactured specifically for this

purpose so that the sensors can be installed during the manufacturing stage. Moreover, it would be almost impossible to reposition these sensors. This entire procedure is complicated and expensive and limits the usability of older existing airframes.

5 Additionally, such used commercial microphones and high-frequency pressure sensors are expensive to purchase, integrate and install, and are also cumbersome to set-up with the associated equipment.

Also, most commercial sensors have an analogue output. To convert the signals to digital, analogue-to-digital converters (ADC) are required. These are expensive and time-consuming to set up.

The article *In-Flight Testing of MEMS Pressure Sensors for Flight Loads Determination*, by Christian Raab et al, describes the use of MEMS pressure sensors to measure flight loads. MEMS have the advantage of being very small and therefore, not causing much disturbance to the airflow. A wing glove equipped with 64 MEMS pressure sensors (BOSCH BMP280) on the wing surface was constructed. The pressure sensors were sampled at a rate of 100 Hz.

By only using absolute pressure sensors, information only about the steady pressure distribution and hence, the local sectional lift or loading could be obtained. This information seemed to be deemed sufficient for the case under investigation featuring the almost straight wing of a glider but however, still misses out on the crucial information on the presence of a turbulent boundary layer. Also, the device is not preferred for more complicated cases, such as a wing under the influence of a propeller slipstream or a wing with vortex generators. The steady pressure data obtained is of little use to acousticians focused on increasing cabin comfort or decreasing noise emissions in the vicinity of airports. The applications where the device can be mounted are limited. The device is also relatively thick, thereby influencing the flow to be measured. Finally, the pressure sensors are likely to get damaged during assembly.

The article *Road to Acquisition: Preparing a MEMS Microphone Array for Measurement of Fuselage Surface Pressure Fluctuations*, by Thomas Ahlefeldt et al, describes the process of using MEMS microphones within a flexible printed circuit board (PCB) array for the measurement of unsteady pressure fluctuations on an airplane fuselage during flight tests.

The MEMS microphones are not able to provide information on local pressure gradients. Therefore, this device will be of very limited use in situations where hydrodynamic fluctuations are significant and important to study, such as on a wing under the influence of a propeller slipstream. The range of applications for this device is severely limited.

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Furthermore, this device is not rugged or stiff enough for more demanding applications.

The outer surface of the device is a printed circuit board, which is vulnerable to foreign object damage. Also, the device may get damaged due to stresses induced by repeated applying, removing, and re-applying tape to fix the device to the fuselage. The tape is to be applied on a silicone coating, while silicone does not provide a good bonding surface.

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CN112758348 provides a pressure distribution measuring device for a flight test and a pressure measuring belt refitting method, and particularly provides a refitting method for a MEMS pressure measuring belt on a flight test machine. The MEMS pressure measuring belt is made of conventional materials such as double-faced adhesive tape and aluminium foil.

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This device has several drawbacks. The use of an aluminium foil bonding to the aircraft wing comes with difficulties, as it can easily wrinkle and applying it over curved surfaces seems challenging. Physical features such as manufacturing errors, rivets or fasteners, steps at plate joint locations, and surface damages would make this process even more difficult. Commonly available double-sided tape is not a particularly strong adhesive and may not hold under fluctuating forces as seen for instance on wings influenced by a propeller's slipstream with periodic suction forces impressed by the tip vortices. The tape is difficult to apply without creating air pockets. The range of applicability of the device is therefore limited.

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The device seems prone to human errors. For instance, the alignment of the holes of the fairing with the pressure sensors is challenging.

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The device does not seem rugged enough to withstand dangerous environmental situations and can be prone to foreign object damage.

US2009/000386 discloses a fairing system developed to reduce the flow disturbance around sensor elements allowing accurate measurement of the pressure distribution on

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an object surface. The fairing also protects the sensors and electronics of the pressure belt from direct exposure to airflow.

5 EP3542552B1 relates generally to Microelectromechanical System (MEMS) devices and, more particularly, to a combo sensor system comprising an acoustic transducer and a pressure sensor.

10 CN105849523B relates to a measuring device which can be attached to an outer wall of a moving object or a stationary object arranged in an air flow to measure a physical quantity. The measuring device comprises a support having a groove with an opening to the outside, in which a sensor is arranged. The device comprises a cavity into which a slot opens and which comprises a flexible printed circuit to which the sensor is connected.

15 US2017/026729A1 describes a microphone comprising a base, a micro electro mechanical system (MEMS) device including a diaphragm and a back plate, an integrated circuit connected to the MEMS device, a pressure sensor and a lid, wherein the base and the lid enclose the MEM device and the integrated circuit.

20 The solutions known from the prior art fail to provide a device that can measure both steady and unsteady pressures on existing surfaces. Also, the prior art fails to disclose a device that is easy to assemble, re-assemble, mount, and re-mount to the airframe. Furthermore, the prior art fails to provide a device that is sufficiently strong to withstand harsh conditions, such as unfavourable climatic conditions, strong fluctuating forces, and heavy loads generated during operation.

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SUMMARY

The object is to provide a pressure measurement device for mounting to a surface, in particular to the outside of a vehicle such as an aircraft, where the pressure measurement device is capable of collecting an accurate and compound pressure measurement data set.

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The object is solved by a pressure measurement device (10) for mounting to a surface, the pressure measurement device (10) comprises

- a printed circuit board (6);
 - 35 - pressure sensors (5, 8) connected to the printed circuit board (6); and
 - a housing (2);
- the housing (2) covering at least a first side of the printed circuit board (6),

the housing (2) comprising ports (21) aligned with the pressure sensors (5, 8),
and

the pressure sensors (5, 8) comprising one or more absolute pressure sensors
(5) and one or more microphones (8).

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The surface may be a surface that is configured to be exposed to an air or gas flow, such
as a vehicle, aircraft, model in a wind tunnel, wind turbine, automobile or a building. The
pressure measurement device may in particular be configured to be mounted to the
outside or airframe of an aircraft. The term aircraft is used to refer to all sorts of flying
vehicles, such as airplanes, helicopters, drones etc.

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The housing 2 may be a planar housing configured to cover one side of the printed circuit
board 6. The housing 2 may also be referred to as a planar housing or a cover layer
configured to cover at least a first side of the printed circuit board 6.

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The ports 21 are aligned with the sensing elements of the pressure sensors 5, 8 on the
printed circuit board 6 such that the pressure sensors 5,8 are exposed to measure the
pressure applied by the air or gas flow on the surface of interest at the chosen locations.
The first side of the printed circuit board 6 is the side facing the housing 2 and facing
away from the surface on which the pressure measurement device 10 is to be mounted.
The first side of the printed circuit board 6 faces away from the aircraft when the pressure
measurement device 10 is mounted to the outside of the aircraft. The first side of the
printed circuit board 6 may also be referred to as the top side of the printed circuit board.

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The term absolute pressure sensor (PCB) is used to refer to a pressure sensor that
measures the local ambient pressure against vacuum. This is advantageous over
pressure sensors that measure a relative pressure by comparison against a known
pressure being separately supplied as reference. That is a relatively expensive device
and laborious to install and maintain, as the supply of a reference pressure is done
through extremely small tubes to each sensor individually.

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By using absolute pressure sensors 5 as proposed here, the pressure measurement
device 10 can work in a standalone fashion and can also be deployed in situations where
such reference pressures are not available.

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The term microphone is used to refer to a pressure sensor that measures pressure
deviations in the local pressure with respect to a reference pressure. The microphone

comprises a sensing membrane that is with one side exposed to the air or gas flow and the other side to a back-chamber where the reference pressure is allowed to vary. The membrane moves or vibrates because of so-called unsteady pressures, i.e. deviations from a local reference pressure, while the absolute value of this local pressure is unknown to the microphone.

While hydrodynamic fluctuations can reach frequencies far greater than acoustic waves, the pressure fluctuations having frequencies within the audible range of human ears are usually interesting to investigate, independent of the source. The insights obtained from studying these quantities are of importance to aerodynamicists, performance engineers, loads and structural engineers, material scientists, aero-acousticians, and vibro-acousticians, to name a few.

The advantage of using both absolute pressure sensors and microphones is that a much better understanding of the flow can be obtained. The steady pressures give a direct indication of the mean forces or mean loads generated on the surface while the unsteady pressures give an indication of the fluctuations about a mean caused by certain flow phenomena and their development over time and space. The data from the absolute pressure sensors will also provide information on the local pressure gradients. As fluid flows are governed by pressure gradients, this information can be combined with the data from the microphones to track and understand the movements of hydrodynamic flow features that display high levels of unsteadiness. An example would be the spanwise movement of a propeller tip vortex that interacts with a wing. A quantitative and detailed understanding of the flow development can be obtained.

By including microphones, information on the presence of a turbulent boundary layer could be obtained which significantly enhances the effectiveness of the obtained dataset, for instance for the case of a glider airplane where a turbulent boundary layer would increase the drag force and decrease the performance, as described above with reference to Raab.

In situations where the unsteady flow features are not of interest, the data from microphones can be disregarded and the data from the absolute pressure sensors may be used for investigating steady loads. This is useful in situations where the mean pressure distribution, and hence integrated sectional lift, are needed on a wing and not the fluctuating pressures.

The pressure fluctuations measured by the microphones can be either from hydrodynamic or acoustic waves. It can be used to specifically measure both. The pressure measurement device 10 can be positioned in the far-field and used to record the acoustic waves emanating from an object. When positioned in the near-field it will measure the combined influences of hydrodynamic and acoustic waves. The contributions from the two sources can be separated through mathematical processing. By applying different coatings to the protective skin 1, as explained later, the physical phenomena being measured and their input levels to the sensors can be tweaked for specific investigations.

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These absolute pressure sensors 5 also measure and provide the ambient temperature. A reference temperature and pressure of the undisturbed airflow in a test environment can be measured and then used to convert all measured data to standard sea-level temperature and pressure. As fluid properties vary with these quantities, it is valuable to measure the undisturbed ambient conditions to better understand the flow phenomena being measured. This correction can be applied to both datasets obtained from the absolute pressure sensors 5 and microphones 8.

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The pressure measurement device 10 as presented here, can advantageously be used as a combined steady and unsteady pressure measuring device for aerodynamic and vibro- and aero-acoustic studies of surfaces exposed to air or gas flows.

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The primary function of the housing 2 is to hold the electronics in the desired position. It also provides a degree of protection from the climate and operational environment. As explained below, the housing 2 may be made up of engineering materials to provide a part with a high tensile strength and modulus while able to withstand higher temperatures. To further increase the stiffness of the housing 2 and provide additional safety, an optional protective skin 1, can be provided on its outer side, which will be explained in more detail below.

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According to an embodiment the one or more microphones (8) are positioned on a second side of the printed circuit board (6), the second side being opposite the first side of the printed circuit board (6).

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The printed circuit board 6 has a planar shape, comprising a first or top side, a second or bottom side and a thin outer circumference. The second side of the printed circuit board 6 is the side facing away from the housing 2. The second side of the printed circuit

board 6 faces towards the aircraft when the pressure measurement device 10 is mounted to the outside of the aircraft.

5 Microphones 8 provided on the second side of the printed circuit board 6 may also be referred to as bottom-port microphones. The bottom-port microphone sensors have a better signal-to-noise ratio than a top-port microphone. They also have higher dynamic ranges and acoustic overload points. The microphones 8 can be installed on the second side of the pressure measurement device 10 where they are protected.

10 The relatively long cavity from the outer openings of the ports 21 in the housing 2, to the microphones 8, helps to attenuate the input pressure signal and increase the frequency range of the microphone. Top-port microphones will have to be positioned on the first side and will have shorter cavities to maintain the same overall minimum thickness of the instrument to avoid a larger penalty.

15 The position on the second side of the printed circuit board 6 also allows coating the microphones 8 in a protective layer 9 such as silicone, that protects microphones 8 from the environment and dampens outside vibrations.

20 So, according to an embodiment the pressure measurement device (10) comprises a protective layer (9) positioned at the second side of the printed circuit board (6), the protective layer (9) surrounding the one or more microphones (8).

25 The protective layer 9 may be a silicone layer or any suitable coating, such as a conformal coating. The term conformal coating is used to refer to a polymeric film forming product that protects circuit boards, components, and other electronic devices from adverse environmental conditions. These coatings 'conform' to inherent irregularities in both the structure and environment of the printed circuit board. They may provide increased dielectric resistance, operational integrity, and protection from corrosive atmospheres, humidity, heat, fungus, and airborne contamination such as dirt and dust.
30 Examples of conformal coating are acrylic resin, silicone resin, urethane (polyurethane) resin, epoxy coating, parylene coating, thin film/nano coating.

35 The protective layer 9 is positioned in between the printed circuit board 6 and the outside of the aircraft when the pressure measurement device 10 is mounted to the aircraft. The protective layer 9 may be positioned against the second side of the printed circuit board 6.

Such a protective layer 9 surrounds the one or more microphones 8. The protective layer 9 protects the exposed electronics including the microphones 8 and dampens the impact of vibrations on the microphones 8, resulting in measurement data of improved quality.

5 External vibrations may be transferred from the surface to which the pressure measurement device 10 is mounted (e.g. the aircraft).

The protective layer 9 may cover the microphones 8 such that the microphones 8 and other components on the printed circuit board 6 are embedded in, i.e. completely covered

10 by, the protective layer 9. The protective layer 9 typically has a thickness sufficient to cover all the exposed electronic components and may be in the range of 0,5 – 1,2mm, measured normal to the printed circuit board 6, as electronic components typically have a maximum height of 1mm.

15 The housing 2 may comprise thickened walls (24) along (part of) its circumference, creating a walled cavity, providing a mould for casting the protective layer. These thickened walls 24 also provide additional surface area to connect the tapered parts 7, as explained in more detail below.

20 According to an embodiment the one or more absolute pressure sensors (5) are positioned on the first side of the printed circuit board (6).

The two types of pressure sensors are present on opposite sides of the printed circuit board 6 and the side with the absolute pressure sensor 5 is the 'outer side' or 'top side'

25 (first side). The microphones 8 are on the 'inner side' or 'bottom side' (second side). In other words, the pressure measurement device 10 may be made up of top-port absolute pressure sensors on the top-side for measuring steady pressures and bottom-port microphones on the bottom-side for measuring pressure fluctuations or unsteady pressures.

30 According to an embodiment the one or more microphones (8) have a first frequency response, the one or more absolute pressure sensors (5) have a second frequency response, wherein the first frequency response is at least 10 times greater or higher than the second frequency response.

35 The term frequency response is used to indicate the range of frequencies which can be measured or wherein the sensor is most sensitive.

According to an embodiment, the one or more absolute pressure sensors 5 typically have a minimum frequency response of 8 Hz. The signals can be sampled at a frequency of 100Hz to obtain statistically converged uncorrelated data. According to an embodiment, the one or more microphones 8 have a typical frequency response in the range of 100Hz to 20kHz, where they are most effective. According to an embodiment, the first frequency response is higher than the second frequency response. According to an embodiment, the first frequency range has a lower limit that is greater than an upper limit of the second frequency response.

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The microphones 8 may have a high frequency response in the range of kilohertz, while the absolute pressure sensors 5 have a low frequency response in the range of hertz. Hence, the microphone can measure pressure signals in time steps of microseconds.

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The microphones are configured to measure unsteady pressures (e.g. caused by propeller induced vortices on a wing, acoustic waves, turbulent boundary layers, and others), while the absolute pressure sensors are configured to measure steady pressures (time averaged mean pressure distribution over a surface leading to the integrated lift force).

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According to an embodiment the housing (2) is configured to receive the printed circuit board (6) in a predefined position.

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The housing 2 is configured to receive the printed circuit board 6 in a predefined position with respect to the housing 2, in which the housing 2 covers one side (the top side) of the printed circuit board. The housing 2 may be configured to receive the printed circuit board 6 in an exact position, thereby ensuring alignment between the pressure sensors 5,8 and the ports 21 provided in the housing 2 and the skin ports 25 in the optional protective skin 1 described below. Alternatively, the housing 2 may be configured to receive the printed circuit board 6 in an approximate position, in which there is still some play between the printed circuit board 6 and the housing 2. Final alignment may then be achieved by using inserts 3,4 as described in more detail below.

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The inner surface or inner side of the housing 2 may have a structure that allows receiving the printed circuit board 6 in the predefined position only.

According to an embodiment the printed circuit board 6 is fixed to an inner surface of the housing (2) by an adhesive. The first side of the printed circuit board 6, which is directed to the housing 2, may be fixed with adhesives to the housing 2. This is an easy and reliable way to attach the printed circuit board 6 to the housing 2. The printed circuit board 6 may be glued into the receiving pocket 26 described above.

The inner surface or inner side of the housing 2 may comprise a receiving pocket 26 dimensioned to (tightly) receive the printed circuit board 6 in the predefined position. This allows for easy and accurate assembly. According to an alternative embodiment, a slightly looser fit can be provided between the circumference of the printed circuit board 6 and inner walls of the pocket 26 to offer some benefits. The excess adhesive that is applied on the printed circuit board 6 to fix it to the housing can flow into this excess space. While assembling a large pressure measurement device 10, it is possible that a pressure sensor 5,8 at some location is slightly askew due to low manufacturing tolerances. This excess space allows the user to account for such an error.

According to an embodiment the pressure measurement device (10) comprises sensor inserts (3, 4) and an inner surface of the housing (2) comprises pockets (22,23) to receive the sensor inserts (3, 4).

The inner surface of the housing 2 is the surface facing the first side of the printed circuit board 6. The pockets (22, 23) to receive the sensor inserts (3, 4) may be provided as pockets or recesses in the receiving pocket (26) dimensioned to (tightly) receive the printed circuit board 6.

The sensor inserts 3,4 may be made of the same material as the housing 2, e.g. plastic. The sensor inserts 3,4 may be microphone inserts 3 and absolute pressure sensor inserts 4.

The sensor inserts 3,4 and the pockets 22,23 in the inner surface of the housing 2 are configured such that the sensor inserts 3,4 can be tightly inserted into the pockets 22,23, e.g. with a snap-fit arrangement. The sensor inserts 3,4 are further configured to receive the respective pressure sensor 5,8 and connect to the printed circuit board 6. All together this provides for an arrangement in which the printed circuit board 6 with pressure sensors 5,8 can be positioned with respect to the housing 2 in an easy and reliable manner.

5 The sensor inserts 3,4 are provided to align the sensing elements of the pressure sensors 5,8 with the ports 21 in the housing. The design of the sensor inserts prevents adhesive, which may be used to attach the printed circuit board 6 to the housing 2, from reaching and damaging the pressure sensors 5,8 while at the same time the sensor inserts 3,4 and the adhesive to fix them create pressure seals, to improve the quality of the pressure data acquired. The housing 2 and the sensor inserts 3,4 can be printed with an engineering resin by the method of stereolithography (SLA), making it possible to achieve the required shape.

10 The pockets 22, 23 are provided to ensure that the cavities from ports 21 and the pressure sensors 5,8 remain normal to the flow or surface. The ports 21 are provided to expose the pressure sensors to the ambient and are aligned with skin ports 25 on the protective skin 1 described later.

15 The sensor inserts 3,4 are first glued on to the printed circuit board 6 and then the printed circuit board 6 is glued in place in the housing 2. The adhesive is always applied on the faces of the sensor inserts 3,4 facing away from the pressure sensors 5,8, thereby significantly decreasing the chances of having the adhesive damage the pressure sensors 5,8. This makes it very easy to assemble the pressure measurement device 10 even when it has tight curves that are hard to access. The alignment of skin ports 25, ports 21, and the sensing elements of the pressure sensors 5,8 to ensure best data quality is easily addressed.

25 The sensor insert 3 can optionally be easily fixed to the top side of the printed circuit board 6 aligned with the sensing element of the microphone 8 to assemble with the housing 2. This ensures a clean and continuous cavity from the outside surface of the housing 2 (or protective skin 1 on top thereof) to the sensing element of the microphone 8 without leaks. Aligning the sensing element of a top-port microphone with the ports in a protective housing is very difficult considering the amount of play that would be present due to production tolerances. There is the risk of damaging the sensing element of the microphone during assembly, having a leak in the cavity, or creating a resonance chamber. The current design results in an overall reduced thickness compared to using top-port microphones. It is also safer as there is little chance of damaging the microphone during assembly where components are joined by adhesives.

35 The absolute pressure sensor 5 is held in a cavity by adhesives. The sensor insert 4 helps to apply this adhesive without damaging the absolute pressure sensor 5. This

protects the absolute pressure sensor 5 from damage caused by applying adhesive directly around the absolute pressure sensor.

5 According to an embodiment the printed circuit board (6) is one of a flexible printed circuit board, a rigid printed circuit board, and a flex-rigid printed circuit board.

Depending on the specific application of the pressure measurement device 10, the most suitable printed circuit board 6 may be selected. For applications on curved surfaces, it is most advantageous to select a flexible or flex-rigid printed circuit board. For application
10 on flat surfaces, a rigid printed circuit board may be selected. In the latter case, the housing 2 may not need to comprise receiving pocket(s) (26), but a flat surface will suffice, although the sensor inserts 3,4 are still preferred for which pockets 22 and 23 may be provided.

15 Using a flexible printed circuit board is in particular advantageous when the housing 2 has a curved shape as explained in more detail below. Flexible printed circuit boards can virtually follow any shape. Also, flexible printed circuit boards are thin, thereby contributing to a thin design of the pressure measurement device 10. Flexible printed circuit boards are more durable and robust and preferred for environments where high
20 vibrations are expected.

Moreover, flexible printed circuit boards allow for high-density connections and can take advantage of the small pressure sensor sizes. Known commercial pressure sensors have individual leads that need to be individually connected to a data processing system.
25 This results in many wires, making it difficult to handle. Flexible printed circuit boards with digital output sensors simply require a flexible flat cable (FFC) connecting the sensor suite to a micro-controller, which then transmits the data to a computer on as few as one ethernet cable. This single cable can also power the digital sensor array.

30 Currently, flexible printed circuit boards are commonly available in limited size, e.g. 400 mm by 400mm. Rigid printed circuit boards and flex-rigid printed circuit boards also have physical size constraints. For pressure measurement devices 10 with a larger size, multiple printed circuit boards can be used next to each other. So, according to an embodiment the pressure measurement device 10 comprises two or more electronically
35 interconnected printed circuit boards. In such an embodiment where the two or more printed circuit boards are connected, the connection may be done by soldering to achieve

the thinnest connection. The protective layer 9 (as described below) will also encompass this solder connection and hence, protect it and prevent the connections from breaking.

According to an embodiment the housing (2) has a curved planar shape.

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The housing 2 may have a curved planar shape or curvilinear 2D shape, to match the shape of a specific part of the outside of the aircraft. The curved planar shape may also be a semi-closed shape, such as a ring shape, which can for instance be fitted over a wing of an aircraft.

10

The term planar is used in this text to refer to a shape having longitudinal and transversal dimensions at least ten times greater than a thickness measured in a direction perpendicular to the longitudinal and transversal direction. The planar housing may have longitudinal and transversal dimensions greater than 5cm, while having a thickness of less than 5mm.

15

The housing 2 may have a curved or curvilinear shape to allow mounting the pressure measurement device 10 flat with respect to curved parts of the aircraft, for instance to a wing. The housing may be curved to match the shape of part of the wing.

20

The housing 2 may be a plastic cover. The housing 2 is preferably made of engineering materials that provide a degree of stiffness to the pressure measurement device 10. A protective skin 1, as explained later, may be provided in the form of a glass fibre skin to increase the stiffness of the pressure measurement device 10.

25

The other components of the pressure measurement device 10, such as the printed circuit board 6 and the protective skin 1 follow the shape of the housing 2, thereby creating a pressure measurement device 10 that matches the shape of a specific part of the aircraft, such as the wing. All these components may have a similar curved planar shape.

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The pressure measurement device 10 may thus be designed as a sleeve that can be mounted on a surface to be exposed to an airflow, such as an aircraft, wherein the surface may be a curved surface like the leading edge of a wing.

35

According to an embodiment, the entire pressure measurement device 10 has a curved planar shape.

According to an embodiment the pressure measurement device (10) has a planar shape with a thickness of less than 7mm, preferably less than 5mm, more preferably less than 3,5 mm.

5

A small thickness is preferred to measure the flow quantities that would exist on the unmodified original surface.

10

A pressure measurement device 10 having such a thickness provides the advantage of minimizing the disturbance to the flow and significantly altering the original flow features the device intends to measure. In an embodiment where the pressure measurement device 10 has a curved planar shape, the pressure measurement device has a thickness of less than 8mm, e.g. 7mm, preferably less than 4mm. The thickness is measured in a direction perpendicular to the first side of the printed circuit board 6.

15

Larger thicknesses are in general not desired as they are expected to significantly distort the flow. The physical quantities being measured will be unrepresentative of the of their original state on the surface.

20

However, a larger pressure measurement device 10 may be used if the shape of the pressure measurement device 10 is not the shape of the original surface but rather, another shape that is desired to be investigated. An example would be the investigation of a wing glove featuring a Natural Laminar Flow air foil mounted over the existing wings of a test aircraft as has been done many times by NASA, among other examples.

25

According to an embodiment a protective skin (1) is provided on an outer surface of the housing (2).

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The protective skin 1, which may also be referred to as a skin, may form the most outer layer of the pressure measurement device 10, and may be provided on the outside of the housing 2 when applicable.

35

The protective skin 1 may be a glass fibre skin. The glass fibre skin may be a composite laminate made from glass-fibre reinforced polymer (GFRP) with skin ports 25 drilled at the locations of the ports 21 in the housing 2 towards the pressure sensors 5,8.

The protective skin 1 may be applied as a skin over the entire pressure measurement device 10, including the circumferential tapered parts 7 described below. The protective skin 1 design provides the required shape through a stiff structure that protects the underlying electronic components.

5

The protective skin 1 provides a workable surface. It can be polished and painted. The surface can be easily cleaned of debris without putting the electronics at risk. The protective skin 1 makes the pressure measurement device 10 usable in harsh climatic or operational environments as the electronics is not exposed to the elements or to foreign objects. Aerodynamic devices such as flow-trips or roughness elements to force transition of the boundary layer, from laminar to turbulent, when desired, can be fixed onto the protective skin 1 when needed. This increases the range of flow regimes in which the pressure measurement device 10 can be used in and may be particularly advantageous in wind tunnels where Reynolds numbers achievable are less than those experienced in full-scale flight.

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Coatings may be applied to this protective skin 1 to increase the range of physical quantities measurable by the microphones 8 and the physical quantity itself. This is explained in more detail below.

20

According to an embodiment the pressure sensors (5, 8) are micro-electromechanical systems (MEMS) sensors.

Both the microphones 8 and the absolute pressure sensors 5 may be MEMS, i.e. microelectromechanical systems. MEMS have the advantage of being relatively cheap. MEMS also have the advantage of being small, allowing to create a pressure measurement device 10 with a minimal height. When these small pressure sensors are used with printed circuit boards, they can be placed extremely close to each other to achieve very high spatial resolutions which are helpful for certain investigations.

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MEMS absolute pressure sensors and microphones have an outer total dimension of around 2mm by 2mm with a height less than 1mm. The sensing element itself is around 0,3mm in diameter.

Off-the-shelf MEMS microphones typically feature a non-flat frequency response within specific frequency ranges at which the microphone's diaphragm resonates, which may result in pressure fluctuations that are amplified, or attenuated, and phase-shifted. The

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application of an in-situ calibration with respect to a reference microphone makes it possible to account for this behaviour and already constitutes an established practice. By applying a correct and repeatable calibration procedure obtaining reliable and accurate measurements is ensured.

5

According to an embodiment the pressure measurement device (10) further comprises tapered parts (7) provided along at least part of the circumference of the housing (2).

10

The tapered parts 7 have a tapered shape, providing a gradual, aerodynamic change in height from the surface (e.g. of the outside of the aircraft) when mounted to the surface to the highest thickness of the pressure measurement device 10. The tapered parts 7 have a thickness which reduces towards a distal end, the distal end protruding away from the housing 2.

15

This shape minimizes the modifications the pressure measurement device 10 makes to the air or gas flow. The tapered parts 7 may be machined from metal alloys. According to an embodiment the tapered parts 7 are integrally formed with the housing 2. According to an alternative embodiment the tapered parts 7 are formed as separate parts and are connected to the housing 2.

20

The tapered parts 7 may be attached to the housing 2, preferably to the thickened walls (24).

25

The tapered parts 7 are preferably provided along the entire circumference of the housing 2.

30

In an embodiment, preferably without the protective skin 1, the tapered parts 7 may be of a continuously tapering design where the maximum thickness is at the side of the housing 2. In an alternate embodiment where it is desirable to use the protective skin 1, the tapered parts 7 may have a flat step on the side of the housing 2.

35

The flat step in the tapered parts 7 allows for the protective skin 1 to be fabricated as a flat plate even where curvature is high, like the leading edge of a wing. This avoids the protective skin 1 from having a double curvature if required to cover the entire surface of the tapered parts 7, which is very hard to manufacture. Moreover, this ensures that the distal end of the tapered part 7 retains its minimal thickness as otherwise the protective

skin 1 would extend till this distal end and increase the thickness, thereby creating a step that could affect the flow.

5 According to an embodiment the pressure measurement device (10) comprises a coating layer covering one or more ports (21, 25) associated with the microphones (8).

The one or more covered ports may be skin ports 25 if a skin layer 1 is present, or ports 21 provided in the housing 2 when no skin layer 1 is present.

10 MEMS microphones, as those that may be chosen here, typically have a frequency response within the audible range of human hearing and a maximum acoustic overload point of around 135dB. While these specifications are sufficient for measuring the far-field noise, in most cases, they may not be sufficient for measuring unsteady pressure
15 pressure fluctuations caused due to hydrodynamic waves due to higher frequencies and larger pressure fluctuations that translate to values greater than 145dB, as seen in propeller tip vortices. The microphone cannot distinguish between wave types and cannot be used to measure near-field noise as the hydrodynamic waves would be expected to dominate the fluctuating pressure field.

20 The presence of the protective skin 1, as described earlier, provides a surface on which coatings may be applied to increase the range of physical quantities measurable by the microphones 8 and the physical quantity itself. In the absence of the protective skin 1, the optional coating layer may directly be applied on the outer side of housing 2.

25 The coating layer may be a thin polyimide film, like Kapton tape manufactured by DuPont Corporation, and may be applied on the protective skin 1 to cover the skin ports 25 that lead to the microphones 8. This may act as a membrane to dampen the pressure fluctuations measured by the microphones 8. This increases the dynamic range of the pressure fluctuations measurable and the effective acoustic overload point, thereby
30 allowing the pressure measurement device 10 to be used to measure quantities that normally would exceed the technical specifications of MEMS microphones.

A fabric coating, like the para-aramid type commercially known as Kevlar by DuPont Corporation, may also be applied as a coating layer on the protective skin 1 to cover the
35 skin ports 25 to the microphones 8. This kind of a perforated coating filters out hydrodynamic pressure waves and allows only acoustic waves to pass through. Such a

coating may be applied to protective skin 1 in situations where hydrodynamic waves exist and need to be filtered out, like in investigations focusing around near-field noise.

5 As these coating layers are optional, it may be neglected altogether if found to not be required. The coatings may be applied to the protective outermost layer skin 1, over skin ports 25, in an embodiment of the pressure measurement device 10 that has this optional layer. In the absence of this optional protective skin 1, the coating layer may be directly applied to the outer side of the housing 2 and over the ports 21.

10 No coating layers are applied on skin ports 25 or ports 21 that connect to the absolute pressure sensor 5.

According to an embodiment the pressure sensors (5,8) are positioned in a grid or matrix configuration.

15 The reduced size of MEMS sensors allows for positioning the pressure sensors 5,8 in a tight configuration, which improves the determination of wall-pressure-derived flow quantities such as correlation length and convection speed. The mutual distance between neighboring pressure sensors 5,8 may be in the order of 2mm (measures from center to center of the sensing element of the pressure sensors 5,8).

20 The advantage of using these pressure sensors over conventional pressure tubes is that the shorter cavity lengths from the measuring surface to the sensing elements significantly decreases the viscous lag. These pressure sensors are extremely small and can allow for high spatial resolutions.

25 According to an embodiment the pressure sensors (5,8) are digital output sensors.

30 The term digital output sensor is used to refer to a sensor providing a digital output representing the reading, in this case being an indication of the pressure for the absolute pressure sensor 5 or the pressure fluctuations about a reference pressure for a microphone 8.

35 Known commercial sensors have analogue output sensors. These require expensive analogue-to-digital converters (ADC) for each sensor to prevent data degradation in highly electromagnetic environments. Digital output sensors like proposed here have analogue-to-digital converters embedded into the pressure sensor. The data are

shielded and do not degrade like analogue signals. In addition to having a single flexible flat cable (FFC) for easy data cable management, digital interface protocols such as I2C and SPI allow for the data to be handled more easily on fewer lines. Each analogue sensor would require a dedicated data line, as scanners for high-frequency sensors are not feasible.

5

The pressure sensors 5,8 may have a digital output connected to the printed circuit board 6 for retaining data quality in electromagnetic environments.

According to a further aspect there is provided an object comprising a pressure measurement device (10) according to any one of the preceding claims mounted to a surface of the object.

10

The object may be a vehicle, like an aircraft or a car, a building, a model, e.g. for use in a wind tunnel, a wind turbine. The surface may be a surface that is configured to be exposed to an air or gas flow, such as the hull or outside of a vehicle, the outer surface of a wind-turbine.

15

As mentioned, the term aircraft is used to refer to all sorts of vehicles which have the capacity to fly, such as airplanes, helicopters, drones etc.

20

The pressure measurement device 10 may be used in flight testing.

According to a further aspect the invention relates to the use of a pressure measurement device (10) as described above for obtaining combined steady and unsteady pressure measurements.

25

The steady pressures measured by the absolute pressure sensors 5 provide an indication of the mean value of the pressure distribution over the surface being measured. This can be integrated to obtain the local lift distribution or load. The unsteady pressures, measured by the microphones 8, about a mean pressure, provide a complementary dataset that provides the fluctuations in the pressure about this mean steady pressure.

30

The combined dataset of steady and unsteady pressures are very valuable information and provide aerodynamicists, performance engineers, acoustic engineers, and structural

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engineers with quantitative information indicating the characteristics of the surface exposed to air or gas flows.

According to a further aspect there is provided a method of mounting a pressure measurement device (10) as described above to an object, the method comprising:

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- positioning the pressure measurement device (10) to a surface of the object,
- fastening the pressure measurement device (10) to the surface.

Fastening may be done by applying tape, in particular speed tape. Also, other adhesives may be used, depending on the application.

10

The pressure measurement device 10 can easily be mounted to a surface by using speed tape. Speed tape is an aluminium pressure-sensitive tape with excellent adhesive properties that is used in high-performance situations including commercial and military flying. It is a temporary tape that can be resistant to water and solvents, high temperatures, and can even reflect ultraviolet rays. A commercial example would be the Aluminium Foil Tape series from 3M.

15

The tape may be applied such that it covers part of the pressure measurement device 10, in particular part of the tapered parts 7, and part of the surface. Preferably, the method comprises cleaning the surfaces to which the speed tape is to be applied before applying the speed tape to ensure a secure connection between the surfaces and the speed tape.

20

The use of speed tape allows for convenient repositioning of the pressure measurement device 10 as desired easy removal and re-application of speed tape.

25

The method may further comprise two steps prior to the positioning step:

- gluing sensor inserts (3, 4) to the printed circuit board (6),
- positioning the printed circuit board (6) in the housing (2), and
- further assembling the pressure measurement device 10.

30

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures, the subject-matter of the invention is schematically shown, wherein identical or similarly acting elements are usually provided with the same reference signs.

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- Figures 1a shows a schematic view of a pressure measurement device in an unassembled state according to an embodiment,
- Figure 1b shows a schematic view of a pressure measurement device in an assembled state according to an embodiment,
- 5 Figure 1c shows a schematic cross-sectional side view of a pressure measurement device in an assembled state according to an embodiment,
- Figures 1d-e show different detailed schematic cross-sectional views of parts of the pressure measurement device in an assembled state according to an embodiment,
- 10 Figure 2a shows a schematic view of the housing of the pressure measurement device according to an embodiment,
- Figure 2b shows a schematic bottom view of the housing of the pressure measurement device according to an embodiment,
- Figure 3a shows a schematic view of a microphone insert according to an embodiment,
- 15 Figure 3b shows a schematic top view of a microphone insert with the sensing element of the microphone according to an embodiment,
- Figure 4a shows a schematic view of an absolute pressure sensor insert with the absolute pressure sensor according to an embodiment,
- 20 Figure 4b shows a schematic top view of an absolute pressure sensor insert with the absolute pressure sensor according to an embodiment, and
- Figure 5 shows a schematic view of a pressure measurement device according to an embodiment mounted on the wing of a plane.

25 DESCRIPTION OF EMBODIMENTS

With reference to the Figures, a pressure measurement device 10 is described which can be applied to a surface that is to be exposed to an air or gas flow, such that it causes minimal disturbance to the air or gas flow. The height or thickness of the pressure measurement device 10 may as small as 3,5mm and is intended for use in air or gas

30 flows with moderate-to-high Reynolds numbers, typically in the range of above 800.000.

The pressure measurement device 10 can be customized for different surface contours and is scalable to different sizes to give the user the freedom to deploy it on different surfaces with the desired spatial resolutions of the sensors. The highest spatial resolution

35 of the pressure sensors 5,8 is dependent on the sensor size and their inserts 3,4 and can reach the order of 2mm between the sensing elements of the pressure sensors 5,8.

Figure 1a shows a pressure measurement device 10 according to an embodiment in an unassembled state. Fig. 1a shows a printed circuit board 6, in this case a flexible printed circuit board, and a housing 2, which may also be referred to as a cover layer. The housing 2 has a flat or planar shape. The housing 2 comprises a plurality of ports 21. In
5 between the housing 2 and the printed circuit board 6, sensor inserts 3,4 are shown: microphone inserts 3 and absolute pressure sensor inserts 4. It is noted that these sensor inserts 3, 4 are optional and mainly provided for ease of assembly and alignment of the different elements.

10 Further shown are three microphones 8 and one absolute pressure sensor 5 but, it will be understood that different numbers of these pressure sensors 5,8 may be provided in alternative embodiments. The printed circuit board 6 can also be featured in different embodiments, most notably, a continuous double-sided printed circuit board instead of
15 the split representation shown here. The shown split representation allows for most efficient assembly of the top-port absolute pressure sensors 5 on the top side of the printed circuit board 6 and the bottom-port microphones 8 on the bottom side of the printed circuit board 6 with the housing 2.

At the bottom of Fig. 1a an optional protective layer 9 is provided. At the top of Fig. 1a
20 an optional protective skin 1, in this case a glass fibre layer, is provided. The protective skin 1 and the housing 2 comprise skin ports 25 and ports 21 respectively, which after assembly are aligned with the sensing elements of the microphone(s) 8 and the absolute pressure sensor(s) 5.

25 Further provided are tapered parts 7 or ramps.

Fig. 1b shows the pressure measurement device 10 in an assembled state. The skilled person will readily understand from the relative positioning of the different components as shown in Fig. 1a how the different components are to be assembled.

30 Preferably, the printed circuit board 6, in whatever form, is first laid out flat. The printed circuit board has PCB ports 27 at the location(s) of the sensing element(s) of the bottom-port microphone(s) 8. The microphone inserts 3 are aligned with these PCB ports 27. A little adhesive is applied on the flat side of the microphone insert 3 (the side not featuring
35 the cylinder and opposite to side 31 shown in Fig. 3a) and then fixed on the printed circuit board 6 aligned with the PCB port 27. By applying the adhesive close to the outer

circumference, care can be taken to ensure that the adhesive does not flow into the PCB port 27 and damage the sensing element of the microphone 8.

5 The absolute pressure sensor insert 4 features an inner profile 43 as shown in Fig. 4a in the shape of the absolute pressure sensor 5 that automatically ensures alignment. Like fixing microphone insert 3, absolute pressure sensor insert 4 is fixed around the absolute pressure sensor 5 with glue. Absolute pressure sensor insert 4 is symmetric and has no top or bottom side that needs to specifically be referred to. Flat face 41 has the same representation on both sides of the absolute pressure sensor insert 4. Sufficient
10 tolerances between the innermost walls 43 of the absolute pressure sensor insert 4 and the absolute pressure sensor 5 are allowed to prevent excess adhesive from damaging the absolute pressure sensor 5. The pockets 42 visible in the x-shaped interior design of the absolute pressure insert 4 also help to prevent damaging the sensor by collecting any excess adhesive.

15 The protective skin 1 may be manufactured as a flat plate and may be made from glass fibre. This is the simplest and best geometry to manufacture it in and avoids encountering any double curvatures. The protective skin 1 is then fixed with adhesive on the housing 2 and/or in a flat step of the tapered part 7, as described in more detail below.

20 Housing 2 is made from plastic and is manufactured with pockets 22,23,26 and ports 21. The housing 2 is then fixed with adhesive to the assembly of tapered parts 7 and protective skin 1. Adhesive on the top or outer side of the housing 2 fixes it to the protective skin 1 and adhesive on the side walls 24 fixes it to the tapered parts 7. Skin
25 ports 25 are now drilled in protective skin 1 using ports 21 in the housing 2 as reference.

Recessed pocket 26 is a first recess to receive the printed circuit board 6 and pockets 22 and 23 are second recesses to receive the sensor inserts 3, 4 and are provided in the receiving pocket 26. Adhesive is now applied to the round base part 31 and vertical
30 cylinder-shaped top part 32 of microphone insert 3 (explained below with reference to Fig.'s 3a/b), and the top side of the printed circuit board 6 with the microphone(s) 8. This modified printed circuit board 6 is then assembled with the assembly of the housing 2, protective skin 1, and tapered parts 7 by pushing it into the receiving pocket 26 of the housing 2 and the microphone sensor insert 3 snap-fits into a corresponding pocket 22.

35 The adhesive seals all the space and creates a pressure seal. Adhesive is also applied on the exposed side of absolute pressure sensor insert 4. The printed circuit board 6 with

the fixed absolute pressure sensor 5 and absolute pressure sensor insert 4 is assembled with the housing 2 by fixing with glue in receiving pocket 26. Absolute pressure sensor insert 4 fits snugly into a corresponding pocket 23. Sufficient adhesive is used during this process to create the pressure seal while holding the assembly together. Tolerances are provided to allow the excess adhesive to flow out and not damage the absolute pressure sensor 5.

Fig. 1c shows a cross sectional view of the pressure measurement device 10 in an assembled state. Shown are two areas IIID and IIIE which are shown in more detail in Fig.'s 1d and 1e respectively. Fig. 1c shows that the pressure measurement device 10 in assembled state is very thin, and may for instance have a thickness T (as indicated in Fig. 1c) of less than 7mm, preferably less than 5mm or even as thin as 3,5mm.

The optional protective skin 1 may have a minimum thickness of around 0,8mm to provide sufficient stiffness in the least demanding environment. The total height of the housing 2 may have a minimum height of around 2,7mm. The printed circuit board 6 may have a minimum thickness of around 0,3mm when manufactured as a fully flexible printed circuit board 6. All electronic components soldered on the printed circuit board 6 have a maximum thickness of 1mm. The housing 2 features recesses 26 at all locations where electronics components are present. By having the recesses, the printed circuit board 6 with soldered components can fit within the size of the housing 2. The microphone insert 3 which fits in the corresponding pocket 22 may have a minimum height of around 1,2mm. Absolute pressure sensor insert 4 which fits in corresponding pocket 23 may have a minimum height of around 0,9mm. The total minimum thickness of this assembly may result in a minimum product thickness of around 3,5mm. The protective layer 9 adds no excess thickness as it fits within the walls 24 of the housing 2.

Fig. 1d shows a detailed schematic cross-sectional view of part of the pressure measurement device 10 comprising a microphone 8 and a microphone insert 3. Fig. 1d shows the microphone insert 3 inserted into a matching microphone insert pocket 22 aligned with skin ports 25 and ports 21 as will be explained in more detail below. The printed circuit board 6 is inserted into receiving pocket 26.

The microphone insert 3 is shown in more detail in Fig.'s 3a and 3b, according to an embodiment. The microphone insert 3 comprises a flat, round base part 31 and a cylinder-shaped top part 32, wherein the round base part 31 has an outer diameter D3 which is greater than an outer diameter D1 of the cylinder-shaped top part 32. The base

part 31 and the cylinder-shaped top part 32 both have a central axis, the base part 31 and the cylinder-shaped top part 32 are connected to each other with their central axes being in line with each other. The microphone insert 3 comprises a through hole or passage 33 having an inner diameter D2 being smaller than outer diameter D1. The PCB ports 27 in the printed circuit board 6 have the same diameter D2. D4 is also shown in Fig 3b to represent the diameter of the sensing element of the microphone 8.

The housing 2 comprises pocket 22 (microphone insert pocket) which is more clearly shown in Fig. 2b, showing a schematic bottom view of an inner surface of the housing 2 of the pressure measurement device 10. The microphone insert pocket 22 is aligned with one of the ports 21. The microphone insert pocket 22 and the microphone insert 3 are dimensioned and shaped such that the microphone insert 3 can be tightly inserted into the microphone insert pocket 22, e.g. with a snap-fit arrangement. The microphone pocket 22 comprises a cylinder-shaped pocket part configured to receive cylinder-shaped top part 32 and a base pocket part configured to receive base part 31.

The base part 31 may have a filleted or bevelled circumferential edge to allow excess adhesive applied to the outer faces of the cylinder 32 and flat face 31, as described above, to flow away from the area, when fixed into position in microphone pocket 22 of housing 2. This excess adhesive will then collect into receiving pocket 26 of housing 2.

Fig. 1e shows a schematic cross-sectional view of part of the pressure measurement device 10 comprising an absolute pressure sensor 5 and an absolute pressure sensor insert 4. Fig. 1e shows the absolute pressure sensor insert 4 inserted into a matching absolute pressure sensor insert pocket 23 aligned with skin ports 25 and ports 21 as will be explained in more detail below.

The absolute pressure sensor insert 4 is shown in more detail in Fig.'s 4a and b. The absolute pressure sensor insert 4 is formed as a flat member 41, possibly comprising one or more openings 42 to reduce the weight and the amount of material needed, increase stiffness to avoid breaking while handling and when placed in environments with high-vibrations, and act as collectors of excess adhesive that will flow around while applying pressure during assembly. The absolute pressure sensor insert 4 further comprises an opening 43 configured to receive the absolute pressure sensor 5.

The housing 2 comprises an absolute pressure sensor insert pocket 23 which is more clearly shown in Fig. 2b. The absolute pressure sensor insert pocket 23 is aligned with

one of the ports 21. The absolute pressure sensor insert pocket 23 and the absolute pressure sensor insert 4 are dimensioned and shaped such that the absolute pressure sensor insert 4 can be tightly inserted into the absolute pressure sensor insert pocket 23. While the assembly of the microphone insert 3 and microphone insert pocket 22 may be a tight snap-fit that requires considerable force to remove, a strong assembly between absolute pressure sensor insert 4 and absolute pressure sensor insert pocket 23 may be achieved with adhesives.

Fig. 1e shows absolute pressure sensor insert 4 inserted into a matching absolute sensor pressure insert pocket 23 and the absolute pressure sensor 5 positioned in opening 43 of the absolute pressure sensor insert 4. It is noted that since Fig. 1e comprises a cross-sectional view of the pressure sensor insert 4, the absolute pressure sensor insert 4 appears as four separate elements in Fig. 1e, while being just one component.

The embodiments shown in the Fig.'s clearly show one or more microphones 8 positioned on a one side of the printed circuit board 6, and the absolute pressure sensors 5 positioned on the opposite side of the printed circuit board 6. The absolute pressure sensors 5 are positioned on a side facing the housing 2, which may be referred to as a top side, while the microphones 8 are positioned on an opposite side, i.e. a side facing away from the housing 2, which may be referred to as a bottom side.

The microphones 8 and the absolute pressure sensors 5 are preferably provided by micro-electromechanical systems (MEMS) sensors.

Fig. 1d shows protective layer 9 surrounding the one or more microphones 8.

Fig.'s 2a and 2b show that housing 2 is shaped to receive the printed circuit board 6 in a predefined position. The inner surface or inner side of the housing 2 comprises a receiving pocket 26 dimensioned to (tightly) receive the printed circuit board 6 in the predefined position. The microphone insert pocket 22 and the absolute sensor pressure insert pocket 23 are positioned in the receiving pocket 26.

The Figures further show a protective skin 1 provided on top of the housing 2 with the skin ports 25 in this protective skin 1 aligned with the ports 21 in the housing 2. The aligned ports provide for a continuous cavity from the surface of the pressure measurement device 10 to the sensing elements of the pressure sensors 5,8.

Figures 1a-c further show tapered parts 7 provided along part of the circumference of the housing 2. The tapered parts 7 (or ramps) help to minimize the disturbance of the air or gas flow to be measured by the pressure measurement device 10.

5 Not shown in the figures is a coating layer, which may be provided as outer layer on the housing 2 or on the optional protective skin 1, possibly extending over the tapered parts. The coating layer covers at least the skin ports 25 associated with the microphones.

10 Fig. 5 shows an example of a pressure measurement device 10 that has a curved planar shape and which is mounted to a surface of an object, in this case a wing of an aircraft.

The embodiments described above with reference to the figures, provide a robust pressure measurement device 10 that can be mounted in specific locations. The (MEMS) pressure sensors 5, 8 are protected against foreign object damage by the housing 2 and optionally the protective skin 1 and outer coating layer. The use of a coating layer, e.g. 15 Kapton tape, protects the skin ports 25 of the microphones from debris such as insects. The protective layer 9 also protects the electronics from the effects of humidity, dust, UV, and other environmental factors while decreasing the vibrations felt by the microphones.

20 The chosen combination of absolute pressure sensors 5 and microphones 8 provides researchers with a composite dataset of steady pressures and unsteady pressure fluctuations. The pressure measurement device 10 as described can be deployed to investigate surface-panel excitations caused due to turbulent boundary layers and flow features such as vortices. The embodiments have been developed to be rugged enough 25 for low-subsonic flight-testing applications at moderate-to-high Reynolds numbers. The sleeve can be installed without making modifications to an existing surface and can be easily repositioned to obtain data over large spans. The protective skin 1 provides a versatile surface to further customise the pressure measurement device 10 for different experiments.

30 This makes the pressure measurement device 10 an attractive investigative tool for researchers working with aerodynamics, vibro-acoustics, and aero-acoustics, at the very least. The application of the sleeve can range from the simple geometries of flat plates tested in wind tunnels to the large wings of aeroplanes. Furthermore, the data obtained 35 by this stiff pressure measurement device 10 can also be used by researchers to develop advanced lightweight materials with improved manufacturing processes. The

aerodynamic data obtained here can be compared with structural data for enhanced aeroelastic investigations.

5 The pressure measurement device 10 can be applied to surfaces exposed to airflow including models in wind tunnels, wind turbines, automobiles, and buildings. In addition, deploying the pressure measurement device 10 on wind-turbine blades or posts will help understand the effects of tip-vortex or wake interactions with these surfaces. It can be used to enhance flow control devices on the blades, improve the structure of the post, and understand the interaction occurring in farms. Furthermore, as it can be used both
10 in the development and post-production phases, it can be used in automobiles to investigate the need for rear wings, spoilers, or different diffuser curvature.

The pressure measurement device 10 may be used for research and investigative purposes. The pressure measurement device 10 may help to contribute to more efficient
15 aerodynamic surfaces and, consequently, decrease the climate impact of product designs.

Fig. 5 shows a schematic view of a pressure measurement device 10 mounted on the wing of a plane 100. Fig. 5 shows that the pressure measurement device 10 has a curved
20 shape that follows the shape of the wing 100. The pressure measurement device 10 is so thin that at the scale shown in Fig. 5 it remains the outer shape of the wing 100 unaffected.

CLAIMS

1. Pressure measurement device (10) for mounting to a surface, the pressure measurement device (10) comprises
- 5 - a printed circuit board (6);
- pressure sensors (5, 8) connected to the printed circuit board (6); and
- a housing (2);
- the housing (2) covering at least a first side of the printed circuit board (6),
- the housing (2) comprising ports (21) aligned with the pressure sensors (5, 8),
- 10 and
- the pressure sensors (5, 8) comprising one or more absolute pressure sensors (5) and one or more microphones (8),
- wherein the one or more microphones (8) are positioned on a second side of the printed circuit board (6), the second side being opposite the first side of the printed circuit board (6).
- 15
2. Pressure measurement device (10) according to claim 1, further comprising a protective layer (9) positioned at the second side of the printed circuit board (6), the protective layer (9) surrounding the one or more microphones (8).
- 20
3. Pressure measurement device (10) according to any one of the preceding claims, wherein the one or more absolute pressure sensors (5) are positioned on the first side of the printed circuit board (6).
- 25
4. Pressure measurement device (10) according to any one of the preceding claims, wherein the one or more microphones (8) have a first frequency response, the one or more absolute pressure sensors (5) have a second frequency response, wherein the first frequency response is at least 10 times greater and/or higher than the second frequency response.
- 30
5. Pressure sensor device (10) according to any one of the preceding claims, wherein the housing (2) is configured to receive the printed circuit board (6) in a predefined position.
- 35
6. Pressure measurement device (10) according to any one of the preceding claims, wherein the pressure measurement device (10) comprises sensor inserts (3, 4) and an

inner surface of the housing (2) comprises pockets (22,23) to receive the sensor inserts (3, 4).

5 7. Pressure measurement device (10) according to any one of the preceding claims, wherein the printed circuit board (6) is one of a flexible printed circuit board, a rigid printed circuit board, and a flex-rigid printed circuit board.

10 8. Pressure measurement device (10) according to any of the preceding claims, wherein the housing (2) has a curved planar shape.

9. Pressure measurement device (10) according to any one of the preceding claims, wherein the pressure measurement device (10) has a planar shape with a thickness of less than 7mm, preferably less than 5mm, more preferably less than 3,5 mm.

15 10. Pressure measurement device (10) according to any one of the preceding claims, comprising a protective skin (1) provided on an outer surface of the housing (2).

20 11. Pressure measurement device (10) according to any one of the preceding claims, wherein the pressure sensors (5, 8) are micro-electromechanical systems (MEMS) sensors.

25 12. Pressure measurement device (10) according to any one of the preceding claims, further comprising tapered parts (7) provided along at least part of the circumference of the housing (2).

13. Pressure measurement device (10) according to any one of the preceding claims comprising a coating layer covering one or more ports (21, 25) associated with the microphones (8).

30 14. Pressure measurement device (10) according to any one of the preceding claims wherein the pressure sensors (5,8) are positioned in a grid or matrix configuration.

35 15. Pressure measurement device (10) according to any one of the preceding claims, wherein the pressure sensors (5,8) are digital output sensors.

16. Object comprising a pressure measurement device (10) according to any one of the preceding claims mounted to a surface of the object.

17. Use of a pressure measurement device (10) according to any one of the claims 1 – 15 for obtaining combined steady and unsteady pressure measurements.
- 5
18. Method of mounting a pressure measurement device (10) according to any of the claims 1 – 15 to an object, the method comprising:
 - positioning the pressure measurement device (10) to a surface of the object,
 - fastening the pressure measurement device (10) to the surface.

Fig. 1A

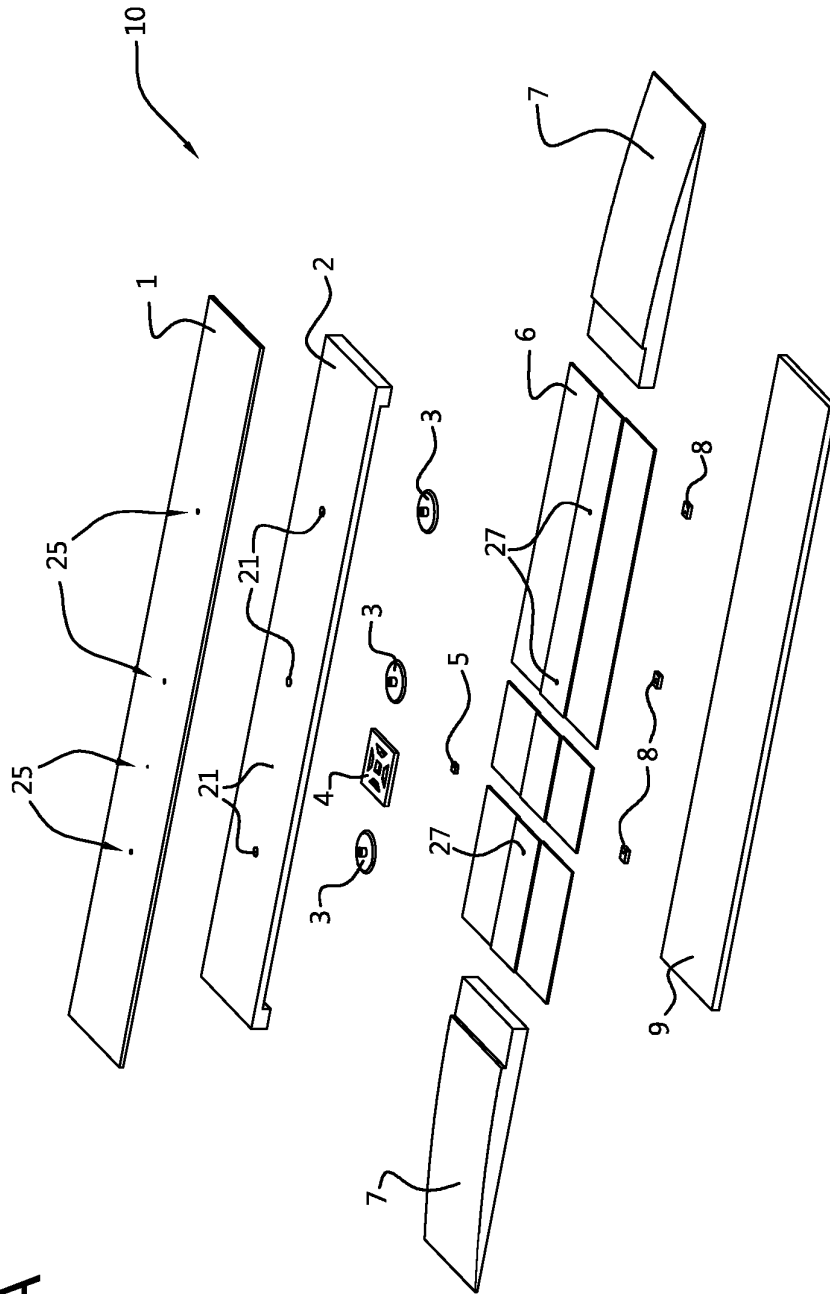


Fig. 1B

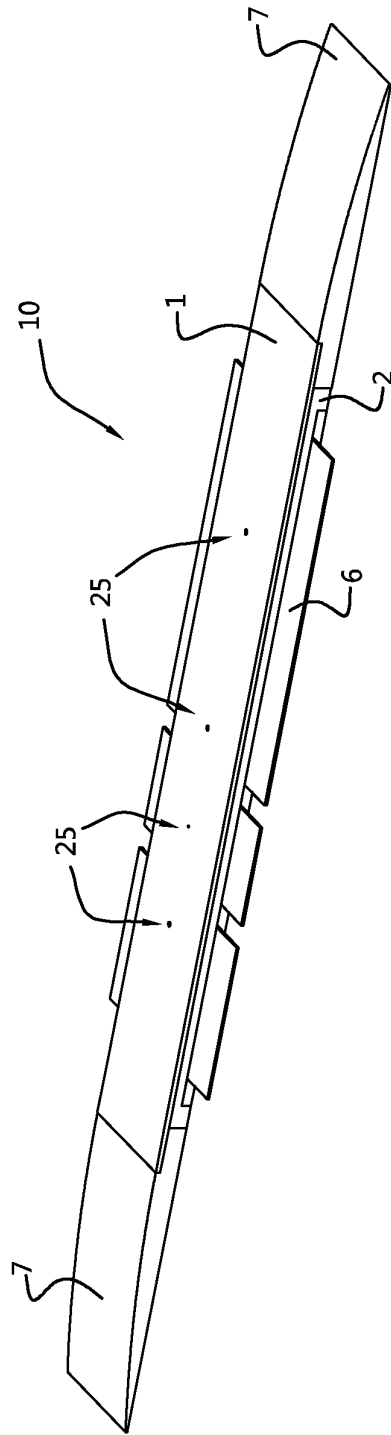


Fig. 1C

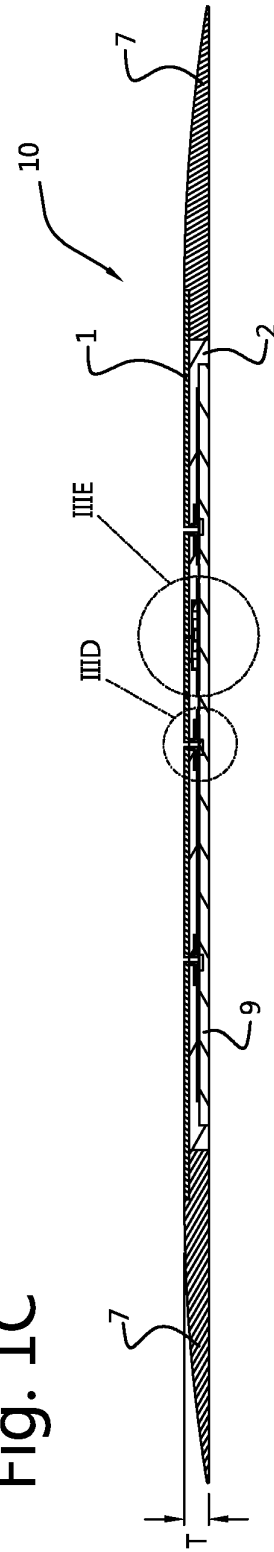


Fig. 1D

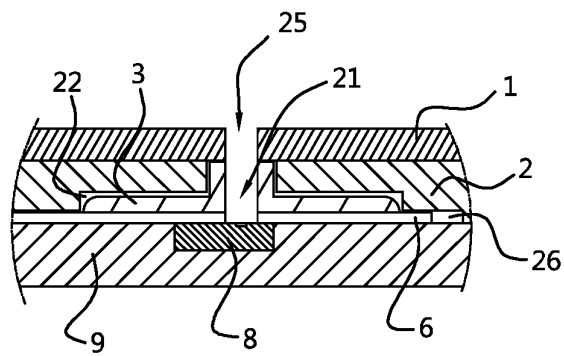


Fig. 1E

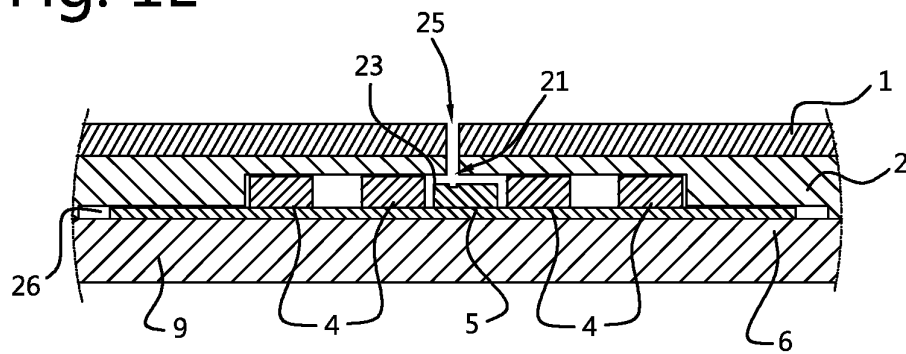


Fig. 2A

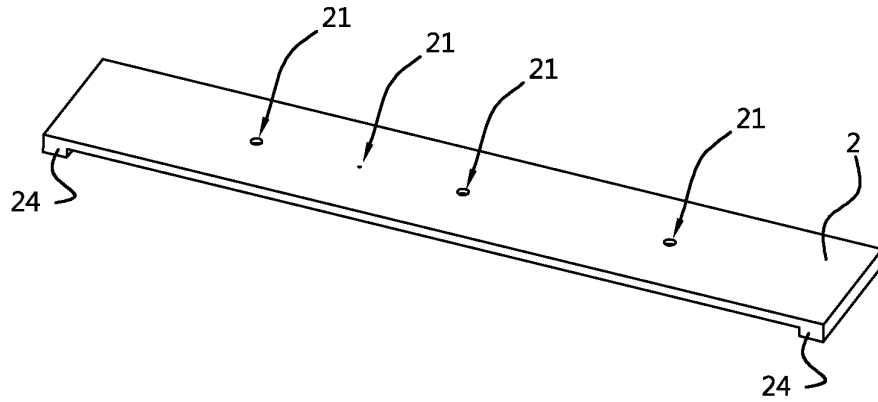


Fig. 2B

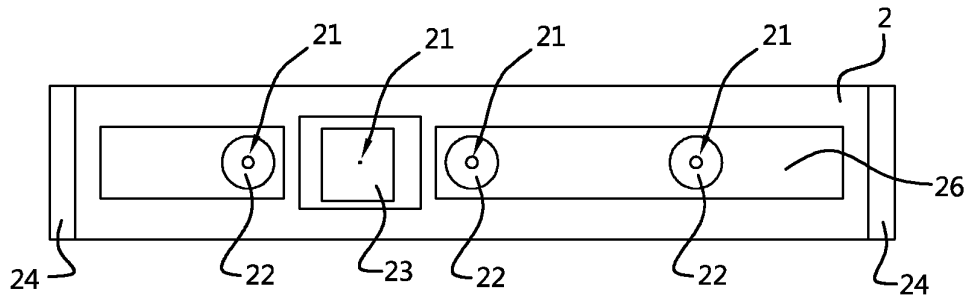


Fig. 3A

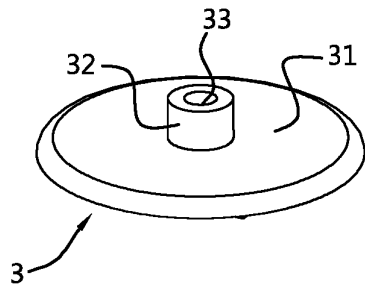


Fig. 3B

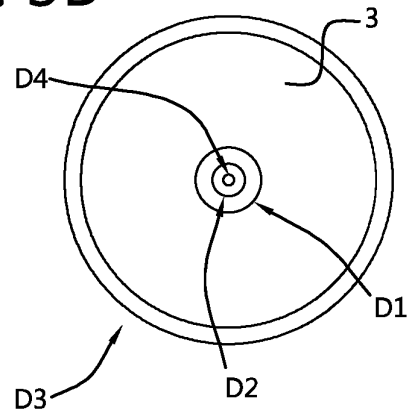


Fig. 4A

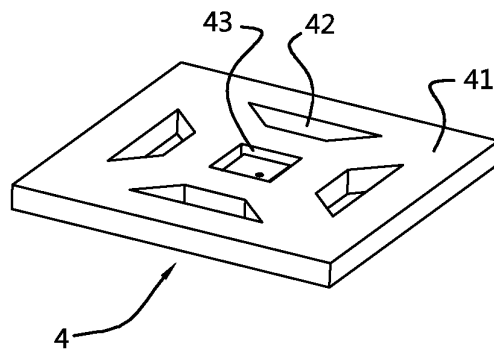


Fig. 4B

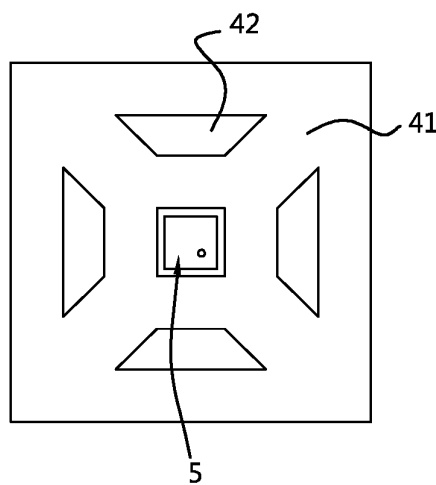
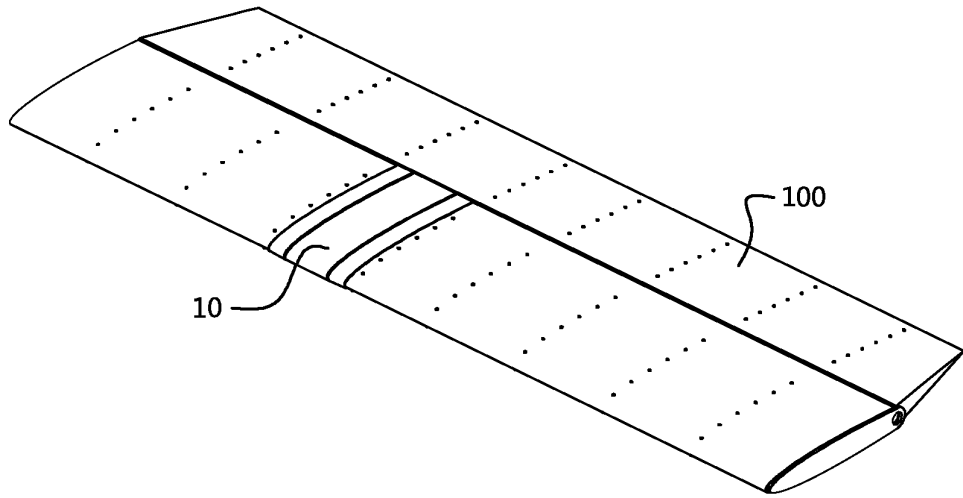


Fig. 5



INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/083765

A. CLASSIFICATION OF SUBJECT MATTER
 INV. G01L15/00 B64F5/60 B81B7/02 G01M9/04 G01M9/06
 H04R1/04 H04R19/00
ADD.
 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)
G01L H04S B64F B82B B81B G01M H04R

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2009/000386 A1 (PARADIS LAWRENCE C [US] ET AL) 1 January 2009 (2009-01-01) paragraph [0036]; figures 3-6 -----	1-18
A	EP 3 542 552 B1 (BOSCH GMBH ROBERT [DE]) 2 June 2021 (2021-06-02) paragraphs [0001], [0009], [0011]; claim 1; figures 1,2a,7b,10 -----	1-18
A	CN 105 849 523 B (AIRBUS OPERATIONS SAS) 8 March 2019 (2019-03-08) claims 1,12; figures 1-3 -----	1-18
A	US 2017/026729 A1 (ALBERS JOHN J [US] ET AL) 26 January 2017 (2017-01-26) claim 1; figures 1,2 -----	1-18

Further documents are listed in the continuation of Box C. See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"E" earlier application or patent but published on or after the international filing date	"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O" document referring to an oral disclosure, use, exhibition or other means	"&" document member of the same patent family
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search 9 January 2025	Date of mailing of the international search report 23/01/2025
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Name and mailing address of the ISA/ European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Authorized officer Cilissen, Marcel
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/EP2024/083765

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