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(54) **Title:** VIBRATION CONTROLLED WINDOW PANE

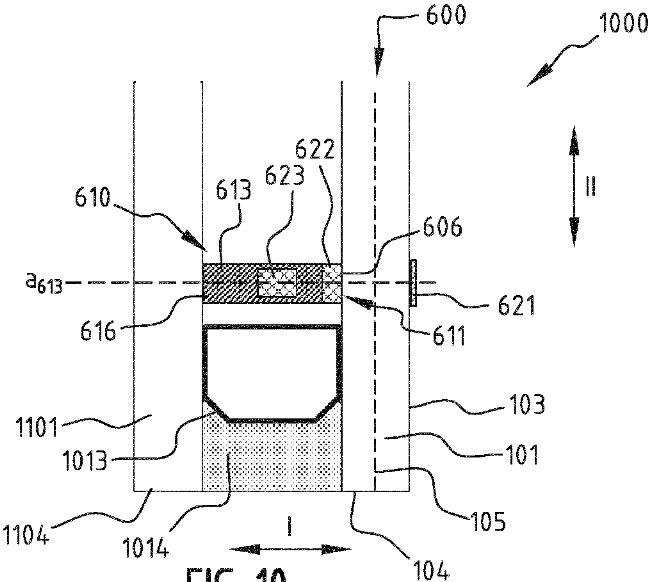

FIG. 10

(57) **Abstract:** Vibration controlled panel, in particular a vibration controlled window pane, comprising: - a panel comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane; and - at least one actuator module comprising an actuation end connected to, or at least contacting, the panel at the actuator connecting section, a second end arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane; - a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at

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least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control the deformation of the panel in the out-of-plane direction.

VIBRATION CONTROLLED WINDOW PANE

The invention relates to a vibration controlled thin panel, in particular a vibration controlled window pane, a multi-panel system, in particular a multi-glazed window, an actuator module and a systems module.

Due to urbanisation, i.e. the increase in the proportion of people living in towns and cities, and the associated population growth of cities, more and more people, and the relating activities, accumulate in ever more densely populated areas. The accumulation leads to an increase in noise generated in these areas. At the same time, available space is becoming sparser, such that even less desirable spaces, such as plots directly adjacent to busy roads, railroads and/or close to flight paths of busy airports are used for building residential and office buildings.

To cope with the increased level of exterior noise, typically increased insulation is applied in the outer shell of the building, although the glass façade and/or windows, of the building typically remain the weakest link. To increase the soundproofing of windows, more window panes having for instance different thicknesses are used in multi-layered windows. Although leading to heavier and more expensive windows, the amount of sound insulation remains limited, such that unwanted noise is still transmitted to the interior of the building and experienced as discomfort by the occupants of the building.

Not only in buildings do the glass façade and/or windows pose a limitation in sound proofing, but also in for instance cars and other vehicles traveling at high speeds, wind noise can have a tiring effect on the driver and/or any passengers. As fatigue has been found to have a significant impact on the driving abilities of a driver, reducing this tiring effect does not only make the driver and/or passengers more comfortable, but can have a beneficial effect on the safety levels on today’s freeways. To reduce noise transmissions, more luxurious cars can be fitted for instance with double glazed windows. Nonetheless, this increases the weight of the car, which is undesirable.

It is a goal of the present invention, next to other goals, to provide for panels, in particular window panes, that allow to reduce the discomfort of exterior noise that the user experiences, in particular to reduce the transfer of noise from the exterior to the interior (and vice versa), wherein at least one of the above mentioned problems is at least partially alleviated.

This goal, amongst other goals, is met by vibration controlled panel, in particular a vibration controlled window pane, comprising:

- a panel comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane; and

- at least one actuator module comprising an actuation end connected to, or at least contacting, the panel at the actuator connecting section, a second end arranged such that movement of the second end, preferably with respect to the panel, is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane;

- a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control the deformation of the panel in the out-of-plane direction.

Out-of-plane vibrations radiate by generating pressure variations in the air. If these pressure variations are in the audible frequency domain of humans (roughly 20 Hz - 20 kHz), persons in the vicinity will experience this as sound. Sounds originating from outside of, for instance buildings, due to, for instance, traffic, wind and or passing people, can excite modes of a window or panel from the outside (i.e. exterior), causing the vibrating windows to radiate the sound on the inside (i.e. interior) and any users on the inside can experience this as noise and thereby as a nuisance. Note that modes can refer to modes originating from any modal decomposition, such as out-of-plane vibration modes of a panel, acoustic radiation modes and the like.

The vibration controlled panel, such as a vibration controlled glass or window pane, thus allows by controlling the (dynamic) deformations of the panel in the out-of-plane direction, or in other words the out-of-plane vibrations of the panel to also control the sound radiating from the panel. Such a vibration controlled panel allows for a reduction of this nuisance using two approaches that can also be combined. Firstly, one can try to cancel out the vibrations of the panel that are responsible for the transfer of sound, such that the sound is hindered in its transfer to the interior, and/or one can force the panel to vibrate to generate a desired sound (like a speaker), such as music or other relaxing sounds, to try and cover the noise that is transferred from the outside to the inside. Hereby, the noise that the user (i.e. occupant) experiences is reduced. Preferably, the vibration controlled panels are at least able to control the out-of-plane vibrations having the largest impact on the sound radiation of the vibration controlled panel.

Other (non-limiting) examples of panels that are suitable for the vibration controlled panel are construction panels, such a plates made of metals, plastics, ceramics, composites and the like, transparent panels, such as glass panels and/or transparent plastics (that may also be semitransparent), made from, for instance, acrylic (polymethylmethacrylate), butyrate (cellulose acetate butyrate), lexan (polycarbonate), PETG (glycol modified polyethylene terephthalate) and the like, acoustic panels that can be, for instance, used in large open office spaces for reducing noise. As explained, suitable uses for the vibration controlled panels are, for instance, glass facades and/or windows of buildings, windows and/or panels of vehicles, such as trains, trucks or cars, acoustic control of flat-screen televisions and/or other large panel displays. Furthermore, the panels can be non-flat, such curved panels or bended panels. The vibration controlled panels are highly suitable for applications involving relatively large and thin panels, and/or thin-walled structural elements wherein radiation and/or control of sound and aesthetics (i.e. wherein actuators and the like are not, or only limited, visible for the average user and/or do not negatively impact the field of view) are of importance.

As the contact between the actuator module and the panel is arranged such that the actuator module is able to (dynamically) apply variations in the out-of-plane bending moments of the panel, the actuator is also able to influence and control the way the panel vibrates and thus radiates sound.

The actuator module is connected to the panel such that the assembly of the panel and the at least one actuator module is asymmetrical with respect to the centre plane of the panel. Or in other words, the actuator module is, for the largest part, arranged towards the first side, or the second side of the panel, as seen with respect to the centre pane. As the actuator connecting section that is arranged asymmetrically with respect to the centre plane, a force that is applied to the actuator connecting section has a moment arm with respect to the centre plane, even if it is applied parallel to, and spaced apart from, the centre plane. Hereby, a force applied in-plane with the panel is able to control, or at least influence, the acoustic radiation and/or out-of-plane vibration of the panel. This also allows to excite the panel from, or near, the edges of the panel, such that it can be integrated in, for instance, window frames, such that the actuator module is hardly, or even not, visible for the user looking through such a window.

The fact that a second end is arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator is arranged to move the actuation end with respect to the second end in order to deform the panel, allows to use small and compact actuator modules that do not require a large mass (or inertia) for transferring the required forces to the panel. Traditional inertial actuators, like used in for instance speakers, rely on relatively large mass (with respect to its stiffness) and thereby also large electric coils for exciting this mass. These types of actuators can often not be made small enough to be hidden near the edges of the panel and would therefore be placed on the parts of the panel where they are visible, thereby hindering the aesthetic appearance of, and unobstructed views through, windows for instance.

It is noted that the second end of the actuator module may be restrained in different ways, wherein restrained refers to limiting, or at least reducing or delaying, the motion (i.e. movement) of the second end. In a preferred embodiment, the second end of the actuator module may be arranged to comprise a movable mass, such that the inertia of the movable mass restrains the second end in such a way that the movement of the second end is limited, or at least reduced (or delayed) in order to be able to apply a force onto the actuator connection section of the panel, thereby enabling to control the vibrations of the panel. Such an actuator module is also referred to as an inertial actuator. It is noted that in some embodiments the movable mass may be the mass of the actuator itself, in some embodiments, an additional mass may be added.

In another preferred embodiment, the second end is, for instance, restrained as it is directly, or indirectly, connected to a fixed structure thereby effectively limiting, or at least reducing, the motion of the second end. Several embodiments presented below comprise such a direct or indirect connection to, for instance, the panel itself, or a frame holding said panel. Thereby the second end is effectively constrained.

The controller can be connected to the panel near the circumferential edge, such that it would be arranged along with the actuator module, but can also be arranged at a distance from the panel. For instance, the controller can be arranged separately, or within the external panel frame, whereby it would be connected to the actuator module using, for instance, a suitable electrical connection.

That the actuator connecting section is arranged at and/or adjacent to the outer circumferential edge can be interpreted as directly arranged on the outer circumferential edge and/or on a section of the front and back sides that is directly adjacent to the outer circumferential edge or that is near the outer circumferential edge, wherein near is to be understood (also throughout the remainder of the text) as preferably no further than 20 times the thickness of the panel from the outer circumferential edge, more preferably no more than 15 times the thickness of the panel, even more preferably no more than 10 times the thickness of the panel, highly preferred to be no more than 8 times the thickness of the panel and mostly preferred no more than 5 times the thickness of the panel.

It is preferred that the actuator is a stacked piezoelectric actuator. Stacked piezoelectric actuators are relatively small actuators that can provide relatively large forces for a wide range of frequencies. Thereby, they allow for the use of compact actuation modules that can be arranged on, or near, the edges of the panel for controlling the out-of-plane vibrations of the panel in a relatively wide bandwidth.

In a preferred embodiment, the actuator module comprises a frame member and wherein the actuator is coupled to the frame member. The frame member allows for supporting the actuator, such that it can easily be installed onto the window and any reaction forces can, at least partly, be taken up by the frame member. The frame member preferably comprises the second end. Hereby, the second end can be securely fastened to a fixed point, such as an external (window) frame or to the panel itself, thereby effectively restraining movement of the second end.

In a preferred embodiment of the vibration controlled panel, the second end is connected to, or at least contacts, the panel for the restraining of movement of the second end. This enables to install the actuator modules directly onto the panel, such that in principle no connection between the actuator module and an external panel frame would be needed. Hereby, the vibration controlled panels can be pre-assembled with the actuator modules already attached to the panel, such that the installation of the vibration controlled panels in an external panel frame would differ little from the installation of traditional panels. After installation, the actuator module could still be in contact with the external frame for additional support, although this is not essential for a proper functioning of the vibration controlled panels.

It is preferred that the second end is connected to, or at least contacts, the front side or back side of the panel at a secondary actuator connecting section, wherein the secondary actuator connecting section is arranged near, or adjacent to, the outer circumferential edge and wherein the secondary actuator connecting section is arranged at a non-zero distance from the actuator connecting section.

Arranging the secondary actuator connecting section near, or adjacent to, the outer circumferential edge allows for connecting the actuator module at the edge of the panel, such that it interferes minimally with the aesthetics of the panel, and/or the allows for an unobstructed view through the vibration controlled window pane. Preferably, the secondary actuator connecting section is comprised in the actuator connecting section that is arranged substantially asymmetrical with respect to the centre plane, thereby allowing to control the bending moment around the central plane, as described above.

In a preferred embodiment, the second end is connected to, or at least contacts, an external frame for mounting and holding the panel for the restraining of movement of the second end. By also connecting, or at least contacting, an external frame with the second end, reaction forces resulting from the actuator module can be effectively taken up by a surrounding supporting structure, thereby preventing applying too much force to the panel.

In a preferred embodiment, the actuator is arranged to move the actuation end by expanding and/or contracting along a longitudinal axis of the actuator. This allows for generating a stroke required for moving the actuation end and thereby to apply a force to the panel through the actuation end.

It is preferred that the actuator is arranged such that a component of the longitudinal axis that is substantially parallel to the centre plane is larger than a component of the longitudinal axis that is substantially perpendicular to the centre plane, and wherein the actuator, or at least the longitudinal axis of the actuator, is arranged at a non-zero distance from the centre plane of the panel, as seen in the direction perpendicular to the centre plane. This arrangement allows for a compact arrangement of the actuator module that is able to control the (dynamic) bending moment of the panel, and thereby the out-of-plane vibrations of the panel. In particular, it allows for arranging the actuator connecting section on the circumferential edge of the panel, such that it can be arranged inside an external panel frame that hides the actuator module from sight. In this case it is preferred that the longitudinal axis of the actuator is substantially parallel to, and arranged at a non-zero distance from, the centre plane of the panel, as seen in the direction perpendicular to the centre plane.

Alternatively, the actuator can be arranged such that a component of the longitudinal axis that is substantially perpendicular to the centre plane is larger than a component of the longitudinal axis that is substantially parallel to the centre plane, and wherein the actuator, or at least the longitudinal axis of the actuator, is arranged inwardly with respect to, and at a non-zero distance from, the outer circumferential edge of the panel. This arrangement also allows for a compact arrangement of the actuator module that is able to control the (dynamic) bending moment of the panel, and thereby the out-of-plane vibrations of the panel. In particular, it allows for arranging the actuator connecting section on the front and/or back sides of the panel, near the outer circumferential edge of the panel, such that it can be arranged inside an external panel frame that hides the actuator module from sight. As the actuator module is at least partly mounted to the front and/or back side, it would be possible that an external panel frame should be made a bit wider to accommodate the actuator module. Preferably, the longitudinal axis of the actuator is substantially perpendicular to the centre plane of the panel, as seen in the direction perpendicular to the centre plane, hereby the force of the actuator would be perpendicular to the centre plane, allowing more simply influencing and/or controlling the modes, such as acoustic radiation modes or out-of-plane vibration modes, of the panel.

In a preferred embodiment, the actuator connecting section is arranged at, preferably only, the front side or back side, adjacent to the outer circumferential edge, such that the actuation end is connected to, or at least contacts, the front side or back side of the panel. Hereby, the actuation end directly contacts the front side or back side of the panel allowing one to apply the control directly to the sides of the panel.

In a preferred embodiment, the actuator module comprises a pre-loading mechanism for applying a compression preload in the longitudinal direction of the actuator, preferably wherein the pre-loading mechanism comprises an adjustment mechanism for adjusting the preload applied to the actuator. Certain types of stacked piezoelectric actuators require a certain amount of (compressive) pre-loading to function properly and reliably. The pre-loading mechanism allows for the setting of the preload. In addition, during assembly the actuator can be freely placed in the actuator module and afterwards fixed using a predefined amount of preload using the pre-loading mechanism. The adjustable pre-loading mechanism preferably comprises an adjustable screw for allowing this.

In a preferred embodiment, the second end of the actuator module comprises a movable mass for restraining motion of the second end. As also explained above, the actuator module (i.e. an inertial actuator module) is arranged to (dynamically) apply forces, through the actuation end, onto the actuator connection section for controlling the out-of-plane bending moments of the panel. By arranging a movable mass at the second end, the second end is (dynamically) restrained. Due to the inertia of the mass any induced motion of the second end, that is due to a sudden dynamic force that is generated by the actuator, is delayed and/or reduced, such that a dynamic force is transferred to the actuator connection section, through the actuation end of the actuator module. The second end of the actuator module is thus effectively restrained by the inertia of the movable mass. Hereby, the second end of the actuator module need not be connected to a fixed point, but can rather be left free, thereby simplifying assembling the actuator module to the panel. As disclosed above, the movable mass may be an additional mass and/or even the own mass of the actuator module that comprises, for instance, the mass of its components, such as a coil and/or a magnet.

The movable mass is, preferably, in the range of 10 grams – 1000 grams, in case of an amplified piezo stack actuator it is more preferably between 50 grams to 250 grams and in case of an electrodynamical inertial actuator it is more preferably in the range of 10 grams – 300 grams, even more preferably between 10 grams – 100 grams.

In a preferred embodiment of the vibration controlled panel, the actuator module comprises a transfer mechanism that couples the actuator and the actuation end and that is arranged for transferring a movement of the actuator to the actuation end. Such a transfer mechanism allows for transferring the motion if, for instance due to space-constraints, a connection between the actuator and the panel is not possible. In addition, it enables to apply a lever to the movement and/or force that is provided by the actuator to the actuation end of the actuator module.

Preferably, the transfer mechanism is arranged for transferring the movement of the actuator along the longitudinal axis of actuator to a movement of the actuation end that is at an acute angle with, or substantially perpendicular to, the longitudinal axis of the actuator. Hereby, the orientation of the actuator within the actuator module can be chosen independently from the direction of motion of the actuation end, such that a more compact actuator module can be obtained.

Additionally, or alternatively, the transfer mechanism can comprise a linkage mechanism for coupling the actuator and the actuation end. Such a linkage mechanism allows for creating a lever effect as described above, and also allows for varying the direction of motion of the actuation end with respect to the orientation of the actuator.

It is preferred that the linkage system is a four bar linkage mechanism, preferably comprising four bars that are successively arranged and coupled with respect to each other at respective nodes by means of hinges for forming a closed loop, preferably wherein the actuation end is connected to a first node and the actuator is coupled at its respective ends to two opposite nodes that are adjacent to the first node, such that a movement of the respective actuator ends is transferred to a movement of the actuation end. Four bar linkage mechanisms are relatively simple and compact transfer mechanisms that can be customized, in terms of leverage provided, by altering the lengths of the respective bars. Thereby, an actuation module can be more easily customized to the size of the panel, as a larger panel would require larger forces for an effective control of the vibrations, while still remaining compact enough to be able to be integrated into, or near, the edges of the panel, for instance in an external panel frame.

In a preferred embodiment, the transfer mechanism is arranged as a compliant mechanism comprising flexible hinges. Flexible hinges have no relative moving parts, as is the case for traditional hinges. These flexible hinges allow for miniaturization and do not suffer from stick-slip effects, thereby allowing one to make compact actuator modules that can be more easily controlled, when compared to systems having traditional hinges. As has been discussed above, by making the actuator modules as small and compact as possible, the aesthetic appearance of the panels (e.g. an unobstructed view through windows) is minimally affected.

In a preferred embodiment, wherein the panel has modes, such as out-of-plane vibration modes or acoustic radiation modes, and wherein at least one mode of the panel has at least one nodal line, such that, when the panel vibrates in the one mode, the panel at the at least one nodal line exhibits substantially no out-of-plane motion, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal line of the certain mode. By arranging the actuator module at a nonzero distance from the nodal line, the amplitude of vibration of that particular mode can be controlled by the actuator. Preferably, the vibration controlled panel is arranged for controlling at least the first four modes of the panel, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal lines of the first four modes. Hereby, the at least one actuator module is arranged to control at least the first four modes, which are responsible for noise propagation in the lowest frequency range of the noise.

In a preferred embodiment, the vibration controlled panel comprises at least two actuator modules that are spaced apart from each other at, or near, the outer circumferential edge and/or wherein the outer circumferential edge comprises an upper edge, lower edge, first side edge and second side edge and wherein at least on actuator module is arranged at, or near, at least two of the upper edge, lower edge, first side edge and second side edge. By arranging more actuator modules, one is able to apply larger total forces to the panel for controlling the out-of-plane vibrations. In addition, it allows for a more optimized placement of the actuator modules, such that the different modes, such as out-of-plane vibration modes or acoustic radiation modes, of interest are more easily controlled. For instance, the first out-of-plane vibration mode will have its maximum out-of-plane displacement around the middle of the panel, hence placing a first actuator module near, or at, the edge in the middle of the respective edge will ensure that this first actuator module has the best possible control (that can be obtained when placing actuator at the edge) of the first mode. The second out-of-plane mode, however, will have a single nodal line that runs substantially through the middle of the panel, such that the first actuator module will not be able to control the second out-of-plane mode. By placing a second actuator module at one quarter, or three quarter, of the length of the panel at, or near, the edge, the second actuator module will make that the second mode can also be controlled. By using even more actuator modules, the controllability of more and more modes, such as acoustic radiation modes or out-of-plane vibration modes, can be improved, thereby also improving the frequency bandwidth in which the vibrations of the panel can be controlled.

A preferred embodiment of the vibration controlled panel comprises at least one sensor configured for determining a state variable associated to the vibration controlled panel, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal to the controller. This allows for applying feedforward and/or feedback control strategies aiming at improving the control of the panel. By feeding the controller with reference input signals, such as the sound pressure acting on the exterior side of the vibration controlled panel, one is able to process the signals in a feedforward loop, thereby reducing the effects of the inputs on the vibratory response of the panel. Alternatively, or additionally, the controller can be fed with error signals characterizing the actual vibration response of the panel, such as accelerations, strains and/or forces. These signals can be applied in the feedback loop that can be arranged for minimizing the out-of-plane vibrations in certain bandwidth, or associated to certain modes, such as acoustic radiation modes or out-of-plane vibration modes. Also, if the controller receives an input signal to in fact generate sound, a bit like a speaker, these reference and/or error signals can be used for correcting any errors between the actual and desired response of the vibration controlled panel. To enable this, the at least one sensor comprises a microphone, strain sensor, vibration sensor and/or force sensor.

It is preferred that the actuator is a piezoelectric actuator and wherein the piezoelectric actuator is configured for determining a movement of the actuator connecting section, such that the at least one sensor comprises the piezoelectric actuator. Based on the capability in reciprocal conversion between the electric and mechanical strain energy, a single piece of piezoelectric material can play the roles of both an actuator and a sensor concurrently. Thus, a piezoelectric stack actuator allows to implement a truly collocated actuator-sensor pair, capable of actuating and sensing a panel in the same time. This type of configuration, so-called “self-sensing actuator” has a number of advantages, such as: better closed-loop stability (because of the perfect collocation); eliminate the possible capacitive coupling between the sensor and the actuator; smaller actuator-module footprint and easier integration into the window frame (i.e. compactness of the actuator module). However, a self-sensing actuator typically uses an additional electric circuit, so-called “bridge circuit” or “Wheatstone bridge” to extract the sensor voltage (i.e. the signal) out of the total voltage (of the actuator and the sensor).

In a preferred embodiment, the at least one sensor comprises a nearly collocated sensor, preferably a vibration and/or force sensor, arranged at the actuation end that is configured for determining the state variable, preferably an out-of-plane movement and/or applied force, at the respective end of the actuator. Collocation means that the error sensor is located at the same place as the actuator, thus forming a collocated actuator-sensor pair. This configuration is particularly used in feedback control strategies because it has the property to guarantee the stability of the control loop. However, in real applications, it is not always possible to locate the actuator and the sensor in the exact same place. However, a nearly collocated setup already has a positive effect on the stability.

In a preferred embodiment, the at least one sensor comprises a closely located sensor, preferably a strain, vibration and/or force sensor, that is configured for determining the state variable at the front side or back side of the panel, near the actuator connecting section or the secondary actuator connecting section, preferably no further than five times the thickness of the panel from the actuator connecting section or the secondary actuator connecting section, more preferably no further than two times the thickness. Hereby the use of a sensor is still enabled in case it cannot be located closer to the actuator.

By, for instance, applying the sensor on the opposite side of the window, it can be placed and replaced, in case of a failure of the sensor, more easily. Therefore, it is preferred that the closely located sensor is configured for determining the state variable at the one of the front side and back side that is opposite to the other of the front side and back side comprising one of the actuator connecting section and the secondary actuator connecting section at substantially the same location as the one of the actuator connecting section and the secondary actuator connecting section, as seen in the out-of-plane direction.

In a preferred embodiment, the at least one sensor comprises a collocated strain sensor that is arranged directly on the actuator for determining the strain of the actuator due to the expansion or contraction of the actuator. As described above, this would allow for a collocated setup, with the difference that the sensor and actuator are not integrated. However, as the self-sensing actuator typically uses an additional electric circuit, so-called “bridge circuit” or “Wheatstone bridge” to extract the sensor voltage out of the total voltage (of actuator and sensor), this is would not be needed in this setup.

In a preferred embodiment, the controller is configured to store a predefined set point for the state variable; and wherein the controller is configured for controlling the actuator in dependence of the predefined set point and the determined state variable. The controller would for instance be configured to fully suppress, using the actuator module(s), certain modes that have the largest effect on the transfer of noise. Alternatively, the controller could be configured to minimize the accelerations measured by accelerometer fitted to the panel.

It is further preferred that the controller is configured for determining and/or predicting out-of-plane vibrations of the panel based on the determined state variable and to control the actuator to deform the panel to vibrate out-of-phase with respect to the determined and/or predicted out-of-plane vibrations of the panel, such that the acoustic radiation of the thin-panel is reduced and/or substantially cancelled out. Urging the panel to move out-of-phase with respect to the out-of-plane vibrations that are measured, could cancel out the vibrations associated to the modes, such as acoustic radiation modes or out-of-plane vibration modes of the panel, such that the out-of-plane movements or acoustic radiation of the entire panel is reduced, or even minimized, and thereby the transfer of noise to the interior can be reduced, or even minimized.

In a second aspect, the invention relates to a multi-panel system, in particular a multi-glazed window, comprising at least a first and second panel, of which at least the first panel is a vibration controlled panel according to any of the embodiments, wherein each of the panels are arranged parallel with respect to each other and spaced apart from each other, wherein the adjacent panels are connected to one another by means of a spacer and sealing means arranged in between the adjacent panels that runs substantially adjacent to the outer circumferential edge of the panels along substantially the full circumference of the panels, such that the adjacent panels and the spacer and sealing means enclose a space. The spacer and sealing means preferably comprising at least a spacer and primary seal, wherein the primary seal is arranged for sealing the connections between the spacer and the first and second panel. Furthermore, a secondary seal can be provided that covers the primary seal over substantially the full circumferential edge of the multi-panel system.

Multiple-glazed windows were originally developed to improve thermal insulation. However, they tend to make the noise transmission even worse than single-glazed windows in the low-to-medium frequency range (50 - 1000 Hz). Hence, by applying a vibration controlled panel according to any of the preceding embodiments allows to reduce the noise transmission.

In a preferred embodiment of the multi-panel system, the at least one actuator module is arranged in the space in between the first and second panel. This enables to install the multi-panel system in a normal panel frame (i.e. window frame).

In a preferred embodiment, wherein the second end is connected to, or at least contacts, the second panel for the restraining of movement of the second end. As has been discussed for the vibration controlled panel, this enables to install the actuator modules directly onto the panels of the multi-panel system, such that in principle no connection between the actuator module and an external panel frame would be needed.

In a preferred embodiment, at least a part of the actuator is coupled to the frame member and, preferably, wherein the frame member comprises the second end. The frame member allows for supporting the actuator, such that it can easily be installed onto the multi-panel system and any reaction forces can, at least partly, be taken up and/or transferred by the frame member.

In a preferred embodiment, the frame member is integrally formed with the spacer and/or sealing means. This allows for a very compact and slender solution, wherein the actuator module is hardly, or not, visible from the outside of the panel.

In a preferred embodiment, the multi-panel system comprises a connectable module comprising a housing member and the at least one actuator module, wherein the housing member is arranged to substantially cover the actuator module at at least one side of the connectable module that faces the first panel, and wherein the connectable module is arranged in the space between the adjacent panels and is connected to the spacer and/or sealing means. Hereby, a standard multi-panel system can more easily be upgraded to a vibration controlled multi-panel system, as it would merely require one to install the connectable module during assembly of the multi-panel system.

Preferably, the housing member comprises a wall section that faces the first panel and wherein the wall section comprises an opening through which the actuation end is arranged that is connected to, or at least contacts, the panel at the actuator connecting section. The wall section hides most of the actuator module from plain sight, such that a visually pleasing multi-panel system is obtained.

In a third aspect, the invention relates to an actuator module as arranged in the vibration controlled panel according to any of the preceding embodiments, comprising an actuation end that is arranged to be connected to, or at least to contact, the panel at the actuator connecting section, a second end arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to, when the actuation end of the at least one actuator module is connected to, or at least contacts, the actuator connecting section, deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane; electrical connecting means arranged for connecting to a controller that is configured to receive at least one input signal and configured to control the at least one actuator of the at least one actuator module to cause the actuator end to move, in dependence of the at least input signal, in order to deform the first panel in at least an out-of-plane direction that is substantially perpendicular to a centre plane, when the actuation end of the at least one actuator module is connected to, or at least contacts, the first panel at the actuator connection section thereof that is arranged asymmetrically with respect to the centre plane. This enables to obtain the vibration controlled panels as described above.

In a further aspect the invention relates to a connectable module for use in the multi-panel system according to any of the preceding embodiments or for use with a vibration controlled panel according to any of the preceding embodiments, wherein the connectable module is arranged to a panel or to be inserted in a space between adjacent first and second panels of the multi-panel system and comprises connecting means for connecting the systems module to the spacer and/or sealing means, the connectable module comprising:

at least one actuator module according to the third aspect;

a housing member arranged to substantially cover the at least one actuator module at at least one side of the connectable module that is arranged to face the first panel; and

a controller configured to receive at least one input signal and that is electrically connected to the at least one actuator and configured to control the at least one actuator of the at least one actuator module to cause the actuator end to move, in dependence of the at least one input signal, in order to deform the first panel in at least an out-of-plane direction that is substantially perpendicular to a centre plane, when the actuation end of the at least one actuator module is connected to, or at least contacts, the first panel at the actuator connection section thereof that is arranged asymmetrically with respect to the centre plane. This enables the relatively easy installation of the module for upgrading a multi-panel system or panel to a vibration controlled multi-panel system or vibration controlled panel.

In a further aspect the invention relates to a method for reducing the transfer of noise through a panel, in particular a window pane comprising a panel, comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane, wherein the method comprises the steps of:

- providing at least one actuator comprising an actuation end and a second end;

connecting or at least contacting the actuation end of the actuator to the actuator connecting section of the panel of the window pane;

- restraining movement of the second end;
- providing a controller;
- receiving, by the controller, at least one input signal;
- controlling, with the controller and in dependence of the at least one input signal, the actuation end to control the deformation of the panel in the out-of-plane direction such that vibrations of the panel that are responsible for the transfer of the noise are reduced.

A preferred embodiment of the method further comprising the step of providing at least one sensor configured for determining a state variable associated to the vibration controlled window pane, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

In a further aspect the invention relates to a kit-of-parts for forming a panel, in particular a window pane, into a vibration controlled panel, in particular a vibration controlled window pane, comprising:

- at least one actuator module comprising an actuation end arranged to connect to, or at least contact, a panel of the window pane at an actuator connecting section of the panel adjacent to an outer circumferential edge of the panel, the panel comprising a centre plane in between a front side of the panel and an opposed back side of the panel, and the actuator connecting section being arranged asymmetrically with respect to the centre plane, wherein the actuator module further comprises a second end arranged such that movement of the second end is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to, when in use, deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane;

- a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control, when in use, the deformation of the panel in the out-of-plane direction such that vibrations of the panel that are responsible for the transfer of the noise are reduced.

In a preferred embodiment, the kit-of-parts further comprises at least one sensor configured for determining a state variable associated to the vibration controlled panel,, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

The present invention is further illustrated by the following figures, which show preferred embodiments of the vibration controlled panel, and are not intended to limit the scope of the invention in any way, wherein:

- Figure 1 schematically shows a window according to the prior art from having double glazing.
- Figure 2 shows out-of-plane vibration modes of a single window pane.

- Figure 3 schematically shows actuator and/or sensor placement locations with respect to the nodal lines of the first eight vibration modes of a panel.
- Figure 4 schematically shows the typical architecture of the components of a vibration controlled panel.
- Figure 5 schematically shows a first embodiment of a vibration controlled panel, in particular a window pane.
- Figure 6 schematically shows a second embodiment of the vibration controlled panel.
- Figure 7 schematically shows a third embodiment of the vibration controlled panel.
- Figure 8 schematically shows a fourth embodiment of the vibration controlled panel.
- Figure 9 schematically shows a fifth embodiment of the vibration controlled panel.
- Figure 10 schematically shows a first embodiment of a multi-panel system, in particular a double glazing unit, comprising a sixth embodiment of the vibration controlled panel.
- Figure 11 schematically shows a second embodiment of the multi-panel system comprising a seventh embodiment of the vibration controlled panel.
- Figure 12 schematically shows a third embodiment of the multi-panel system comprising an eight embodiment of the vibration controlled panel.
- Figure 13 schematically shows a fourth embodiment of the multi-panel system comprising a ninth embodiment of the vibration controlled panel.
- Figure 14 schematically shows a panel in a panel frame comprising a feedforward microphone integrated on an exterior side of the panel frame.
- Figure 15 schematically shows a panel in a panel frame comprising a feedback or error-microphone integrated in an interior side of the panel frame.
- Figure 16 schematically a 3D perspective of yet another embodiment of the multi-panel system, wherein the actuator module comprises a transfer mechanism.

Figure 1 schematically shows a typical window 1 according to the prior art from having a double glazing unit 10. The double glazing unit 10 comprises a first (e.g. exterior) window pane 11 and a second (e.g. interior) window pane 12 that are coupled by means of the spacer and primary seal 13 and the secondary seal 14 at the outer circumferential edge 16. The primary seal is typically a thin elastomeric material located at the areas of contact between the spacer and the window panes (i.e glazings). It allows the bonding of the window panes with the spacer and thereby seals the space, or cavity, 15 between the two panes. The double glazing unit 10 is held in a window frame 2 comprising at least rubber seals 21 for holding an sealing the double glazing unit 10 in an aluminum window frame 2, which typically comprises extruded aluminum parts 22 that are interconnected by means of so called thermal breaks 23 for preventing thermal bridges forming through the window frame 2. Note that panel and/or window frames can also be made from different materials, such a plastics (PVC), wood and/or other metals, such as steel. The space 15 formed in between the window panes is typically a gas-filled or vacuum space to reduce heat transfer. These double glazing units (or multi-glazing units) however suffer from a lack of soundproofing performances in the low-to-medium frequency range because of the first (out-of-plane vibration or acoustic radiation modes) modes of the glass and/or window panes 11, 12. The first modes of the glass and/or window pane 11, 12 induce a high acoustic radiation of the glass and/or window pane 11, 12 in the low-to-medium frequency range and are therefore responsible for the high noise transmission through the double glazing units 10.

Examples of the first four out-of-plane vibration modes 30, 40, 50, 60 of a single (rectangular) flat panel (i.e. plate) are shown in figure 2. The modes 30, 40, 50, 60 have different combinations of sinusoidal displacement shapes along the two directions x, y of the plate, thereby creating a series of valleys 42, 52, 62 and peaks 31, 41, 51, 61, which a separated by small zones 43, 53, 63 showing substantially no out-of-plane displacement, which are also referred to as the nodal lines 43, 53, 63 of the modes. These types of out-of-plane vibration modes 30, 40, 50, 60 thus induce the high acoustic radiation of the glass and/or window pane 11, 12. Controlling the amplitudes of the modes 30, 40, 50, 60 thus allows for controlling the acoustic radiation of the window panes 11, 12.

Figure 3 schematically shows actuator and/or sensor placement locations 71 with respect to the nodal lines 72 of the first eight modes, such as acoustic radiation modes or out-of-plane vibration modes, of a panel, or window pane 11. The actuator and/or sensor placement locations 71 are all arranged along the circumferential edge 16 of the panel 11 and are spaced with respect to each other and with respect to the nodal lines 72, such that the respective modes are observable and controllable.

The ability to vibrate all the modes in the desired frequency range (so-called “controllability”) is important because it means that the actuators are able to reproduce any vibration pattern, which is always a combination of the different modes of the panel 11. If some modes can not be reproduced by the actuators, they will not be able to control some frequencies efficiently. In the same way, the ability to sense all the modes in the desired frequency range (so-called “observability”) is also important because it means that the error sensors are able to pick up all the information required by the controller so that he can determine the optimal driving signals for the actuators.

This requires a proper selection of actuator and/or sensor placement locations 71 along the outer circumferential edge 16 of the panel 11 such that they are not located on a nodal line 72 of any mode to be controlled or sensed. Mode frequencies as well as location of the respective nodal lines 72 can be determined in a number of different ways which are well known to those skilled in the art (experimental modal analysis, finite element model, analytical formulation). Once obtained, optimal actuator and/or sensor placement locations 71 can be estimated, knowing that the maximum actuation/sensing efficiency for a given mode is reached when the actuator and/or sensor placement locations 71 are on the axis of one extrema of the mode.

Figure 4 schematically shows the typical architecture of the components of a vibration control system 80 as used for obtaining a vibration controlled panel. The signals picked up by the sensors, preferably at least one error sensor 81 and optionally at least one reference sensor 82 in case of a feedforward control strategy, can be processed by a sensor conditioning unit 83 for filtering & amplification and fed to the control unit 84. The latter then uses this data to determine the optimal signals to drive the actuator 85 (or actuator module) through the actuator amplifier unit 87. An objective of the control unit 84 can be to minimize a residual error signal at the error sensors locations. Optionally, software 86 can be provided that is configured to adjust the main parameters of the control unit 84 at the initialization phase. Note that any combination of the control unit 84, sensor conditioning unit 83 and actuator amplifier unit 87 is typically referred to as the controller.

The components of the vibration control system 80 (sensors 81, 82, actuators 85, electronics and mechanical parts) are preferably placed inside the extruded profile 22 constituting the frame 2 of a window 1. Modern PVC or aluminum window frames are typically composed of a hollow structure divided into several cavities, as depicted in figure 1.

Figure 5 schematically shows a first embodiment of a vibration controlled panel 100, in particular a window pane. The vibration controlled window pane 100 comprises a window pane 101 having a first side 102, a second side 103 opposed to the first side, a circumferential outer edge 104 and a centre plane 105 in between the first and second sides 102, 103. The vibration controlled panel 100 further comprises an actuator module 110 having an actuation end 111 that contacts, or can be even connected to, the circumferential outer edge 104 of the window pane 101. The actuator connecting section 106 of the panel 101, i.e. section of the panel 101 where the panel 101 is connected to, or at least in contact with, the actuator module 110 is mostly arranged on the part of the circumferential edge 104 that is closest to the first side 102 and is thus asymmetrical with respect to the centre pane 105. In this embodiment, the actuator connecting section is thus only arranged on the outer circumferential edge 104.

The actuator module 110 further comprises a frame member 112 that holds an actuator, i.e. a stacked piezoelectric actuator 113 that is arranged to expand and/or contract in dependence of an electric signal applied to the stacked piezoelectric actuator 113. The actuator module 110 is, in the current embodiment, connected at a second end (not shown), by means of the frame member 112, to an external frame (not shown) for mounting and holding the panel 101 for the restraining of movement of the second end. Alternatively, the frame member 112 may not be connected to an external frame, such that the mass of the frame member 112 forms a movable mass that restrains the motion of the second end by means of inertial forces, as is described above. In order to assure a proper contact between the actuation end 111 and the circumferential outer edge 104, or to pre-load the stacked piezoelectric actuator 113 with an predefined preload, a an adjustable pre-loading mechanism 114, comprising for instance an adjustable screw 115 which is configured for increasing and decreasing the amount of preload in dependence, can be provided.

The actuator module 110 is arranged for applying a force and/or to induce a deformation to the circumferential outer edge 104 along the in-plane direction II, that is substantially parallel to the centre plane 105 of the panel 101. As the actuation end 111 is arranged asymmetrically with respect to the centre plane 105, the force and/or induced deformation is applied along a longitudinal axis a110 of the actuator module at a certain (non-zero) distance d1 with respect the centre plane 105. The force and/or induced deformation thus results in a bending moment that is induced with respect to the centre line 105, which will in turn result in a bending of the panel 101 and thus in a deformation of the panel 101 in the out-of-plane direction I. Hereby, the actuator module 110 is able to, at least partly, control the out-of-plane deformations of the panel 101.

As an example, the panel 101 vibrates (due to for instance a sinusoidal varying sound pressure having a predetermined frequency applied at the first side 102) in a certain out-of-plane vibration mode (see for instance modes 20, 30, 40, 50 of figure 2) having the same frequency of vibration. If the actuator module 110 is configured to excite (i.e. to apply a force and/or deformation) the panel to vibrate at the same frequency of vibration in a synchronized manner, the amplitude of vibration will increase, thereby actually causing an amplification of the sound pressure acting the first side 102 to the second side 103. If the actuator module 110 is configured to excite the panel to vibrate at the same frequency of vibration in a anti-synchronized manner (i.e. having a 180 degree phase difference), the amplitude of vibration is actively counteracted, such that it will decrease, thereby actually causing a reduction of the sound pressure acting the first side 102 to the second side 103. The effect of the latter is also often referred to as “active noise cancellation”.

As the actuator module 110 is arranged at the outer circumferential edge 104 of a window pane 101, the actuator module 110 does not, or minimally, interfere with the visual properties of the window pane. In other words, no modules have to be fitted within, or near, the central sections of the window pane 101, which would obstruct the free view, and also the aesthetics of the window.

Figure 6 schematically shows a second embodiment of a vibration controlled panel 200, in particular a vibration controlled window pane 200. The vibration controlled panel 200 according to the second embodiment is for the largest part similar to the vibration controlled panel 100 according to the first embodiment, with the difference that vibration controlled panel 200 can comprise a number of additional sensors 221, 222, 223. It is preferred however, that for simplicity and cost reduction less sensors 221, 222, 223 are used, hence preferably the vibration controlled panel 200 comprises only one of the additional sensors 221, 222, 223 per actuator module 210 comprised in the vibration controlled panel 200.

A first sensor 221 can be arranged on, and connected to, the first or second side 102, 103 and be configured for determining strain in the panel 101 at the first or second side 102, 103. The first sensor 221 can also be a traditional strain gauge that measures a variation in resistance due to the strain induced onto the sensor 221 by the out-of-plane deformation caused by the vibrations. The variation in resistance is then transformed into an equivalent change in voltage, usually through the use of a so-called “Wheatstone bridge”. A strain gauge has a small form factor which allows easy integration.

The first sensor 221 can also be a piezoelectric patch, also called PZT. When bonded to the surface of the first or second side 102, 103, it converts the strain into electrical charge. Its very small size (e.g. 5 x 5 x 0.3 mm) allows easy integration. On the basis of the measured strain and material properties of the panel 101 (i.e. glass pane), the first sensor 221 can also be used for estimating local stress in the material and/or to estimate local bending moments in the panel 101.

The first sensor 221 can also be an accelerometer which measures the local vibration (acceleration) of the panel 101 at the first or second side 102, 103. Some industrial accelerometers, such as so-called “MEMS accelerometers” can have a small form factor such that they can be made small enough for a simple integration within the vibration controlled panel 200.

Second sensor 222 can be arranged at the actuation end 211 of the actuator module 210. The second sensor 222 can be configured for measuring force and/or acceleration at the actuation end 211. Second sensor 222 can be regarded as the second sensor unit 222 in case it is arranged for measuring both force and acceleration, as can then comprise both a dedicated accelerometer of measuring vibrations and a dedicated force sensor for measuring the force that the actuator module 210 applies onto the panel 101. Hereby, one measures the force and vibrations at practically the same position, such that (almost) collocated measurements can be obtained. Collocation means that the sensor is located at the same place as the actuator, thus forming a collocated actuator-sensor pair. This configuration is particularly useful in feedback control strategies because it has the property to guarantee the stability of the control loop. However, in real applications, it is not always possible to locate the actuator and the sensor in the exact same place.

A third sensor 223 can be arranged directly on the stacked piezoelectric actuator 113 that can be configured for measuring the strain of the stacked piezoelectric actuator 113, which can be used for determining the applied force of the stacked piezoelectric actuator 113 and/or for determining the induced deformation of the stacked piezoelectric actuator 113 for measuring the vibrations induced (by the panel 101) onto the stacked piezoelectric actuator 113. Hereby, one can also obtain an (almost) collocated measurement of the force and vibration. Note that any combination of the above described sensors 221, 222, 223 can be applied to any embodiment of the vibration controlled panel.

Figure 7 schematically shows a third embodiment of the vibration controlled panel 300, which is again similar to the first and second embodiments 100, 200 of the vibration controlled panel. The difference with respect to the second embodiment 200 is in the arrangement of the second end 316 of the actuator module 310 and the placement of the first sensor 321.

In this embodiment 300, the actuator connecting section 106, 307 is arranged on the outer circumferential edge 104, as was also the case for the previous embodiments 100, 200, but also comprises a second part 307 of the actuator connecting section that is arranged on the first side 102 of the panel 101, at a section of the first side 102 that is adjacent to the outer circumferential edge

104. As such, the actuator connecting section 106, 307 is again arranged asymmetrically with respect to the centre plane 105.

The second end 316 of the actuator module 310, which is comprised in frame member 312, is connected to the second part 307 of the actuator connecting section that is arranged on the first side 102 of the panel 101. Hence, the force and/or induced deformation as applied by the stacked piezoelectric actuator 113 that is along a longitudinal axis a113 of stacked piezoelectric actuator (that can even overlap with the centre plane 105), is at a non-zero distance d2 with respect to the second part 307 which acts as a moment arm. Hereby, expansion and/or contraction of the stacked piezoelectric actuator 113 leads to inducing bending moments with respect to the centre plane 105 in the panel 101, such that the out-of-plane deformation (and modes, such as acoustic radiation modes or out-of-plane vibration modes) can be controlled by the actuator module 310.

The first sensor 321 can be arranged on the second side 103, such that it is arranged substantially opposite to the second part 307 of the actuator connecting section. The functionality of the first sensor 321 can be arranged to be equal to the first sensor 221 of the second embodiment.

Figure 8 schematically shows a fourth embodiment of the vibration controlled panel 400. The vibration controlled panel 400 comprises mostly of the same parts as the vibration controlled panels 100, 200, 300 of the previous embodiments, but has been arranged differently with respect to the panel 101. The actuator module 410 is, in the current embodiment, arranged on the first side 102 of the panel (i.e. glass pane) 101.

The actuator module 410 again comprises a frame member 412 that holds an actuator, i.e. a stacked piezoelectric actuator 413 that is arranged to expand and/or contract in dependence of an electric signal applied to the stacked piezoelectric actuator 413. The actuator module 410 is, in the current embodiment, connected at a second end 416, by means of the frame member 412, to the first side 102 of the panel 101, more in particular to the second part 407 of the actuator connection section 406 for the restraining of movement of the second end 416. In order to assure a proper contact between the actuation end 411 and the first side 102, more in particular the actuator connection section 406, or to pre-load the stacked piezoelectric actuator 413, the adjustable pre-loading mechanism 414, comprising the adjustable screw 415, can be provided. Again, the actuator connection section 406, 407 is arranged asymmetrical with respect to the centre plane 105. As the actuator module 410 is arranged near, or adjacent to, the outer circumferential edge 104 of the panel, the actuator module has no, or a minimal, effect on the visual appearance of the panel 101, in particular on an unobstructed view through window 101. For this, the actuator module 410 is preferably arranged no further than 20 times the thickness of the panel 101 from the circumferential edge 104, more preferably no further than 15 times the thickness, even more preferably no further than 10 times the thickness, most preferably no further than 8 times the thickness. Note that this holds for all embodiments according to the appended claims.

The actuator module 410 is arranged for applying a force and/or to induce a deformation to the first side 102 along the out-of-plane direction I, that is substantially perpendicular to the centre plane 105 of the panel 101. As the actuation end 411 is arranged at a distance d4 from the second end 416 of the actuation module (as seen with respect to the respective axes a412, a413), the force and/or induced deformation that is applied induces a (local) shear force and bending moment around the central plane 105 in the panel 101, which will in turn mainly result in a bending of the panel 101 and thus in a deformation of the panel 101 in the out-of-plane direction I. Hereby, the actuator module 410 is able to, at least partly, control the out-of-plane deformations of the panel 101.

Figure 9 schematically shows a fifth embodiment of the vibration controlled panel 500 comprising panel 101. The actuator module 510 comprises a frame member 512 that holds an actuator, i.e. a stacked piezoelectric actuator 513 that is arranged to expand and/or contract in dependence of an electric signal applied to the stacked piezoelectric actuator 513. The actuator module 510 is, also in the current embodiment, connected at the actuator connecting section 506 of the panel 101, which is arranged at a section of the first side 102 near, or adjacent to, the circumferential edge 104. A bottom of the frame member 512 forms the actuation end 511. The stacked piezoelectric actuator 513 is arranged such that its longitudinal axis a513 is arranged substantially parallel to the centre plane 105 at a distance d5 from the first side 102 of the panel. The stacked piezoelectric actuator 513 is connected at its first end 517 to the adjustable pre-loading mechanism 514, in particular to the adjustable screw 515, and the opposing end 518 is coupled, through the second sensor 522, to the frame member 512. In other words, the frame member 512 is substantially U-shaped, wherein the bottom section 519 forms the actuation end 511 that is connected to the first side 102 and the legs of the U are coupled by means of the stacked piezoelectric actuator 513. The bottom section 519 of the frame member 512 is flexible, i.e. made of an elastic material, such that upon expansion or contraction of the stacked piezoelectric actuator 513, the legs of the U respectively spread apart, or come closer together, such that the bottom section 519 bends. The bending of the bottom section

519 is in turn transferred to the actuator connecting section 506, thereby introducing the bending (moment) into the panel 101, allowing to control the out-of-plane deformation (i.e. out of plane vibrations) of the panel 101 in a dynamic manner.

Figure 10 schematically shows a first embodiment of a multi-panel system 1000, in particular a double glazing unit, comprising a sixth embodiment of the vibration controlled panel 600. The multi-panel system 1000 comprises a first panel 101, which is similar to the panels 101 of the previous embodiments of the vibration controlled panel, and second panel 1101 that are coupled by means of the spacer and primary seal 1013 and the secondary seal 1014, that are arranged adjacent to the outer circumferential edges 104, 1104 of the respective panels 101, 1101. It is noted that the first panel 101, in particular first window pane, and the second panel 1101, in particular second window pane, can respectively be the inner panel that is directly adjacent to an interior of a space, room and/or building and the exterior panel that is directly adjacent to an exterior of a space, room and/or building, and vice versa.

The vibration controlled panel 600 comprises the first panel 101 and actuator module 610, which comprises a stacked piezoelectric actuator 613. The stacked piezoelectric actuator is coupled at its actuating end 611, through the second sensor 622, to the actuator connecting section 606 that is arranged at the first side 102 of the first panel. At the second end 616, the actuator module 610 is connected to, or contacts, the second panel 1101 for restraining the motion of the second end 616. Hereby, the reaction force generated due restraining the second end 616 is transferred to the second panel 1101, such that second panel 1101 is also excited by the actuator module 610, which could potentially lead to undesirable and/or uncontrolled (out-of-plane) vibrations in the second panel.

The actuator module 610 is arranged, at a non-zero distance, but near, or adjacent to, the spacer 1013, such that the actuator module 610 and the spacer 1013 are spaced apart. As the actuator module 610 is arranged near, or adjacent to, the spacer 1013 of the multi-panel system 1000, the actuator module has no, or a minimal, effect on the visual appearance of the multi-panel system 1000, in particular on an unobstructed view through multi-glazed window 1000.

The actuation end 611 of the actuator module 610 is arranged to move (in particular due to the expansion and/or contraction of the stacked piezoelectric actuator 613) with respect to the second end 616 along the longitudinal axis a613 of the stacked piezoelectric actuator 613, which is arranged substantially perpendicular to the centre plane 105 of the first panel 101, such that a shear force and bending moment, which respect to the can be introduced with respect to centre plane 105. This allows for controlling the deformation (i.e. vibrations) of the first panel 101 in the out-of-plane direction I.

Any embodiment of the multi-panel system according to the appended claims can further comprise any combination of the respective first, second and third sensors, as has been explained for the second embodiment of the vibration controlled panel 200.

Figure 11 schematically shows a second embodiment of a multi-panel system 2000, in particular a double glazing unit, comprising a seventh embodiment of the vibration controlled panel 700. Multi-panel system 2000 and vibration controlled panel 700 are similar to multi-panel system 1000 and vibration controlled panel 600, whereby the differences between the embodiments are discussed below. The actuator module 710 is integrated within the spacer 2013 of the multi-panel system 2000. The spacer 2013 is thus used as a frame member for holding the stacked piezoelectric actuator 713.

The vibration controlled panel 700 comprises the first panel 101 and actuator module 710, which comprises a stacked piezoelectric actuator 713. The stacked piezoelectric actuator is coupled at its actuating end 711, through the second sensor 722, to the actuator connecting section 706 that is arranged at the first side 102 of the first panel. At the second end 716, the actuator module 710 can be connected to, or contact, the second panel 1101 for restraining the motion of the second end 716, or the second end 716 can be connected, and thereby restrained, by the spacer 2013. In the latter case, the reaction force generated due to restraining the second end 716 is transferred to the spacer 2013, instead of the second panel 1101, such that second panel 1101 is not, or minimally, excited by the actuator module 710, thereby reducing the possibility of exciting any undesirable and/or uncontrolled (out-of-plane) vibrations in the second panel 1101.

Figure 12 schematically shows a third embodiment of a multi-panel system 3000, in particular a double glazing unit, comprising an eighth embodiment of the vibration controlled panel 800. Multi-panel system 3000 and vibration controlled panel 800 are similar to multi-panel systems 2000 and vibration controlled panel 700, whereby the differences between the embodiments are discussed below. The actuator module 810 is integrated within the secondary seal 3014 of the multi-panel system 3000, instead of the primary seal 2013 in case of the multi-panel system 2000. The spacer 3013 is thus used as a frame member for holding the stacked piezoelectric actuator 813.

Similar to the multi-panel system 2000, the actuator module 810 can, at its second end, be connected to, or contact, the second panel 1101 for restraining the motion of the second end 816, or the second end 816 can be arranged in the secondary seal 3014. The reaction force generated due restraining the second end 816 is mainly transferred to the second panel 1101. However, depending on the material properties of the secondary seal 3014, it may take up some force. The main advantage of this embodiment, and the one of figure 11, is that the actuator module 810 can be fully hidden from sight when the multi-panel system 2000 is installed in a standard external frame, i.e. window frame.

Figure 13 schematically shows a fourth embodiment of the multi-panel system 4000 comprising a ninth embodiment of the vibration controlled panel 900. The multi-panel system and vibration controlled panel 900 are again similar to the previously shown multi-system panel 1000, 2000, 3000 and the vibration controlled panels 600, 700, 800.

The actuator module 910 is connected to, and/or contacts, by means of the frame member 912 the spacer 4013, the first side 102 of the first panel 101 and/or the first side 1102 of the second panel 1101. The actuator end 911 is coupled to the first side 102 of the first panel, in the current embodiment through second sensor 922. The stacked piezoelectric actuator 913 is thus arranged, along longitudinal axis a913 that is parallel to the out-of-plane direction I, in between the frame member 912 and the second sensor 922. The second end 916 of the actuator module 910 is formed by the bottom section 919 of the frame member 912 and is arranged as described above. Upon expansion and/or contraction of the stacked piezoelectric actuator 913, the actuation end 911 of the actuator module 910 is urged to move with respect to the second end 916, i.e. the frame member 912, thereby applying a force and/or deformation to the first panel 101 that is substantially perpendicular to the centre plane 105. The applied force and/or induced deformation induces a (local) shear force and bending moment around the central plane 105 in the panel 101, which will in turn mainly result in a bending of the panel 101 and thus in a deformation of the panel 101 in the out-of-plane direction I. Hereby, the actuator module 910 is able to, at least partly, control the out-of-plane deformations of the panel 101.

The vibration controlled panel 900 comprises a connectable module 930 that comprises a housing member 931 and the at least one actuator module 910, wherein the housing member 931 is arranged to substantially cover the actuator module 910, and wherein the connectable module 930 is arranged in the space 4100 between the adjacent panels 101, 1101 and is connected to the spacer 4013. The housing member 931 comprises an opening 933 to allow for the actuation end 911 of the of the actuator module 910 to contact, or be connected to, the first side 102 of the first panel 101. It is preferred if the connectable module 930 is releasably mounted to the spacer 4013 by means of a releasable connection 932 arranged on the frame member 912 and/or housing member 931. Hereby, the connectable module 930 can be easily placed in during assembly of the multi-panel system 4000, as all the parts are pre-assembled in the connectable module 931. An electrical connection 934 can then be made from the connectable module, through, or past, the spacer 4013 and secondary seal 1014, such that the module can be connected to a suitable controller and/or power source (not shown). Such a connectable module 930 also has the benefit of creating a solution that is aesthetically pleasing and only needs placement at edges of the window unit, such that the visual characteristics of the window unit are minimally affected.

In addition to the first, second and third sensors discussed for the embodiments above, figures 14 and 15 respectively schematically show two embodiments of vibration controlled panels 5000, 6000 further comprising an additional sensor. In figure 14 a vibration controlled panel 5001 according to any of previously discussed embodiments and/or according to the appended claims is shown, wherein the vibration controlled panel 5001 is arranged in a panel frame 5002, in particular a window frame 5002, for holding the vibration controlled panel 5001. The vibration controlled panel 5001 coupled to the window frame 5002 by rubber seals 5021 for holding and sealing the vibration controlled panel 5001 in the panel frame 5002.

On the side of the frame 5002 that is arranged in contact with an exterior 5200 (i.e. on the outside) a reference microphone 5024 is mounted for determining incoming noise disturbance before it reaches the vibration controlled panel 5001. In case of a feedforward control strategy, at least one of the reference sensor 5024 is used to pick up the incoming noise disturbance. The location of these sensors is thus arranged to be upstream with respect to the propagation path of the noise disturbance.

Figure 15 schematically shows the vibration controlled panel 5001 according to any of previously discussed embodiments and/or according to the appended claims arranged in a panel frame 6002. On the side of the frame 6002 that is arranged in contact with an interior 5100 (i.e. on the inside) an error microphone 6024 is mounted. The error sensor picks up the noise in the interior 5100 (i.e.

in an indoor space), where a certain sound performance, such as a noise reduction of the exterior noise, is aimed for.

The microphones 5024, 6024 can be spaced apart from any of the actuators present in the vibration controlled panel 5001. This results in non-collocated sensors. Non-collocation means that the error and/or reference sensor is not located at the same place as the actuator. This configuration is more adapted to feedforward than feedback control strategies, as it may lead to instabilities in the control loop in the latter case.

Note that the embodiments of figures 14 and 15 can be combined, to include both at least one reference sensor 5024 and at least one error sensor 6024. Also, these at least one reference sensor 5024 and at least one error sensor 6024 can be combined with all embodiments of the vibration controlled panel and all embodiments of the multi-panel system shown thus far.

Figure 16 schematically a 3D perspective of yet another embodiment of the multi-panel system 7000, wherein the actuator module 7110 comprises a transfer mechanism 7150. The multi-panel system 7000, in particular double-glazing unit 7000, comprises a first panel 101 and a second panel 1102 that are arranged, like the previous embodiments of multi-panel systems 1000, 2000, 3000, 4000, spaced apart and parallel with respect to each other and coupled to each other by means of a spacer (and primary seal) 7013, thereby forming and maintaining a sealed off space 7015 in between the panels 101, 1101. The multi-panel system 7000 can further comprise a secondary seal 7014.

The transfer mechanism 7150 couples the actuator, in particular the stacked piezoelectric actuator 7113 and the actuation end 7111 and is arranged for transferring a movement of the actuator 7113, by means of a linkage mechanism 7151, to the actuation end 7111. The linkage system 7151 is a four bar linkage mechanism, comprising four bars 7152, 7153, 7154, 7155 that are successively arranged and coupled with respect to each other at respective nodes 7156, 7157, 7158, 7159 by means of, for instance, flexible hinges for forming a closed loop. The actuation end 7111 is arranged on a first node 7156, that in the current example also comprises second sensor 7122, and the actuator is coupled at its respective ends to two opposite nodes 7157, 7159 that are adjacent to the first node 7156, such that a movement of the respective actuator ends is transferred to a movement of the actuation end 7111.

The last node 7158 is arranged for connecting the transfer mechanism 7150 to the frame member 7112. The second end 7116 of the actuator module 7110 is formed by the frame member 7112. The actuator module 7110 is connected to, and/or contacts, by means of the frame member 7112 the spacer 7013, the first side 102 of the first panel 101 and/or the first side 1102 of the second panel 1101.

Upon expansion and/or contraction of the stacked piezoelectric actuator 7113, the actuation end 7111 is then urged, through the transfer mechanism 7150, to move with respect to the second end 7116, i.e. the frame member 7112, thereby applying a force and/or deformation to the first panel 101 that is substantially perpendicular to the surface of the first panel 101 and to the longitudinal axis of the stacked piezoelectric actuator 7113. The applied force and/or induced deformation induces a (local) shear force and bending moment around a neutral bending plane in the panel 101, which will in turn mainly result in a bending of the panel 101 and thus in a deformation of the panel 101 in the out-of-plane direction. Hereby, the actuator module 7110 is able to, at least partly, control the out-of-plane deformations of the panel 101.

Similar to the ninth embodiment of the vibration controlled panel 900, the actuator module 7110 can be comprised in a connectable module (not shown), comprising a housing member to cover the actuator module 7110 that can be easily placed during assembly of the multi-panel system 7000, as all the parts can be pre-assembled in the connectable module. . It is also preferred that the connectable module is releasably mounted to the spacer 7013 by means of a releasable connection arranged on the frame member 7112 and/or housing member (not shown).

The present invention is not limited to the embodiment shown, but extends also to other embodiments falling within the scope of the appended claims. It is further noted that all the embodiments of the vibration controlled panel can be applied in multi-panel systems, in particular multi-glazed window units, such as double glazing windows. Furthermore, all the embodiments presented enable obtaining a vibration controlled panel having a compact actuator module that is hardly, or even not, visible for the user looking through such a window, or to such a panel.

Embodiments

1. Vibration controlled panel, in particular a vibration controlled window pane, comprising:

- a panel comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane; and

- at least one actuator module comprising an actuation end connected to, or at least contacting, the panel at the actuator connecting section, a second end arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane;

- a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control the deformation of the panel in the out-of-plane direction.

2. Vibration controlled panel according to embodiment 1, wherein the actuator is a stacked piezoelectric actuator.

3. Vibration controlled panel according to embodiment 2, wherein the actuator module comprises a frame member and wherein the actuator is coupled to the frame member.

4. Vibration controlled panel according to embodiment 3, wherein the frame member comprises the second end.

5. Vibration controlled panel according to any of the preceding embodiments, wherein the second end is connected to, or at least contacts, the panel for the restraining of movement of the second end.

6. Vibration controlled panel according to embodiment 5, wherein the second end is connected to, or at least contacts, the front side or back side of the panel at a secondary actuator connecting section, wherein the secondary actuator connecting section is arranged adjacent to the outer circumferential edge and wherein the secondary actuator connecting section is arranged at a non-zero distance from the actuator connecting section.

7. Vibration controlled panel according to any of the preceding embodiments, wherein the second end is connected to, or at least contacts, an external frame for mounting and holding the panel for the restraining of movement of the second end.

8. Vibration controlled panel according to any of the preceding embodiments, wherein the actuator is arranged to move the actuation end by expanding and/or contracting along a longitudinal axis of the actuator.

9. Vibration controlled panel according to embodiment 8, wherein the actuator is arranged such that a component of the longitudinal axis that is substantially parallel to the centre plane is larger than a component of the longitudinal axis that is substantially perpendicular to the centre plane, and wherein the actuator, or at least the longitudinal axis of the actuator, is arranged at a non-zero distance from the centre plane of the panel, as seen in the direction perpendicular to the centre plane.

10. Vibration controlled panel according to embodiment 8 or 9, wherein the longitudinal axis of the actuator is substantially parallel to, and arranged at a non-zero distance from, the centre plane of the panel, as seen in the direction perpendicular to the centre plane.

11. Vibration controlled panel according to embodiment 8, wherein the actuator is arranged such that a component of the longitudinal axis that is substantially perpendicular to the centre plane is larger than a component of the longitudinal axis that is substantially parallel to the centre plane, and wherein the actuator, or at least the longitudinal axis of the actuator, is arranged inwardly with respect to, and at a non-zero distance from, the outer circumferential edge of the panel.

12. Vibration controlled panel according to embodiment 8 or 11, wherein the longitudinal axis of the actuator is substantially perpendicular to the centre plane of the panel, as seen in the direction perpendicular to the centre plane.

13. Vibration controlled panel according to any of the preceding embodiments, wherein the actuation end is connected to, or at least contacts, the outer circumferential edge of the panel.

14. Vibration controlled panel according to any of the preceding embodiments 1 - 12, wherein the actuator connecting section is arranged at, preferably only, the front side or back side, adjacent to

the outer circumferential edge, such that the actuation end is connected to, or at least contacts, the front side or back side of the panel.

15. Vibration controlled panel according to any of the preceding embodiments, wherein the actuator module comprises a pre-loading mechanism for applying a compression preload in the longitudinal direction of the actuator, preferably wherein the pre-loading mechanism comprises an adjustment mechanism for adjusting the preload applied to the actuator.

16. Vibration controlled panel according to any of the preceding embodiments, wherein the actuator module comprises a transfer mechanism that couples the actuator and the actuation end and that is arranged for transferring a movement of the actuator to the actuation end.

17. Vibration controlled panel according to embodiment 16, wherein the transfer mechanism is arranged for transferring the movement of the actuator along the longitudinal axis of actuator to a movement of the actuation end that is at an acute angle with, or substantially perpendicular to, the longitudinal axis of the actuator.

18. Vibration controlled panel according to embodiments 16 or 17, wherein the transfer mechanism comprises a linkage mechanism for coupling the actuator and the actuation end.

19. Vibration controlled panel according to embodiment 18, wherein the linkage system is a four bar linkage mechanism, preferably comprising four bars that are successively arranged and coupled with respect to each other at respective nodes by means of hinges for forming a closed loop, preferably wherein the actuation end is connected to a first node and the actuator is coupled at its respective ends to two opposite nodes that are adjacent to the first node, such that a movement of the respective actuator ends is transferred to a movement of the actuation end.

20. Vibration controlled panel according to embodiments 16 - 19, wherein the transfer mechanism is arranged as a compliant mechanism comprising flexible hinges.

21. Vibration controlled panel according to any of the preceding embodiments, wherein the panel has modes, such as acoustic radiation modes or out-of-plane vibration modes, and wherein at least one mode of the panel has at least one nodal line, such that, when the panel vibrates in the one mode, the panel at the at least one nodal line exhibits substantially no out-of-plane motion of the

panel, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal line of the certain mode.

22. Vibration controlled panel according to clam 21, wherein the vibration controlled panel is arranged for controlling at least the first four modes, such as acoustic radiation modes or out-of-plane vibration modes, of the panel, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal lines of the first four modes.

23. Vibration controlled panel according to any of the preceding embodiments comprising at least two actuator modules that are spaced apart from each other at, or near, the outer circumferential edge and/or wherein the outer circumferential edge comprises an upper edge, lower edge, first side edge and second side edge and wherein at least on actuator module is arranged at, or near, at least two of the upper edge, lower edge, first side edge and second side edge.

24. Vibration controlled panel according to any of the preceding embodiments, further comprising at least one sensor configured for determining a state variable associated to the vibration controlled panel, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

25. Vibration controlled panel according to embodiment 24, wherein the at least one sensor comprises a microphone, strain sensor, vibration sensor and/or force sensor.

26. Vibration controlled panel according to embodiment 24 or 25, wherein the actuator is a piezoelectric actuator and wherein the piezoelectric actuator is configured for determining a movement of the actuator connecting section, such that the at least one sensor comprises the piezoelectric actuator.

27. Vibration controlled panel according to any of the preceding embodiments 24 - 26, wherein the at least one sensor comprises a nearly collocated sensor, preferably a vibration and/or force sensor, arranged at the actuation end that is configured for determining the state variable, preferably an out-of-plane movement and/or applied force, at the respective end of the actuator.

28. Vibration controlled panel according to any of the preceding embodiments 24 - 27, wherein the at least one sensor comprises a closely located sensor, preferably a strain, vibration and/or force sensor, that is configured for determining the state variable at the front side or back side of the panel, near the actuator connecting section or the secondary actuator connecting section, preferably no further than five times the thickness of the panel from the actuator connecting section or the secondary actuator connecting section, more preferably no further than two times the thickness.

29. Vibration controlled panel according to embodiment 28, wherein the closely located sensor is configured for determining the state variable at the one of the front side and back side that is opposite to the other of the front side and back side comprising one of the actuator connecting section and the secondary actuator connecting section at substantially the same location as the one of the actuator connecting section and the secondary actuator connecting section, as seen in the out-of-plane direction.

30. Vibration controlled panel according to embodiment 8 and any of the preceding embodiments 24 - 29, wherein the at least one sensor comprises a collocated strain sensor that is arranged directly on the actuator for determining the strain of the actuator due to the expansion or contraction of the actuator.

31. Vibration controlled panel according to any of the preceding embodiments 24 - 30, wherein the controller is configured to store a predefined set point for the state variable; and wherein the controller is configured for controlling the actuator in dependence of the predefined set point and the determined state variable.

32. Vibration controlled panel according to any of the preceding embodiments 24 - 31, wherein the controller is configured for determining and/or predicting out-of-plane vibrations of the panel based on the determined state variable and to control the actuator to deform the panel to vibrate out-of-phase with respect to the determined and/or predicted out-of-plane vibrations of the panel, such that the acoustic radiation of the thin-panel is reduced and/or substantially cancelled out.

33. Multi-panel system, in particular a multi-glazed window, comprising at least a first and second panel, of which at least the first panel is a vibration controlled panel according to any of the preceding embodiments, wherein each of the panels are arranged parallel with respect to each other and spaced apart from each other, wherein the adjacent panels are connected to one another by

means of a spacer and sealing means arranged in between the adjacent panels that runs substantially adjacent to the outer circumferential edge of the panels along substantially the full circumference of the panels, such that the adjacent panels and the spacer and sealing means enclose a space.

34. Multi-panel system according to embodiment 33, wherein the at least one actuator module is arranged in the space in between the first and second panel.

35. Multi-panel system according to embodiment 34, wherein the second end is connected to, or at least contacts, the second panel for the restraining of movement of the second end.

36. Multi-panel system according to embodiment 33 - 35, wherein at least a part of the actuator is coupled to the frame member and, preferably, wherein the frame member comprises the second end.

37. Multi-panel system according to any of the preceding embodiments 33 - 36, wherein the first panel is a vibration controlled panel according to any of the preceding embodiments 15 - 19.

38. Multi-panel system according to embodiment 36, wherein the frame member is integrally formed with the spacer and sealing means.

39. Multi-panel system according to any of the preceding embodiments 33 - 37, comprising a connectable module comprising a housing member and the at least one actuator module, wherein the housing member is arranged to substantially cover the actuator module at at least one side of the connectable module that faces the first panel, and wherein the connectable module is arranged in the space between the adjacent panels and is connected to the spacer and/or sealing means.

40. Multi-panel system according to embodiment 39, wherein the housing member comprises a wall section that faces the first panel and wherein the wall section comprises an opening through which the actuation end is arranged that is connected to, or at least contacts, the panel at the actuator connecting section.

41. Actuator module as arranged in the vibration controlled panel according to any of the preceding embodiments, comprising an actuation end that is arranged to be connected to, or at least to

contact, the panel at the actuator connecting section, a second end arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to, when the actuation end of the at least one actuator module is connected to, or at least contacts, the actuator connecting section, deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane; electrical connecting means arranged for connecting to a controller that is configured to receive at least one input signal and configured to control the at least one actuator of the at least one actuator module to cause the actuator end to move, in dependence of the at least one input signal, in order to deform the first panel in at least an out-of-plane direction that is substantially perpendicular to a centre plane, when the actuation end of the at least one actuator module is connected to, or at least contacts, the first panel at the actuator connection section thereof that is arranged asymmetrically with respect to the centre plane.

42. Connectable module for use in the multi-panel system according to any of the preceding embodiments 33 - 39, wherein the connectable module is arranged to be inserted in a space between adjacent first and second panels of the multi-panel system and comprises connecting means for connecting the systems module to the spacer and/or sealing means, the connectable module comprising:

at least one actuator module according to embodiment 41;

a housing member arranged to substantially cover the at least one actuator module at at least one side of the connectable module that is arranged to face the first panel; and

a controller configured to receive at least one input signal and that is electrically connected to the at least one actuator and configured to control the at least one actuator of the at least one actuator module to cause the actuator end to move, in dependence of the at least one input signal, in order to deform the first panel in at least an out-of-plane direction that is substantially perpendicular to a centre plane, when the actuation end of the at least one actuator module is connected to, or at least contacts, the first panel at the actuator connection section thereof that is arranged asymmetrically with respect to the centre plane.

Claims

1. Vibration controlled window pane for reducing the transfer of noise from an exterior to an interior or vice versa, comprising:

- a panel comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane; and

- at least one actuator module comprising an actuation end connected to, or at least contacting, the panel at the actuator connecting section, a second end arranged such that movement of the second end with respect to the panel is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane;

- a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control the deformation of the panel in the out-of-plane direction such that vibrations of the panel that are responsible for the transfer of the noise are reduced.

2. Vibration controlled window pane according to claim 1, further comprising at least one sensor configured for determining a state variable associated to the vibration controlled window pane, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

3. Vibration controlled window pane according to claim 2, wherein the at least one sensor comprises a microphone, strain sensor, vibration sensor and/or force sensor.

4. Vibration controlled window pane according to any of the preceding claims 2 - 3, wherein the controller is configured for determining and/or predicting out-of-plane vibrations of the panel based on the determined state variable and to control the actuator to deform the panel to vibrate out-of-phase with respect to the determined and/or predicted out-of-plane vibrations of the panel, such that the acoustic radiation of the thin-panel is reduced and/or substantially cancelled out.

5. Vibration controlled window pane according to any of the preceding claims, wherein the panel has modes, such as acoustic radiation modes or out-of-plane vibration modes, and wherein at least one mode of the panel has at least one nodal line, such that, when the panel vibrates in the one mode, the panel at the at least one nodal line exhibits substantially no out-of-plane motion of the panel, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal line of the certain mode.

6. Vibration controlled window pane according to claim 5, wherein the vibration controlled window pane is arranged for controlling at least the first four modes, such as acoustic radiation modes or out-of-plane vibration modes, of the panel, and wherein the at least one actuator module is arranged at a non-zero distance from the nodal lines of the first four modes.

7. Vibration controlled window pane according to any of the preceding claims comprising at least two actuator modules that are spaced apart from each other at, or near, the outer circumferential edge and/or wherein the outer circumferential edge comprises an upper edge, lower edge, first side edge and second side edge and wherein at least on actuator module is arranged at, or near, at least two of the upper edge, lower edge, first side edge and second side edge.

8. Vibration controlled window pane according to any of the preceding claims, wherein the actuator is a stacked piezoelectric actuator.

9. Vibration controlled window pane according to any of the preceding claims, wherein the actuator module comprises a frame member and wherein the actuator is coupled to the frame member and wherein the frame member comprises the second end.

10. Vibration controlled window pane according to any of the preceding claims, wherein the second end is connected to, or at least contacts, an external frame for mounting and holding the panel for the restraining of movement of the second end.

11. Vibration controlled window pane according to any of the preceding claims 1 - 9, wherein the second end of the actuator module comprises a movable mass for restraining motion of the second end.

12. Vibration controlled window pane according to any of the preceding claims, wherein the actuator connecting section is arranged at, preferably only, the front side or back side, adjacent to the outer circumferential edge, such that the actuation end is connected to, or at least contacts, the front side or back side of the panel.

13. Vibration controlled window pane according to any of the preceding claims, wherein the actuator module comprises a transfer mechanism that couples the actuator and the actuation end and that is arranged for transferring a movement of the actuator to the actuation end.

14. Vibration controlled window pane according to claims 13, wherein the transfer mechanism comprises a linkage mechanism for coupling the actuator and the actuation end.

15. Vibration controlled window pane according to claim 14, wherein the linkage system is a four bar linkage mechanism, preferably comprising four bars that are successively arranged and coupled with respect to each other at respective nodes by means of hinges for forming a closed loop, preferably wherein the actuation end is connected to a first node and the actuator is coupled at its respective ends to two opposite nodes that are adjacent to the first node, such that a movement of the respective actuator ends is transferred to a movement of the actuation end.

16. Multi-glazed window, comprising at least a first and second panel, of which at least the first panel is a vibration controlled window pane according to any of the preceding claims, wherein each of the panels are arranged parallel with respect to each other and spaced apart from each other, wherein the adjacent panels are connected to one another by means of a spacer and sealing means arranged in between the adjacent panels that runs substantially adjacent to the outer circumferential edge of the panels along substantially the full circumference of the panels, such that the adjacent panels and the spacer and sealing means enclose a space.

17. Multi-glazed window according to claim 16, comprising a connectable module comprising a housing member and the at least one actuator module, wherein the housing member is arranged to substantially cover the actuator module at at least one side of the connectable module that faces the first panel, and wherein the connectable module is arranged in the space between the adjacent panels and is connected to the spacer and/or sealing means.

18. Method for reducing the transfer of noise through a window pane, the window pane comprising a panel comprising a front side, back side opposed to the front side and an outer circumferential edge, the panel further comprising a centre plane in between the front and back sides, and, at and/or adjacent to the outer circumferential edge, an actuator connecting section that is arranged asymmetrically with respect to the centre plane, wherein the method comprises the steps of:

- providing at least one actuator comprising an actuation end and a second end;
- connecting or at least contacting the actuation end of the actuator to the actuator connecting section of the panel of the window pane;
- restraining movement of the second end;
- providing a controller;
- receiving, by the controller, at least one input signal;
- controlling, with the controller and in dependence of the at least one input signal, the actuation end to control the deformation of the panel in the out-of-plane direction such that vibrations of the panel that are responsible for the transfer of the noise are reduced.

19. The method of claim 18, further comprising the step of providing at least one sensor configured for determining a state variable associated to the vibration controlled window pane, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

20. Kit-of-parts for forming a window pane into a vibration controlled window pane, comprising:

- at least one actuator module comprising an actuation end arranged to connect to, or at least contact, a panel of the window pane at an actuator connecting section of the panel adjacent to an outer circumferential edge of the panel, the panel comprising a centre plane in between a front side of the panel and an opposed back side of the panel, and the actuator connecting section being arranged asymmetrically with respect to the centre plane, wherein the actuator module further comprises a second end arranged such that movement of the second end is restrained, and at least one actuator arranged to move the actuation end with respect to the second end in order to, when in use, deform the panel in at least an out-of-plane direction that is substantially perpendicular to the centre plane;

- a controller that is configured to receive at least one input signal and that is electrically connected to, and configured to control, the at least one actuator of the at least one actuator module to cause the actuation end to move in dependence of the at least one input signal, in order to control, when in use, the deformation of the panel in the out-of-plane direction such that vibrations of the panel that are responsible for the transfer of the noise are reduced.

21. Kit-of-parts according to claim 20, further comprising at least one sensor configured for determining a state variable associated to the vibration controlled window pane, such as an applied force, an out-of-plane movement of the panel, strain of the panel and/or sound pressure acting on the panel, and wherein the at least one sensor is configured to provide the determined state variable as the at least one input signal of the controller.

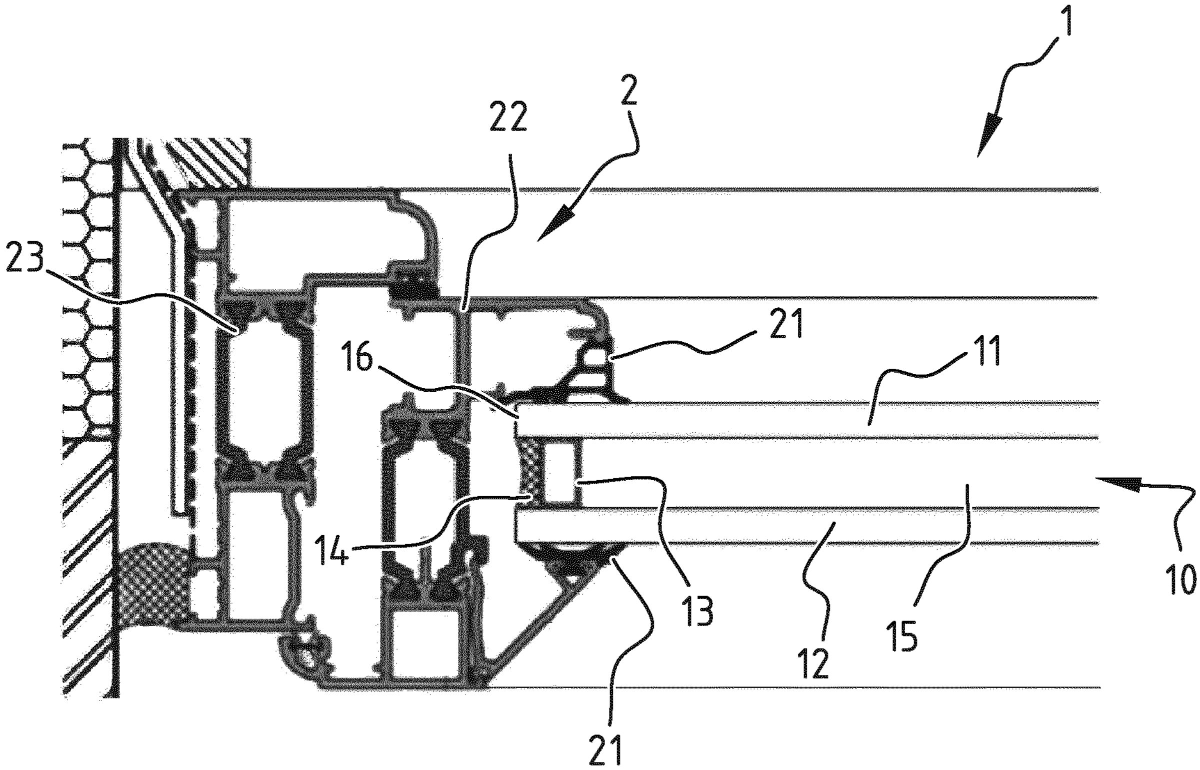


FIG. 1

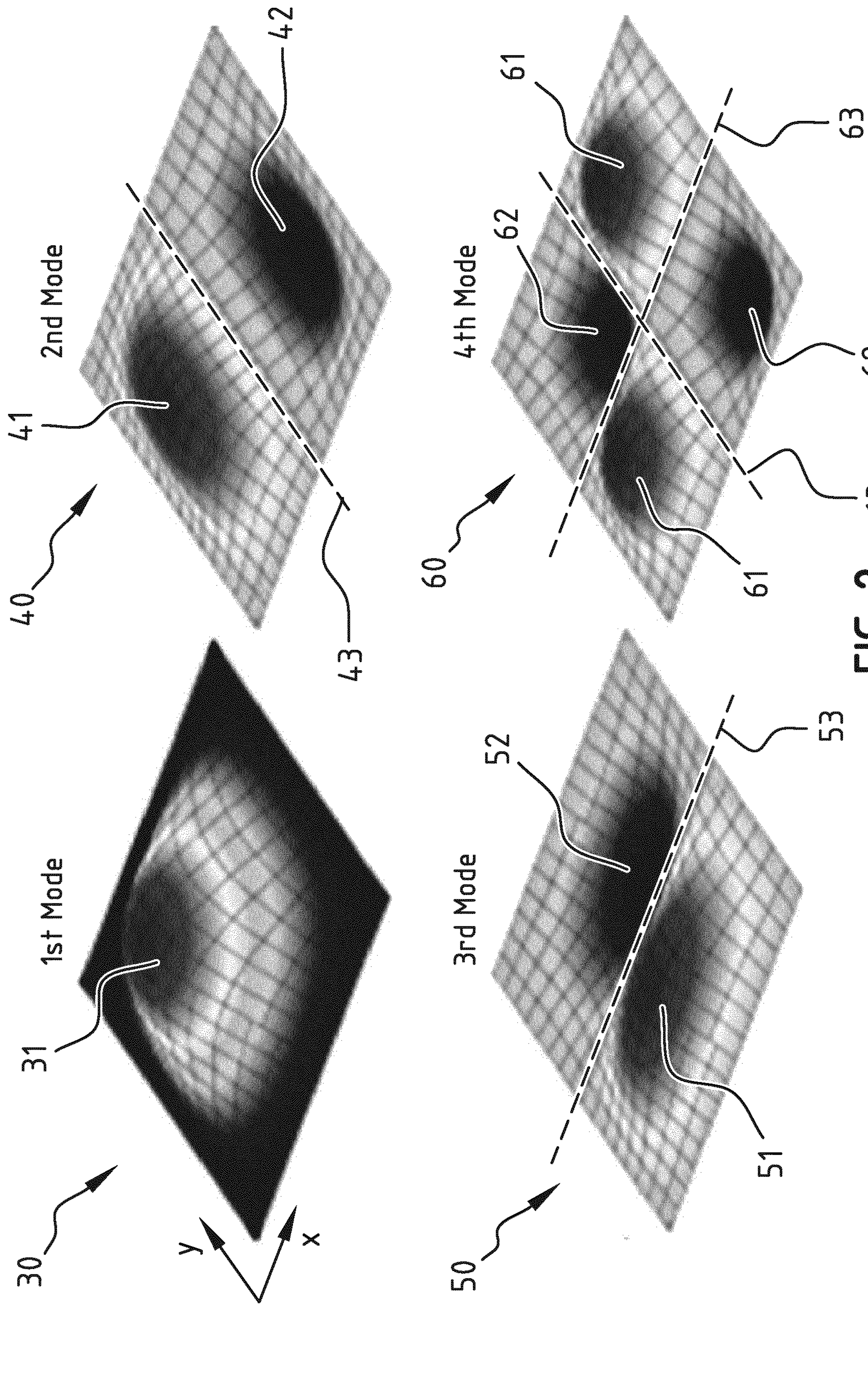

1st Mode
2nd Mode
3rd Mode
4th Mode
30
31
40
41
42
43
50
51
52
53
60
61
61
62
62
63
63
x
y

FIG. 2

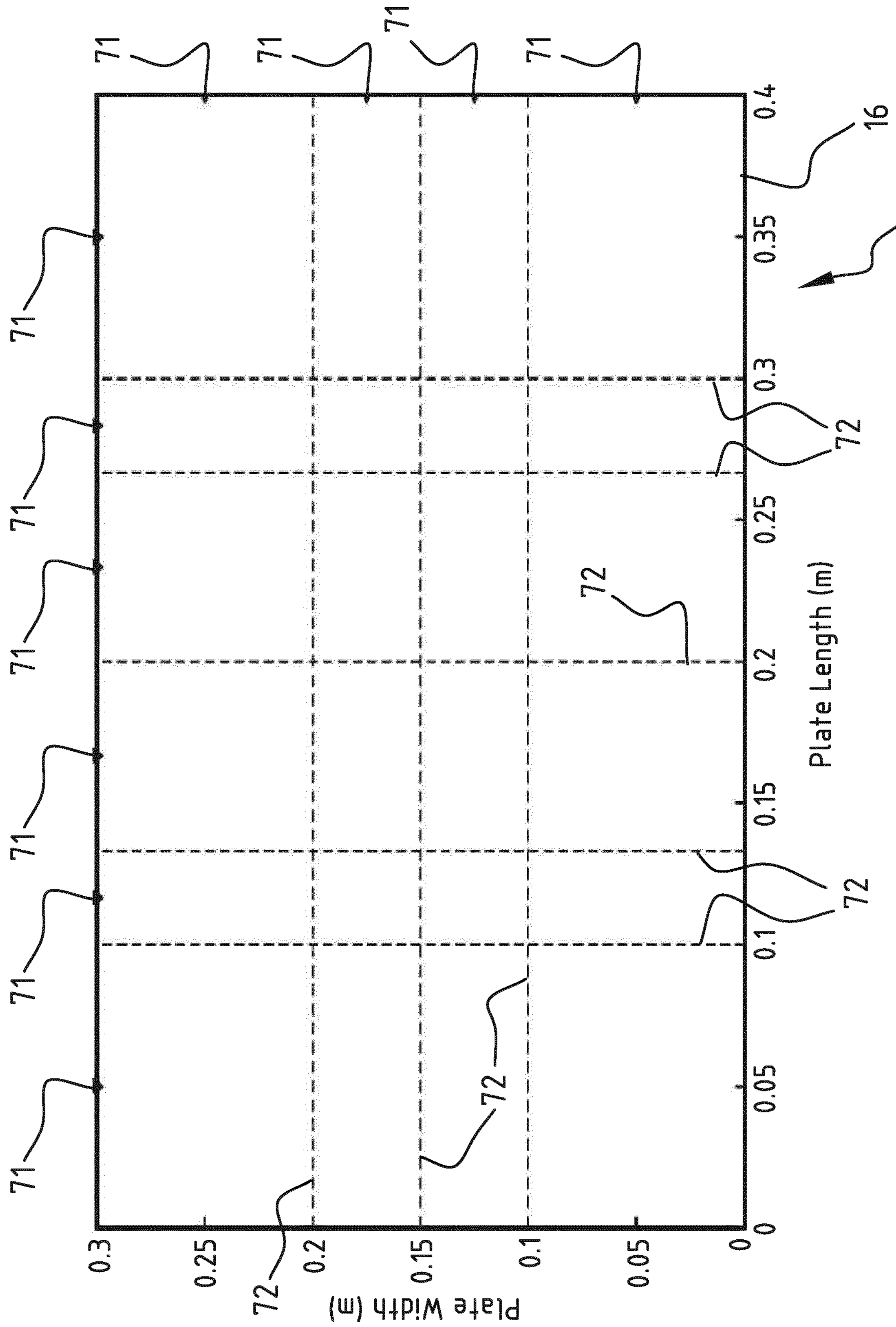


Plate Length (m)
Plate Width (m)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
71
72
16
11

FIG. 3

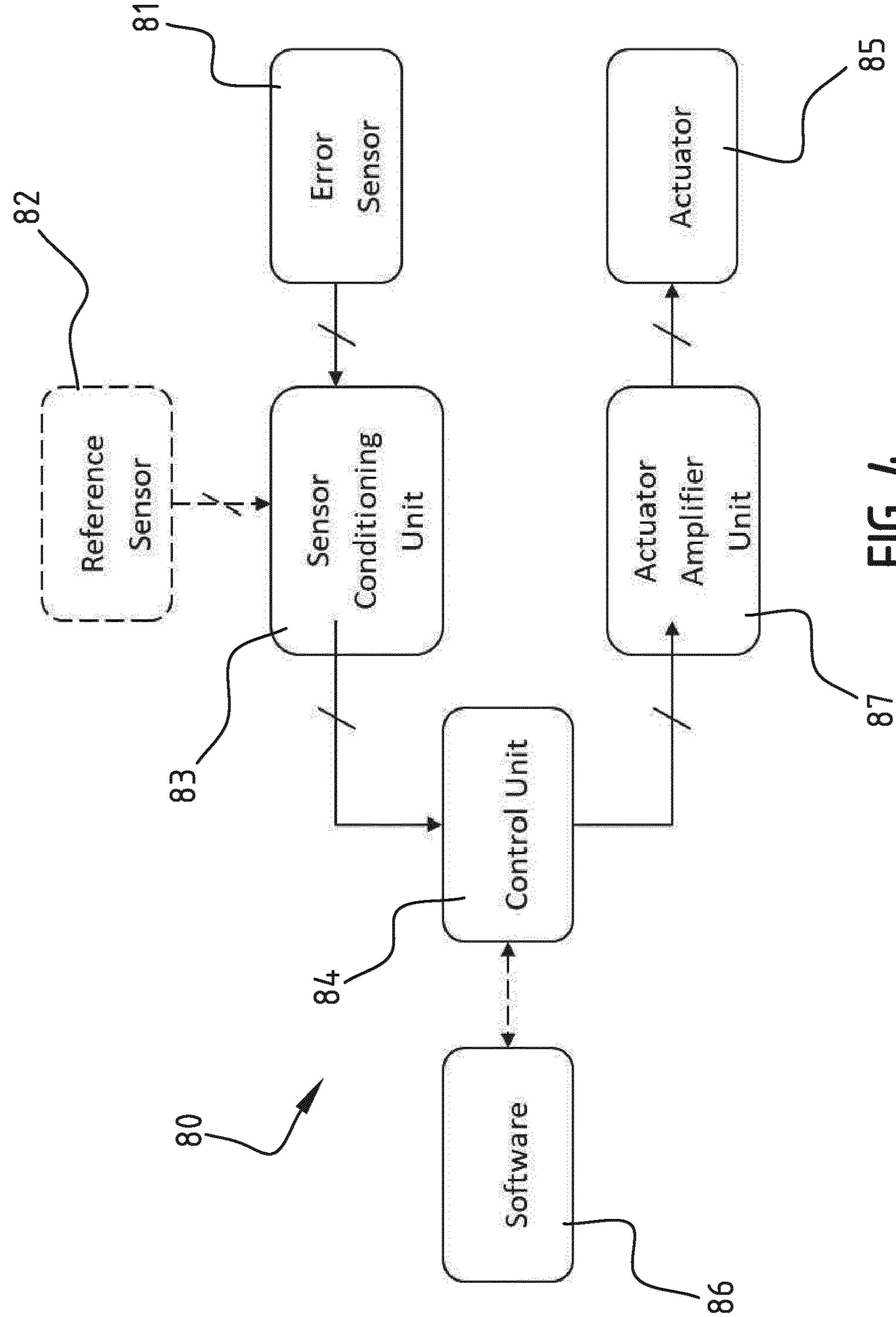

81
Error Sensor
82
Reference Sensor
Sensor Conditioning Unit
83
Control Unit
84
Software
86
80
Actuator
85
Actuator Amplifier Unit
87

FIG. 4

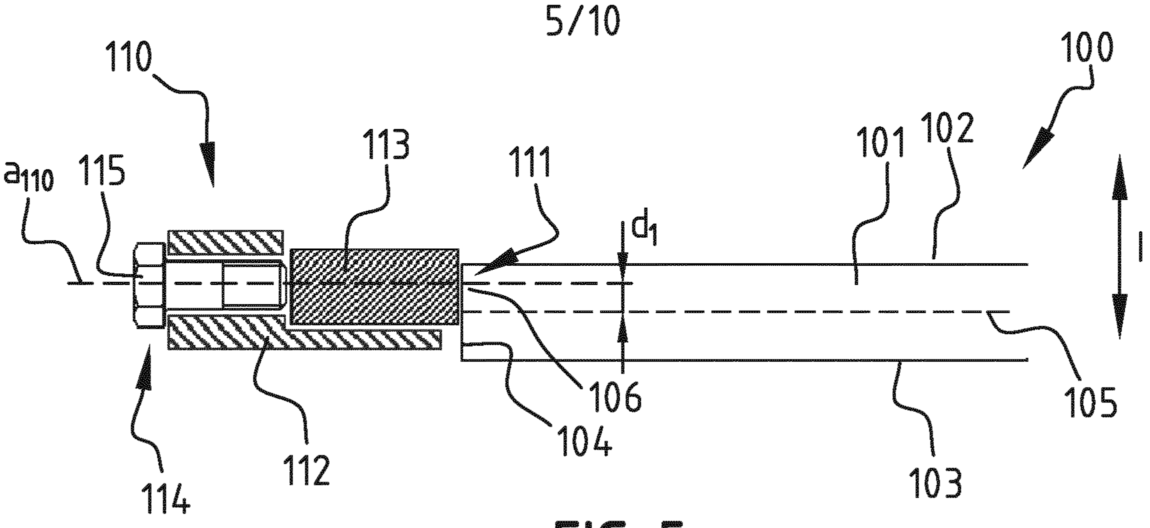


FIG. 5

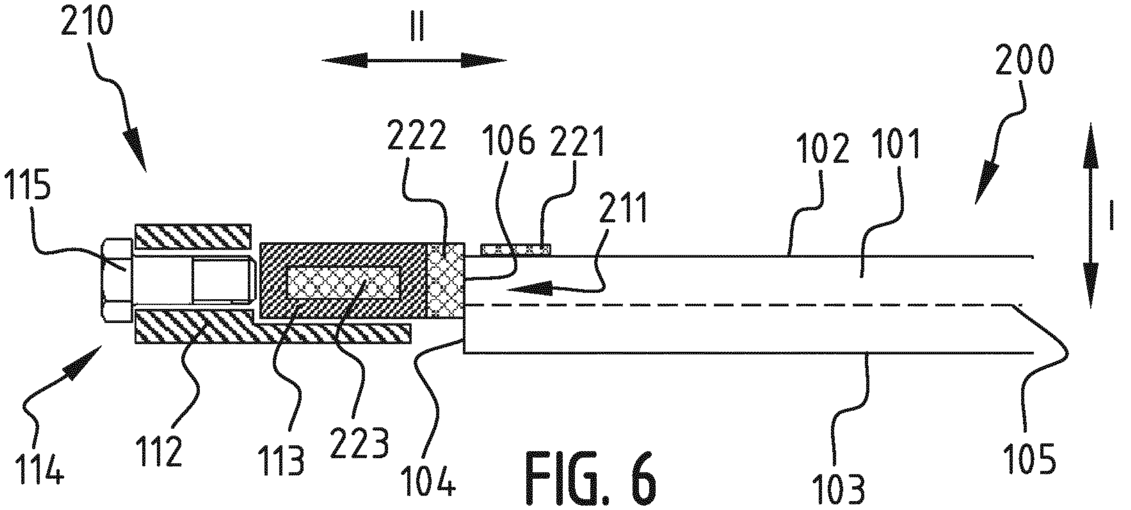


FIG. 6

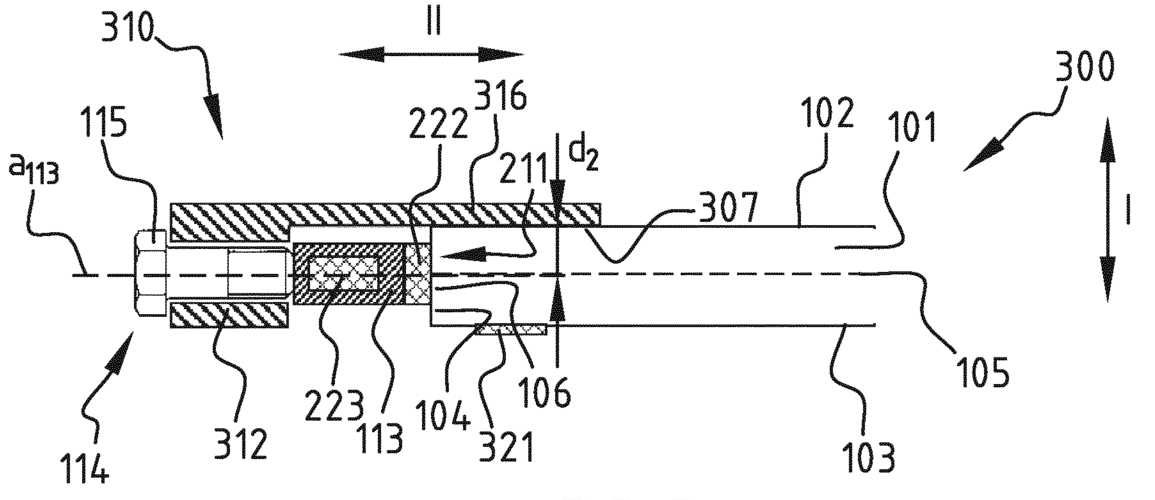
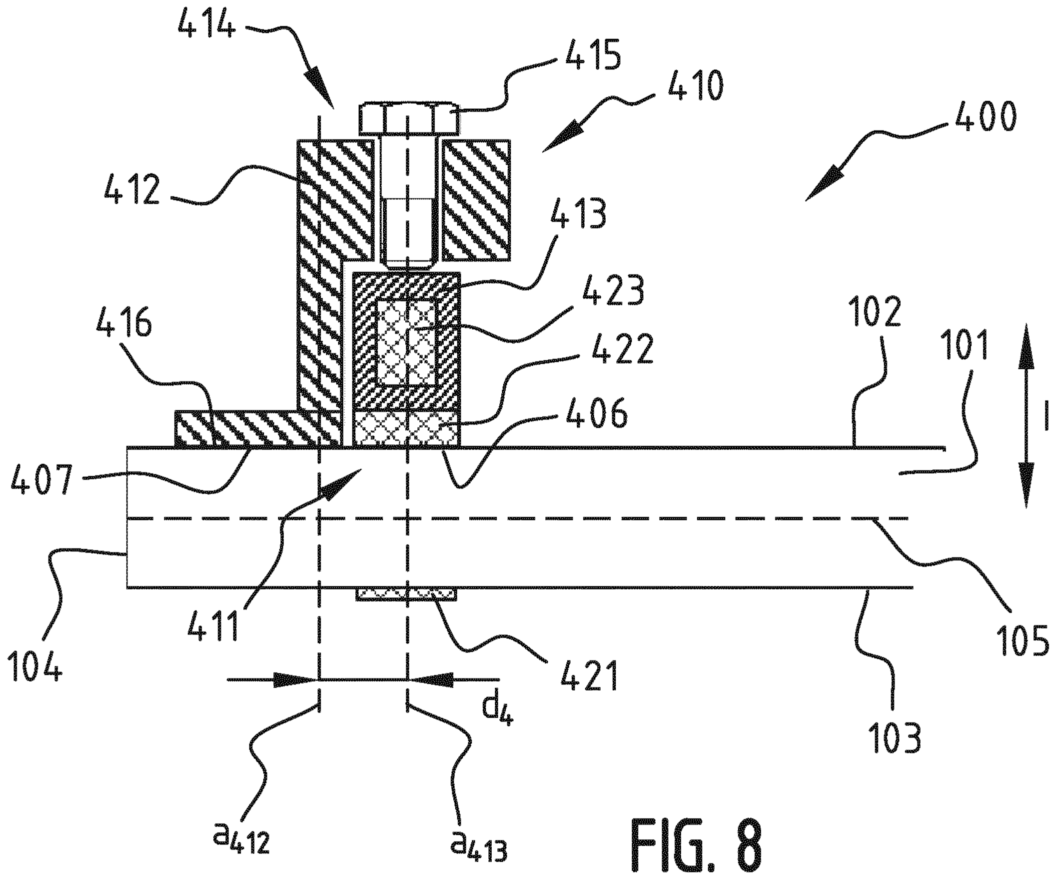


FIG. 7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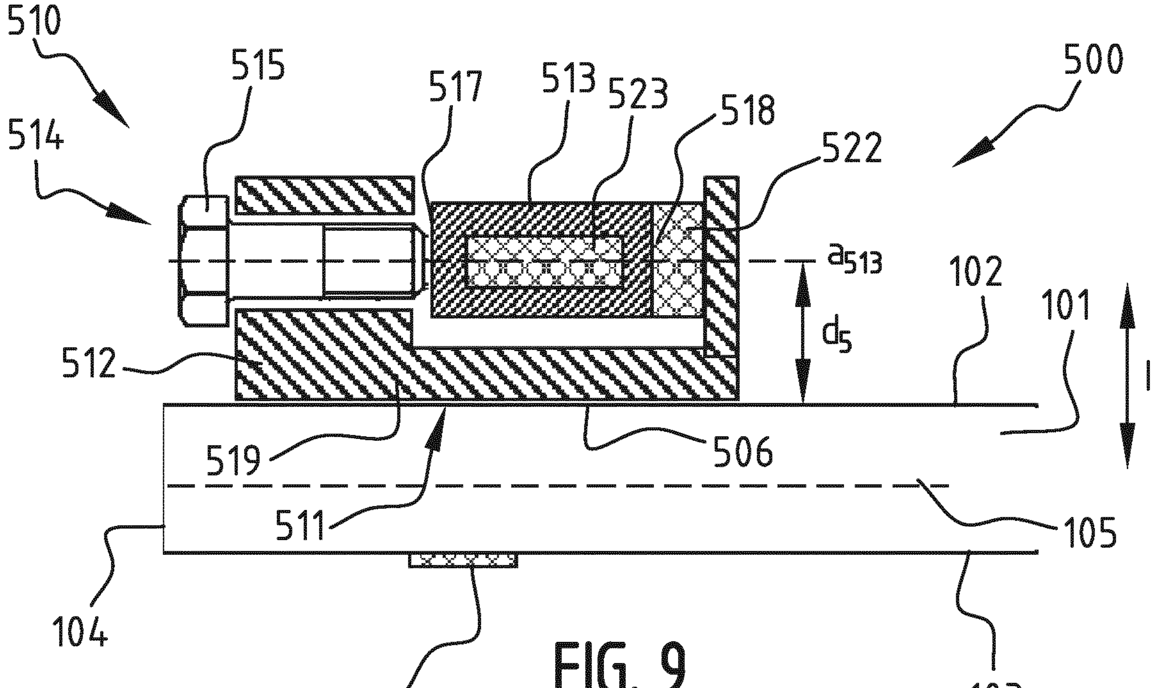
a412
a413

FIG. 8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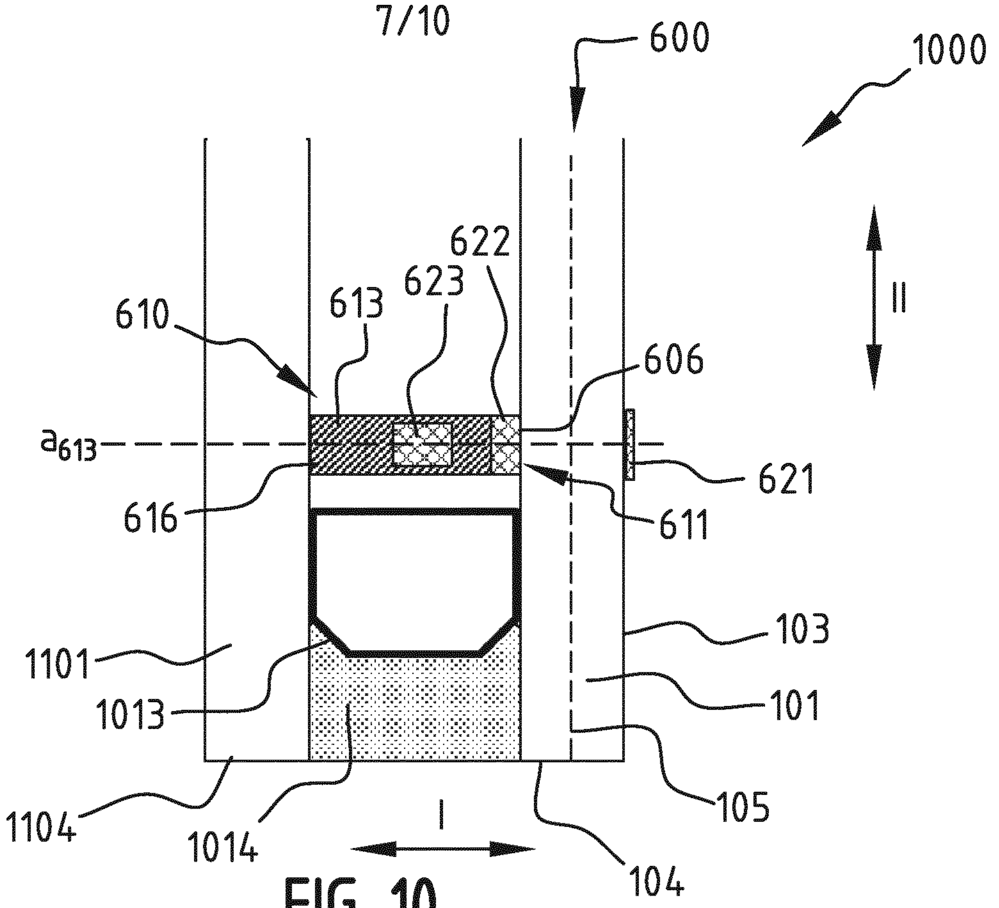
103

FIG. 9



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621
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611
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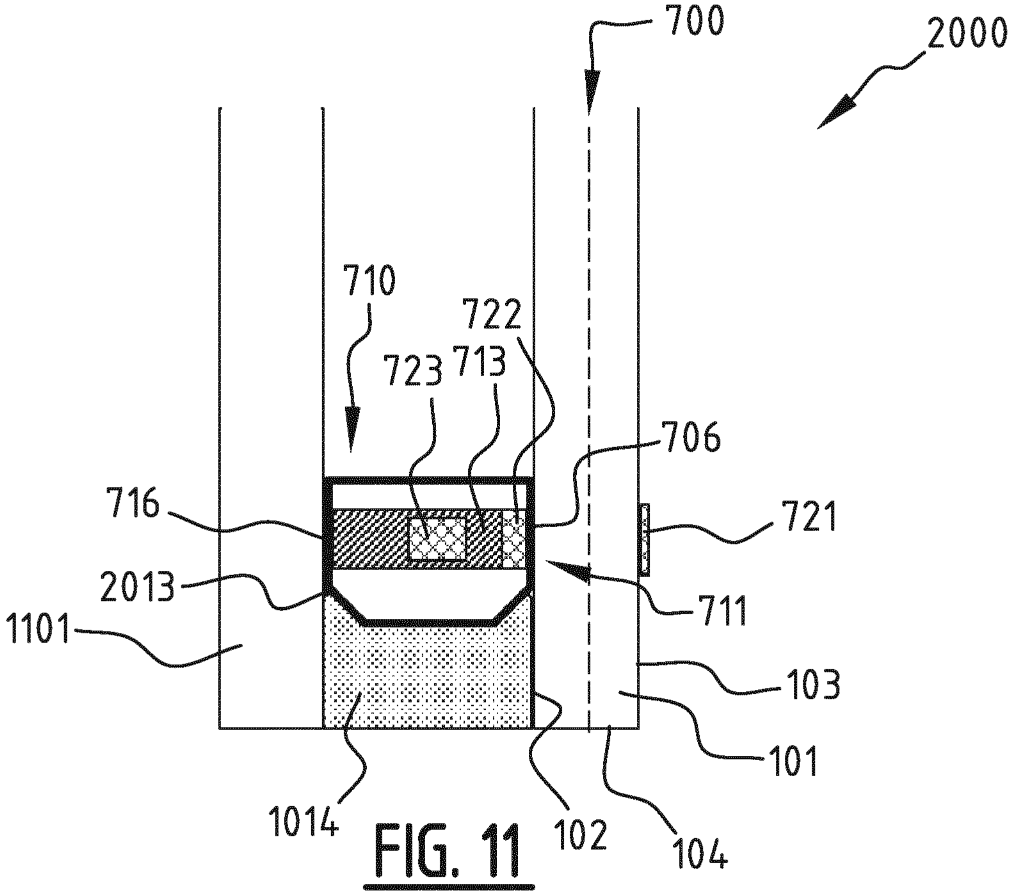
1104
1014
I
104

FIG. 10



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2013
711
1101
103
101
1014
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104

FIG. 11

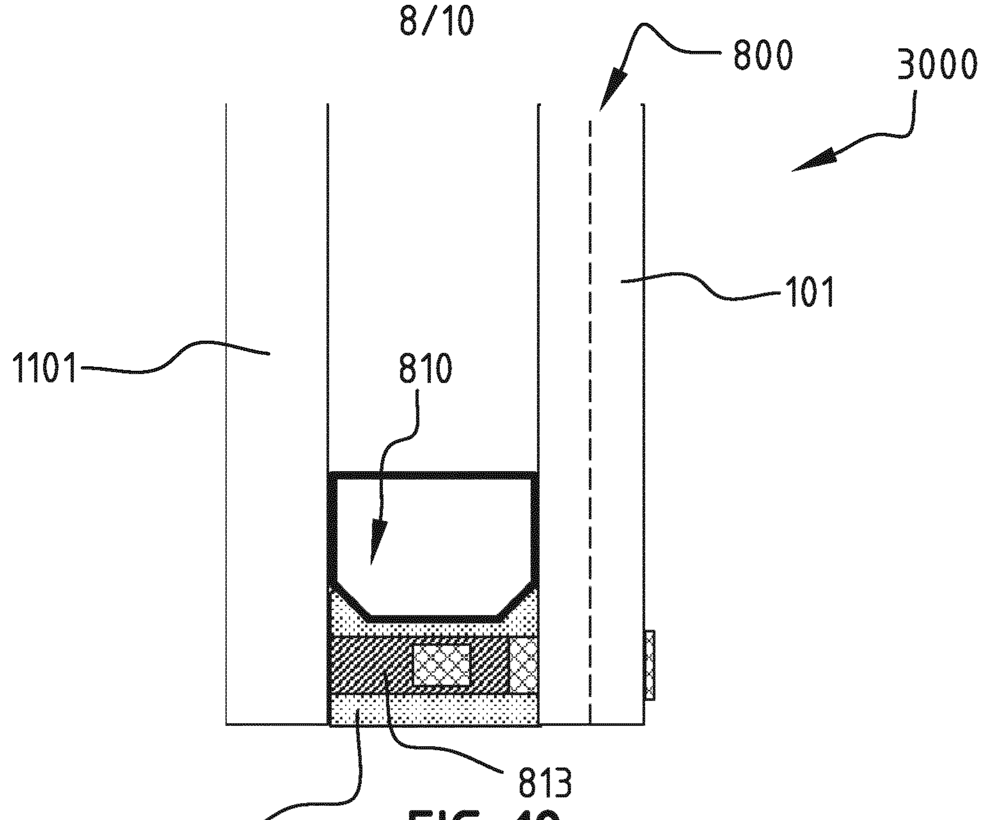
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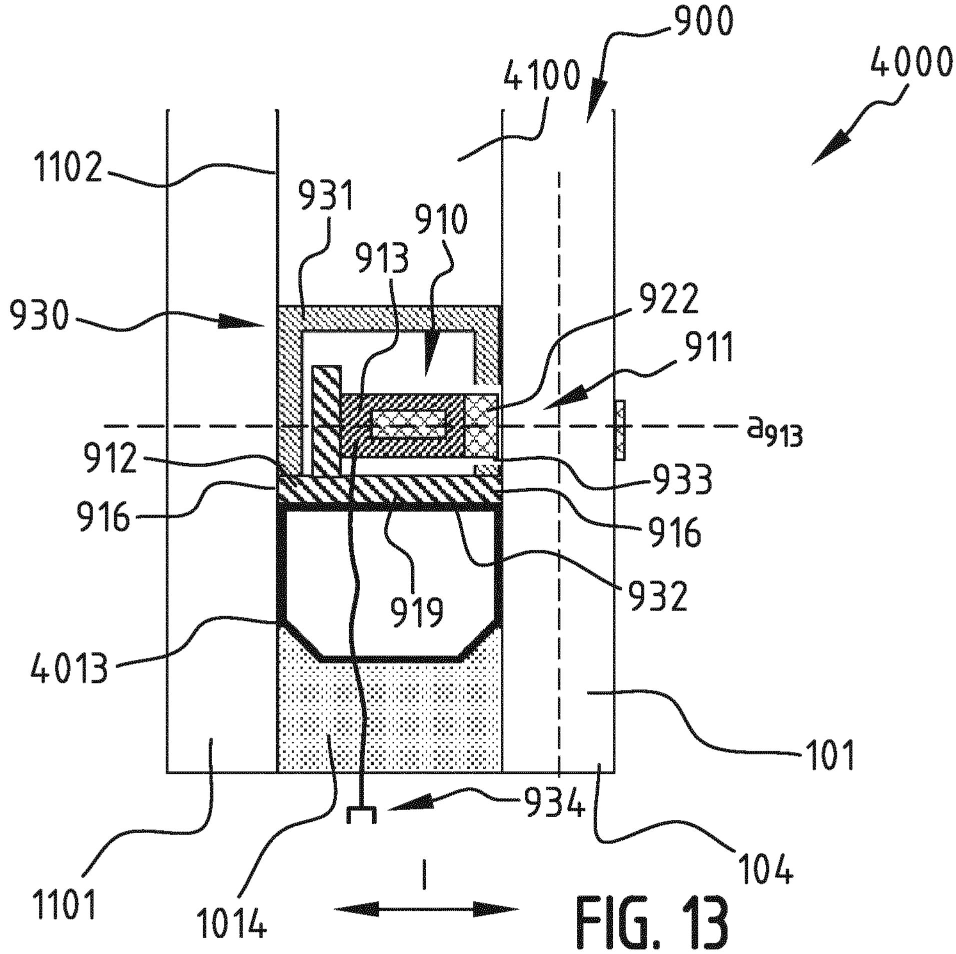
FIG. 12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916
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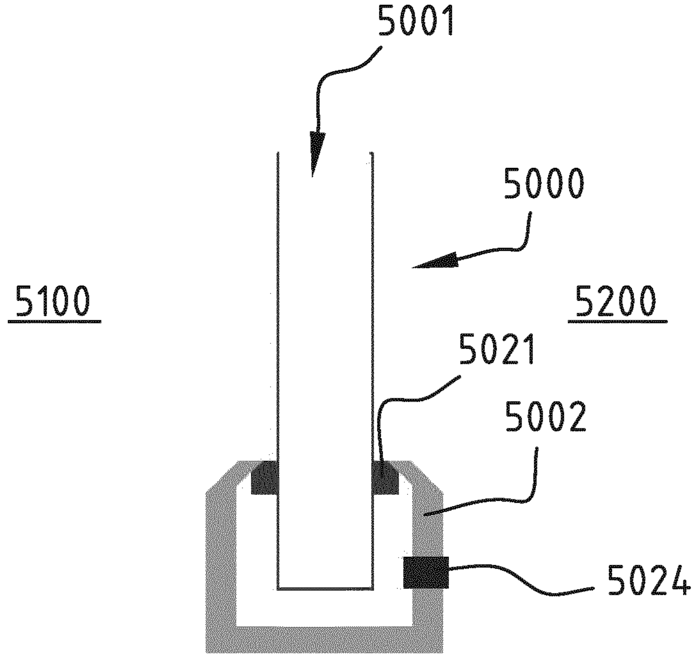
932
4013
101
934
1101
1014
104
I

FIG. 13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5002
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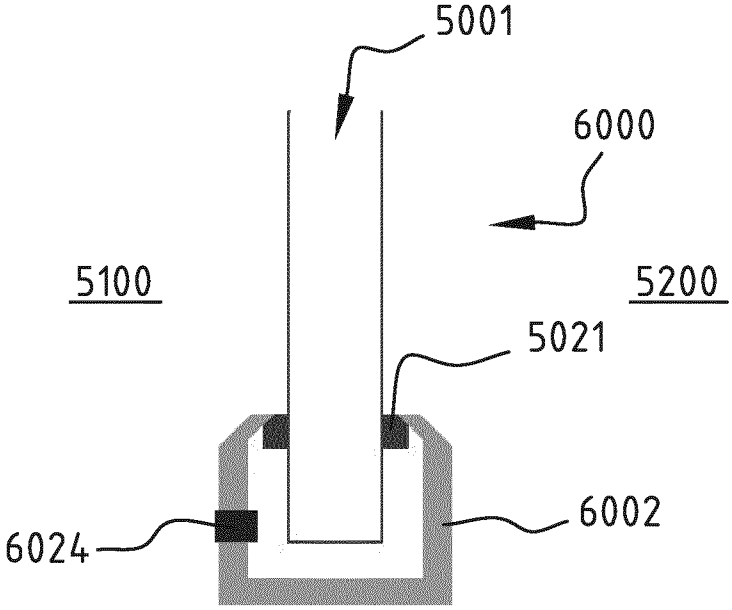
FIG. 14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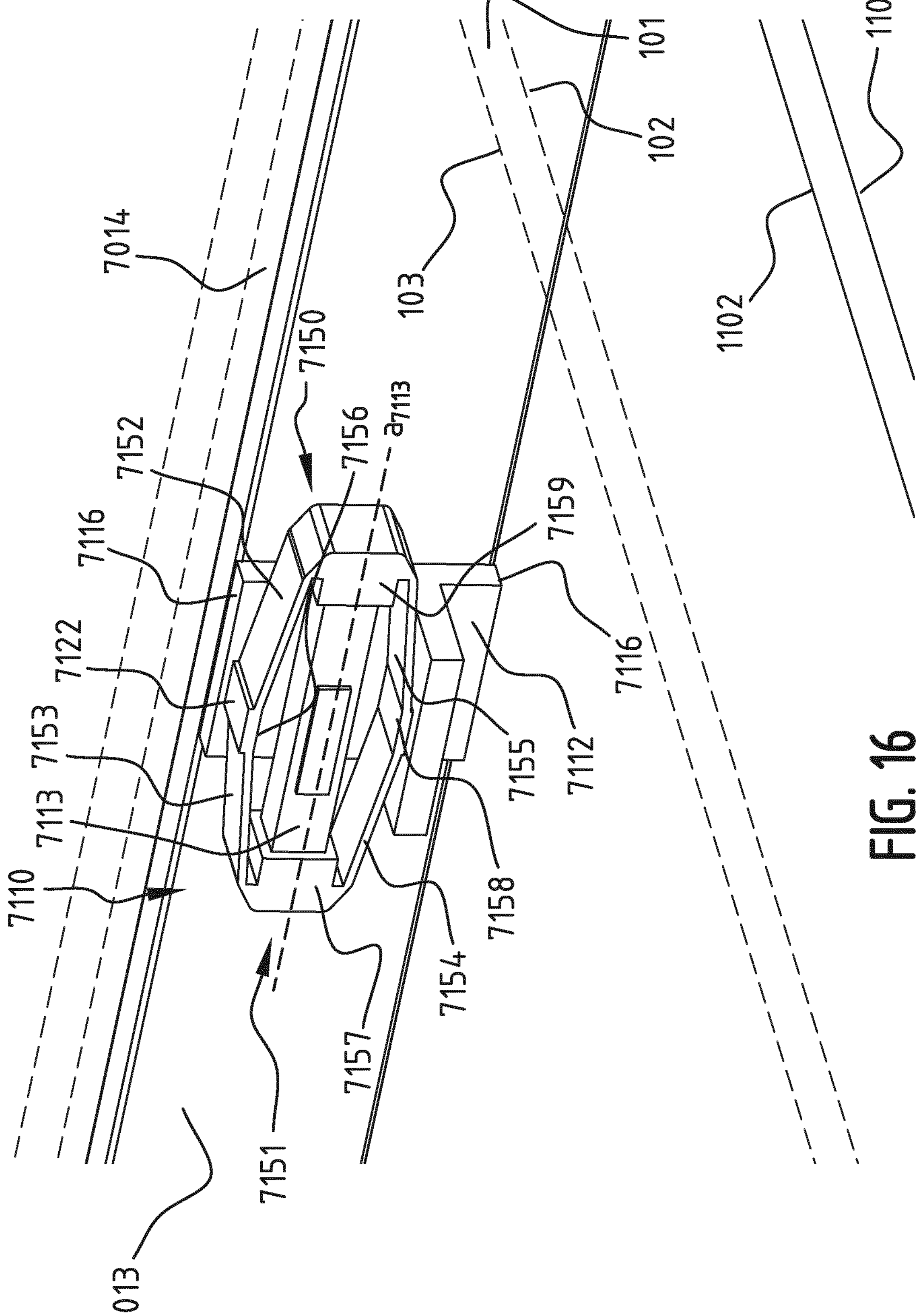
6024
6002

FIG. 15



101
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1101
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7014
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7152
7156
a_{7113}
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7110
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FIG. 16

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2021/080553

A. CLASSIFICATION OF SUBJECT MATTER
INV. G10K11/178 E06B5/20
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)
G10K E06B

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.
X	US 2020/175955 A1 (GANDHI UMESH N [US]) 4 June 2020 (2020-06-04) paragraphs [0003] - [0005], [0016], [0030], [0039] - [0040]; figures 1A, 2A-C -----	1-21
X	EP 0 964 387 A2 (DAIMLER CHRYSLER AG [DE]) 15 December 1999 (1999-12-15) paragraphs [0007] - [0008], [0025] - [0027]; claims 1, 6; figures 5-8 -----	1-15, 18-21
X	DE 101 16 166 A1 (DAIMLER CHRYSLER AG [DE]) 10 October 2002 (2002-10-10) paragraphs [0015], [0023], [0029]; claims 1-7; figures 1-4 ,6 -----	1-21
	-/--	

[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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"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

"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

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
27 January 2022	04/02/2022

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Naujoks, Marco

1

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C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2018/130455 A1 (PLUMMER DAVID D [US] ET AL) 10 May 2018 (2018-05-10) paragraphs [0006], [0030] - [0036], [0040] - [0042]; figures 2-10 -----	1-21
A	US 6 320 113 B1 (GRIFFIN STEVEN F [US] ET AL) 20 November 2001 (2001-11-20) column 14, lines 25-40 figures 1, 3, 7, 20, 22, 25, 29 column 18, line 62 - column 19, line 50 -----	1-21

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2021/080553

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			EP 0964387	A2	15-12-1999
DE 10116166	A1	10-10-2002	NONE		
US 2018130455	A1	10-05-2018	US 2018130455	A1	10-05-2018
			WO 2018089345	A1	17-05-2018
US 6320113	B1	20-11-2001	NONE		