(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
16 May 2019 (16.05.2019)

WIPO | PCT

(10) International Publication Number
WO 2019/094691 A1

(51) International Patent Classification:
F04D 29/70 (2006.01) *F15D 1/00* (2006.01)

(21) International Application Number:
PCT/US2018/059980

(22) International Filing Date:
09 November 2018 (09.11.2018)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
62/583,538 09 November 2017 (09.11.2017) US

(71) Applicants: **FLORIDA STATE UNIVERSITY RESEARCH FOUNDATION, INC.** [US/US]; 2000 Levy Avenue, Building A, Suite 351, Tallahassee, Florida 32310-5792 (US). **EBARA CORPORATION** [JP/JP]; 11-1 Haneda Asahi-Cho, Ohta-Ku, Tokyo 144-8510 (JP).

(72) Inventors: **TAIRA, Kunihiko**; 2003 Levy Avenue, Tallahassee, Florida 32310 (US). **LIU, Qiong**; 2003 Levy Avenue, Tallahassee, Florida 32310 (US). **AN, Byungjin**; 4-2-1 Honfujisawa, Fujisawa, Kanagawa 251-8502 (JP). **NOHMI, Motohiko**; 4-2-1 Honfujisawa, Fujisawa, Kanagawa 251-8502 (JP). **OBUCHI, Masashi**; 4-2-1 Honfujisawa, Fujisawa, Kanagawa 251-8502 (JP).

(74) Agent: **KING, Kevin W.** et al.; Eversheds Sutherland (US) LLP, 999 Peachtree Street, NE, Atlanta, Georgia 30309-3996 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

(54) Title: SYSTEMS AND METHODS FOR ACTIVELY CONTROLLING A VORTEX IN A FLUID

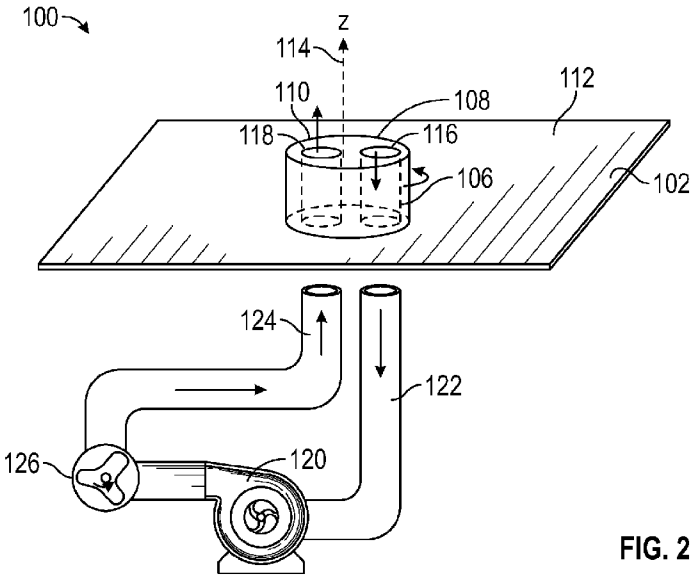


FIG. 2

(57) Abstract: A vortex control device for modifying a vortex in a fluid stemming from a wall is disclosed. The device includes a rotatable hub disposed within an opening in the wall. The device also includes an inlet port and an outlet port in the rotatable hub. The inlet port forms a suction port to suction fluid from or about the vortex, and the outlet port forms an injection port to inject fluid into or about the vortex.

[Continued on next page]

WO 2019/094691 A1

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*

Published:

— *with international search report (Art. 21(3))*

SYSTEMS AND METHODS FOR ACTIVELY CONTROLLING A VORTEX IN A FLUID

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The disclosure claims priority to and the benefit of U.S. provisional patent application No. 62/583,538, filed November 9, 2017, which is incorporated by reference herein in its entirety.

FIELD OF THE DISCLOSURE

[0002] The disclosure generally relates to vortices and more particularly relates to systems and methods for actively controlling a vortex in a fluid.

BACKGROUND

[0003] Wall-bounded vortex arises in both nature and various engineering applications. There have been efforts to understand the dynamics of vortices and to develop techniques to modify their behavior. Flow control is often employed to diminish the appearance of vortices or alter the characteristics of vortices in a liquid. For example, in a sump pump, the emergence of submerged vortices may degrade pump performance. If the submerged vortices are sufficiently strong, these vortices can include strong low-pressure cores, which can entrain air/vapor along their vortex cores. If such hollow-core vortices are engulfed by the pump, they can cause unbalanced loading and vibration, leading to undesirable noise and possible structural failure. Strong wall-normal vortices appear inside and outside of many fluid-based machines as well as in natural settings, including tornadoes and hurricanes.

[0004] There have been numerous attempts to introduce passive vortex control techniques to prevent the generation of the aforementioned vortices or alter their pressure distributions. Yet passive control techniques do not offer the ability to adaptively adjust the control efforts to unsteady flow conditions (beyond design conditions). Moreover, some passive control devices are difficult to manufacture. Thus, these past efforts have shortcomings in offering reliable techniques to modify the pressure distribution of these vortices. Designing a more efficient and flexible vortex control strategy remains a challenge.

SUMMARY

[0005] In certain embodiments, a vortex control device for modifying a vortex in a fluid stemming from a wall is disclosed. The device includes a rotatable hub disposed within an opening in the wall. The device also includes an inlet port and an outlet port in the rotatable hub. The inlet port forms a suction port to suction fluid from or about the vortex, and the outlet port forms an injection port to inject fluid into or about the vortex. The device may therefore alter a pressure distribution of the vortex by injecting momentum perturbations to the flow.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The detailed description is set forth with reference to the accompanying drawings. The use of the same reference numerals may indicate similar or identical items. Various embodiments may utilize elements and/or components other than those illustrated in the drawings, and some elements and/or components may not be present in various embodiments. Elements and/or components in the figures are not necessarily drawn to scale. Throughout this disclosure, depending on the context, singular and plural terminology may be used interchangeably.

[0007] FIG. 1 depicts a vortex control device in accordance with one or more embodiments of the disclosure.

[0008] FIG. 2 depicts a vortex control device in accordance with one or more embodiments of the disclosure.

[0009] FIG. 3 depicts a vortex control device in accordance with one or more embodiments of the disclosure.

[0010] FIG. 4 depicts a vortex control device in accordance with one or more embodiments of the disclosure.

[0011] FIG. 5 depicts a vortex model based on Burgers vortex in accordance with one or more embodiments of the disclosure.

[0012] FIG. 6 depicts a computational setup for a vortex model in accordance with one or more embodiments of the disclosure.

[0013] FIGS. 7A to 7D depict a baseline flow field visualization of an instantaneous flow field in accordance with one or more embodiments of the disclosure.

[0014] FIG. 8 depicts a baseline flow field visualization of a vortex bursting structure in accordance with one or more embodiments of the disclosure.

[0015] FIG. 9 depicts the control effect of counter- and co-rotating mass injection in accordance with one or more embodiments of the disclosure.

[0016] FIG. 10 depicts the control effect of co-rotating mass injection in accordance with one or more embodiments of the disclosure.

[0017] FIG. 11A depicts the control effect of co-rotating mass injection in accordance with one or more embodiments of the disclosure.

[0018] FIG. 11B depicts the control effect of counter-rotating mass injection in accordance with one or more embodiments of the disclosure.

[0019] FIG. 12 depicts a computational setup for a vortex model with an off-centered control device in accordance with one or more embodiments of the disclosure.

[0020] FIG. 13A depicts the location of the control device in a counter-rotating simulation in accordance with one or more embodiments of the disclosure.

[0021] FIG. 13B depicts the time averaged flow fields for the counter-rotating simulation in FIG. 13A in accordance with one or more embodiments of the disclosure.

[0022] FIG. 14A depicts the time-averaged vortex core pressure distributions along the axial direction for co-rotating simulations in accordance with one or more embodiments of the disclosure.

[0023] FIG. 14B depicts the time-averaged vortex core pressure distributions along the axial direction for counter-rotating simulations in accordance with one or more embodiments of the disclosure.

[0024] FIG. 15 depicts a vortex control device in accordance with one or more embodiments of the disclosure.

DETAILED DESCRIPTION

[0025] The present disclosure is directed to spreading the core region of a coherent wall-normal vortex and alleviating the low-pressure in the core in a flow field. Such vortices are ubiquitous in nature and engineering systems, ranging from hydrodynamic/aerospace applications to nature, such as hurricanes and subsurface vortices. Many passive control techniques exist for wall-normal vortices, but none include active flow control methods that can be applied in an adaptive manner. To solve this problem, the present disclosure introduces a control device comprising forcing input (e.g., a fluid jet and suction) at or near the core region of the vortex to destabilize the local flow and spread the core region. The injected fluid modifies the dynamics of the

vertical flow and lowers the local angular velocity, increasing the core pressure of the vortex. The increase of the pressure has engineering benefits because low pressure at the core can create detrimental engineering effects for vortices in air and liquids. In some instances, the forced input follows a sinusoidal form in time and in a co-rotating/counter-rotating direction for effective breakup of the vortex.

[0026] The present disclosure provides a more adaptive technique than passive controls for alleviating the low-pressure effect of the vortex core using active flow control techniques. That is, the present disclosure provides a vortex control technique and device for control of vortices stemming from the wall in different flow conditions. To achieve this, two different types of control strategies are disclosed based on co-rotating and counter-rotating mass injection and suction from the wall surface on which the vortex resides. The control strategy is employed on the wall where the vortex core is positioned and the mass injection/suction device is placed underneath the surface. The control device may be centered or off-centered from the core of the vortex. The control input is adjusted with its frequency, amplitude, and direction of mass injection/suction. The control device may draw fluid from the system that the vortex is formed and inject said fluid back into the system. That is, the same fluid in which the vortex is formed may be injected/suctioned at or about the vortex. In other instances, the control device may inject fluid from outside the system into the vortex. In some instances, injection/suction is introduced from multiple locations in a rotational manner with respect to the vortex core. These devices allow the control input to be tuned for vortices with different strengths.

[0027] Vortex Control Device

[0028] FIGS. 1-4 and 15 depict examples of a vortex control device 100. The vortex control device 100 may be disposed at or below a wall plate 102 to which a vortex 104 is pinned. The vortex 104 may be formed in a fluid. The fluid may be a liquid or a gas. In some instances, a plurality of vortex control devices 100 may be used. That is, two, three, or more of the vortex control devices 100 may be disposed at various locations about the wall plate 102 around the vortex 104.

[0029] In certain embodiments, the vortex control device 100 includes a hub 106. The hub 106 may be disposed within an opening 108 in the wall plate 102. In some instances, the hub 106 includes a surface 110 that is flush with a surface 112 of the wall plate 102. In other instances, the surface 110 of the hub 106 may not be flush with the wall plate 102. That is, the surface 110 of the hub 106 may be recessed within the wall

plate 102, or the surface 110 of the hub 106 may protrude out from the wall plate 102. The hub 106 may be any suitable size, shape, or configuration. The hub 106 may act as a stationary or rotating manifold for the vortex control device 100.

[0030] In certain embodiments, as depicted in FIG. 1, the hub 106 is stationary. That is, the hub 106 may not rotate. In such instances, the hub 106 may include a port 109. The port 109 may be fixed in place and act as an inlet port (suction port) or an outlet port (injection port) depending its attachment to a pump and the control device configuration. In some instances, the port 109 is located at or near a core of the vortex 104. In other instances, the port 109 is disposed around a perimeter of the vortex 104. The port 109 may be located in any suitable location at or about the vortex 104. The number of ports 109 may be increased. That is, a number of ports 109 may be located at or about the vortex 104. In some instances, the ports 109 may all be suction ports. In other instances, the ports 109 may all be injection ports. In yet other instances, some of the ports 109 may function as injection ports while other ports 109 function as suction ports. In some instances, the ports 109 may be operated simultaneously. In other instances, the ports 109 may be selectively operated. That is, some ports 109 may be turned "on" while other are turned "off" at certain, potentially variable, times.

[0031] The angle of the port 109 may be controlled (e.g., tilted or the like) to further modify the vortex 104. For example, the blow or suction angle of the port 109 may be adjusted relative to the surface 110 of the hub 106. In other instances, the hub 106 itself may be manipulated (e.g., tilted) so as to adjust the blow and/or suction angles.

[0032] In one embodiment, the vortex control device 100 includes a pump 120 in fluid communication with the hub 106. In some instances, the pump may be in fluid communication with two conduits. For example, a first conduit 122 can be fluidly coupled to the port 109 such that the port 109 functions as a suction port. In other instances, the port 109 can be fluidly coupled to a second conduit 124 such that the port 109 functions as an injection port. The vortex control device 100 also may include a valve 126 to control the mass flow of the vortex control device 100. In this particular embodiment, the valve 126 is a rotary valve. However, any suitable valve 126 may be used. In other instances, the mass flow may be controlled via an inverter to control the pump speed.

[0033] As used herein, the term "fluidly couples" refers to the coupled parts being operably connected together and effective for a fluid to be communicated therebetween.

[0034] In other instances, as depicted in FIGS. 2-4, the hub 106 rotates about a central axis 114. In such instances, the hub 106 can rotate in either direction (i.e., clockwise or counterclockwise). Depending on the rotation of the vortex 104, the hub 106 may rotate with the vortex 104 (i.e., co-rotate) or rotate opposite the vortex 104 (i.e., counter-rotate).

[0035] In some instances, the hub 106 includes an inlet port 116 and an outlet port 118. The inlet port 116 may form a suction port, and the outlet port 118 may form an injection port. In some instances, the inlet port 116 and the outlet port 118 are located at or near a core of the vortex 104. In other instances, the inlet port 116 and the outlet port 118 are disposed around a perimeter of the vortex 104. The inlet port 116 and the outlet port 118 may be located in any suitable location about the vortex 104. In some instances, the vortex control device 100 may include a plurality of the number of inlet ports 116 and outlet ports 118. When a plurality of inlet ports 116 and outlet ports 118 are present, the inlet ports 116 and outlet ports 118 may be operated simultaneously. In other instances, the inlet ports 116 and outlet ports 118 may be selectively operated, such as in a predetermined sequence, e.g., serially. That is, some the inlet ports 116 and outlet ports 118 may be turned "on" while other are turned "off" at various times.

[0036] In any case, fluid, e.g., a liquid, may be drawn into the inlet port 116 and expelled out of the outlet port 118. As the hub 106 rotates within the wall plate 102, the location of the inlet port 116 and the outlet port 118 may rotate about the central axis 114. In some instances, the core of the vortex may be aligned with the central axis 114. In other instances, the core of the vortex may be offset from the central axis 114. To modify the vortex 104, the outlet port 118 is used to inject fluid, e.g., a liquid, into or about the vortex 104, and the inlet port 116 is used to suction fluid from or about the vortex 104. The inlet port 116 and the outlet port 118 may be operated simultaneously. That is, the inlet port 116 may suction fluid from or about the vortex 104 at the same time that the outlet port 118 injects fluid into or about the vortex 104. In other instances, the inlet port 116 and the outlet port 118 may not operate simultaneously. That is, only one of the inlet port 116 and the outlet port 118 may operate at once.

[0037] In certain embodiments, the angle of the inlet port 116 and the outlet port 118 may be controlled (e.g., tilted or the like) to further modify the vortex 104. For example, the blow angle of the outlet port 118 may be adjusted relative to the surface 110 of the hub 106. Similarly, the suction angle of the inlet port 116 may be adjusted relative to the

surface 110 of the hub 106. In other instances, the hub 106 itself may be manipulated (e.g., tilted) so as to adjust the blow and/or suction angles.

[0038] In one embodiment, the vortex control device 100 includes a pump 120 in fluid communication with the hub 106. For example, a first conduit 122 fluidly couples the inlet port 116 to the pump 120, and a second conduit 124 fluidly couples the outlet port 118 to the pump 120. The vortex control devices 100 also may include a valve 126 to control the mass flow of the vortex control device 100. In this particular embodiment, the valve 126 is a rotary valve. However, any suitable valve 126 may be used. In other instances, the mass flow may be controlled via an inverter to control the pump speed.

[0039] As depicted in FIG. 15, the vortex control device 100 may include a controller 128 in electrical communication with the various components of the vortex control device 100. The controller 128 may be any computing device capable of controlling the operation of the vortex control device 100. The controller 128 may include one or more processors in communication with one or more memory. In some instances, the controller 128 may include wireless communication capabilities. That is, the controller 128 may wirelessly communicate with the various components of the vortex control device 100 or other outside devices, such as a computer or server.

[0040] The controller 128 may be in communication with at least one hub actuator 130, which may be in electrical and/or mechanical communication with the hub 106. In this manner, the hub actuator 130 may be configured to control the movement of the hub 106. For example, the hub actuator 130 may control the rotation or tilt of the hub 106 or the ports associated therewith. The controller 128 also may be in communication with at least one valve actuator 132, which may be in electrical and/or mechanical communication with the valve 126. In this manner, the valve actuator 132 may be configured to control the operation of the valve 126. In addition, the controller 128 may be in communication with the pump 120. In this manner, the controller 128 may be configured to control the operation of the pump 120.

[0041] Vortex Model

[0042] Extensive numerical simulation and experimental investigations were performed on a vortex control device. For example, FIG. 5 depicts a vortex model using Burgers vortex. Burgers vortex is an axis symmetric vortex subjected to an axial strain field of constant strain rate γ. The velocity field is expressed in cyclical coordinates (r, θ, z) as

$u_r = -\frac{1}{2}\gamma r$, $u_\theta = \frac{\Gamma}{2\pi r}\left[1 - exp\left(-\frac{r^2}{a_0^2}\right)\right]$, $u_z = \gamma z$, and $a_0^2 = \frac{4\nu}{\gamma}$, where vortex core size $a_0 = 1$, circulation: $\Gamma = 9.848$, u_θ, max = 1, and $Re = \Gamma/\nu = 5000$.

[0043] In one example, a submerged vortex model was a modification of Burgers vortex by a no-slip boundary condition along the symmetry plane. As depicted in FIG. 6, a no-slip boundary condition was included along the symmetry plane. To examine the effectiveness of the vortex control device using unsteady mass injection on the lower control region, incompressible 3D direct numerical simulation ("DNS") was performed on the submerged vortex model generated by the Burger vortex velocity profile. In this manner, FIG. 6 depicts the computational setup of a 3-D direct numerical simulation of the submerged vortex model generated by the Burgers vortex-type velocity profile. In this computation, the geometric setup was as follows: r radius u_r; θ azimuthal angle u_θ; and z axis u_z,. The boundary conditions were defined as follows:

Inlet : (u_r, u_θ, u_z); Outlet: $\frac{\partial u}{\partial n} + (u \cdot n)\frac{\partial u_z}{\partial z} = 0$; and Bottom: u = 0. The control input comprised unsteady mass injection imposed from the lower surface, where $u_s = A\cos(\theta + \omega_c t)e^{-r^2}$, where ω_c is the control frequency, and A is amplitude. The control efforts were evaluated using

$C_\mu = \frac{\rho\infty u_s^2 \mathcal{A}_{act}}{\frac{1}{2}\rho\infty u_{\theta,max}^2 \mathcal{A}}$, $\mathcal{A} = a_0 z^*$; $z^* = 1$ (axial unit length); and

$u_s^2 \mathcal{A}_{act} = \frac{1}{T}\int_0^T \int_0^{2\pi} \int_{-\infty}^{+\infty} (u_s)^2 dr d\theta dt$.

[0044] FIGS. 7A-7D and FIG. 8 depict a baseline flow field visualization of the computational setup. FIGS. 7A to 7D depict the instantaneous flow field of the computational setup, and FIG. 8 depicts the vortex bursting structure of the computational setup.

[0045] Mass Injection

[0046] The vortex control devices disclosed herein provide effective unsteady forcing for single-phase vortex modification. Co-rotating and counter-rotating forcing can excite vortex wake and instability, respectively. In the co-rotating vortex control case, as depicted in FIGS. 9 and 11A, the core pressure tends to be more uniform at the near-wall

region. The low-pressure region enlarges but with increased pressure along the vortex core axis and modifies the vortex behavior. In the co-rotating mass injection control, as depicted in FIG. 11A, the toroidal structure encloses the columnar vortex, splits to the thinner vortex rings, and sweeps upward. On the other hand, in the counter-rotating vortex control case, as depicted in FIG. 10 and 11B, the low-core pressure increases immediately at the lower core region, the vortex diffuses, and small-scale helical vertical structures are stripped from the controlled vortex taking advantage of the hydrodynamic instabilities. As depicted in FIG. 13B, during counter-rotating control, the columnar vortex exhibits a waving structure, which is no longer vertical, especially in the higher region. A number of small-scale short wavelength helical waves are stripped from the columnar vortex and diffuse. Both co-rotating and counter-rotating forcing techniques successfully increased the time-average core pressure of the vortex.

[0047] As depicted in FIGS. 9, 10, and A-11B, the two different control approaches include mass injection/suction variation over time in a rotational manner. The overall concept is applicable not only to a sump pump but also to wall-normal vortices in general, which appear in a wide range of engineering and natural fluid flow settings.

[0048] Off-Centered Vortex Control

[0049] The robustness of the vortex control was evaluated using an off-centered approach. That is, the vortex control device was disposed off-center from the core of the vortex. As depicted in FIG. 12, actuation input was placed R away from the baseline vortex center. R was normalized by the vortex core radius. Both co-rotating and counter-rotating control inputs were examined. In particular, the robustness of the control to increase core pressure was examined via numerical simulation. As depicted in Table 1, six simulations were conducted with off-center control inputs.

	Co-rotation	Counter-rotation
R	1	1
	2	2
	3	3

Table 1

[0050] The arrow in FIG. 13A indicates the location of the control device in a counter-rotating simulation. In this simulation, A = 1; $f_c = 0.08$; Q-criterion = 2 and $\|\omega\|$

= 2. FIG. 13B depicts the corresponding time averaged flow fields for the counter-rotating simulation in FIG. 13A. Table 2 depicts the time-averaged vortex core pressure distributions along the axial direction for co-rotating and counter-rotating simulations, where $P_{increase}\% = \frac{P^{c}_{avg,min} - P^{b}_{avg,min}}{P^{b}_{avg,min}}$.

	Co-rotating		Counter-rotating	
	$P_{avg,min}$	$P_{increase}\%$	$P_{avg,min}$	$P_{increase}\%$
R=0	-1.397	59.02%	-2.098	38.48%
R=1	-2.503	26.59%	-1.699	50.16%
R=2	-1.242	63.58%	-2.141	37.23%
R=3	-1.826	46.45%	-1.523	55.33%
Baseline	-3.410	—	-3.410	—

Table 2

[0051] FIG. 14A depicts the time-averaged vortex core pressure distributions along the axial direction for co-rotating simulations, and FIG. 14B depicts the time-averaged vortex core pressure distributions along the axial direction for counter-rotating simulations. The control robustness has been assessed by shifting the action away from the core vortex. Both co-rotation and counter-rotation off-centered control attained significant vortex core pressure increases. The off-centered control setup confirms the robustness of the vortex pressure increase device discussed above.

[0052] The disclosed device/technique enables the modification of the vortex and alleviates the low-pressure core by introducing active mass injection/suction at ports on the surface in a circulation arrangement around the vortex core (e.g., centered and off-center). The blowing direction can be tuned but in general is oriented in a normal manner to the surface. Suction is also introduced with injection at different ports but at the same time. The strengths of injection and suction changes in time along the ports along their

circular arrangement. The device can introduce mass injection and suction in a co-rotating or counter-rotating manner with respect to the wall-normal vortex.

[0053] Although specific embodiments of the disclosure have been described, numerous other modifications and alternative embodiments are within the scope of the disclosure. For example, any of the functionality described with respect to a particular device or component may be performed by another device or component. Further, while specific device characteristics have been described, embodiments of the disclosure may relate to numerous other device characteristics. Further, although embodiments have been described in language specific to structural features and/or methodological acts, it is to be understood that the disclosure is not necessarily limited to the specific features or acts described. Rather, the specific features and acts are disclosed as illustrative forms of implementing the embodiments. Conditional language, such as, among others, "can," "could," "might," or "may," unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments could include, while other embodiments may not include, certain features, elements, and/or steps. Thus, such conditional language is not generally intended to imply that features, elements, and/or steps are in any way required for one or more embodiments.

CLAIMS

We claim:

1. A vortex control device for modifying a vortex in a fluid stemming from a wall, the device comprising:

a rotatable hub disposed within an opening in the wall; and

an inlet port and an outlet port in the rotatable hub, wherein the inlet port forms a suction port which is configured to suction the fluid from or about the vortex, wherein the outlet port forms an injection port which is configured to inject the fluid into or about the vortex, and wherein the suctioning and the injecting of the fluid is effective to disrupt the vortex.

2. The device of claim 1, wherein a surface of the hub is flush with a surface of the wall.

3. The device of claim 1, wherein the inlet port and the outlet port are located at or near a core of the vortex.

4. The device of claim 1, wherein the inlet port and the outlet port are disposed around a perimeter of the vortex.

5. The device of any one of claims 1 to 4, wherein the hub is configured to co-rotate with the vortex.

6. The device of any one of claims 1 to 4, wherein the hub is configured to counter-rotate with the vortex.

7. The device of any one of claims 1 to 4, wherein the inlet port is configured to suction fluid from or about the vortex at the same time that the outlet port is configured to inject fluid into or about the vortex.

8. The device of claim 7, wherein an angle, rotation speed/direction, and blowing/suction rate of the inlet port and/or the outlet port are controllable.

9. The device of claim 1, further comprising a pump in fluid communication with the hub.

10. The device of claim 9, further comprising a valve configured to control a mass flow of the fluid from the inlet port and to the outlet port.

11. The device of claim 1, which is configured to be off-set from a vortex core of the vortex.

12. A method of disrupting a vortex in a fluid, the method comprising:
suctioning the fluid from or about the vortex; and
injecting the fluid into or about the vortex,
wherein the suctioning and the injecting of the fluid is effective to disrupt the vortex.

13. The method of claim 12, further comprising:
rotating a location of an inlet of the suction of the fluid about the vortex; and
rotating a location of an outlet of the injection of the fluid about the vortex.

14. The method of claim 13, wherein the location of the suction and injection are configured to co-rotate with the vortex.

15. The method of claim 14, wherein the location of the suction and injection are configured to counter-rotate with the vortex.

16. The method of any one of claims 12 to 15, further comprising offsetting a control device from a vortex core of the vortex.

17. The method of any one of claims 12 to 15, wherein the fluid comprises water in a sump basin.

18. A method for modifying a vortex in a fluid, the method comprising:
rotating a suction port and an injection port about the vortex;
suctioning the fluid from or about the vortex; and
injecting the fluid into or about the vortex.

19. The method of claim 18, wherein the suction port and the injection port are configured to co-rotate with the vortex or counter-rotate with the vortex.

20. The method of claim 19, further comprising:
rotating a location of an inlet of the suction port about the vortex; and
rotating a location of an outlet of the injection port about the vortex.

21. The method of any one of claims 18 to 20, wherein the fluid is a liquid.

22. The method of claim 21, wherein the suctioning and the injecting of the fluid is effective to disrupt the vortex.

23. A method for modifying a vortex in a liquid, the vortex stemming from a wall plate, the method comprising:
operating the vortex control device of claim 1 in a manner effective to modify and disrupt the vortex.

24. The method of claim 23, wherein the operating comprising:
rotating a location of the suction port about the vortex; and
rotating a location of the injection port about the vortex.

25. The method of claim 24, wherein the suction port and the injection port are configured to co-rotate with the vortex or counter-rotate with the vortex.

26. A system for disrupting a vortex in a liquid, the system comprising:
a rotatable hub which comprises an inlet port and an outlet port, wherein the inlet port is operable as a suction port to suction the liquid about the vortex, and the outlet port is operable as an injection port to inject liquid into or about the vortex;

a pump in fluid communication with the hub; and

a valve configured to control a mass flow of the liquid from the inlet port and to the outlet port.

a controller operably connected to the pump and the valve to control the rate of suction of liquid into the inlet port and/or the rate of injection of liquid to outlet port.

27. The system of claim 26, wherein the controller is operably connected to the hub to control the angle, rotation speed, and/or rotation direction of the hub.

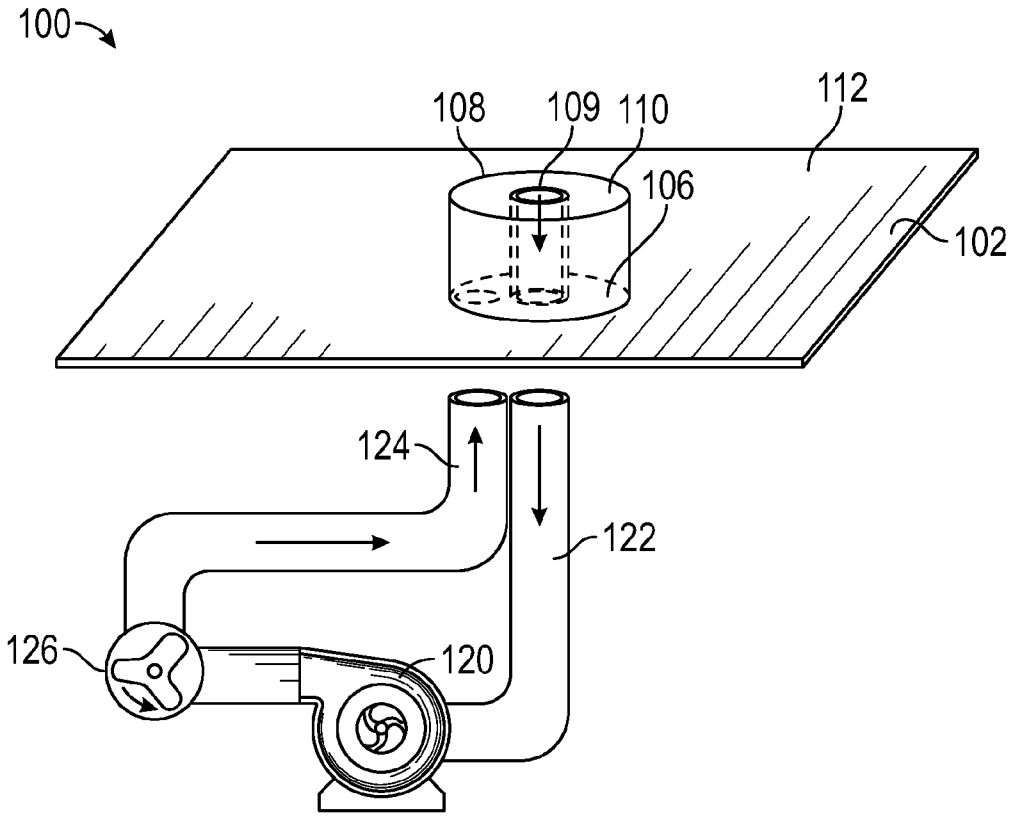

100
108
109
110
112
106
102
124
122
126
120

FIG. 1

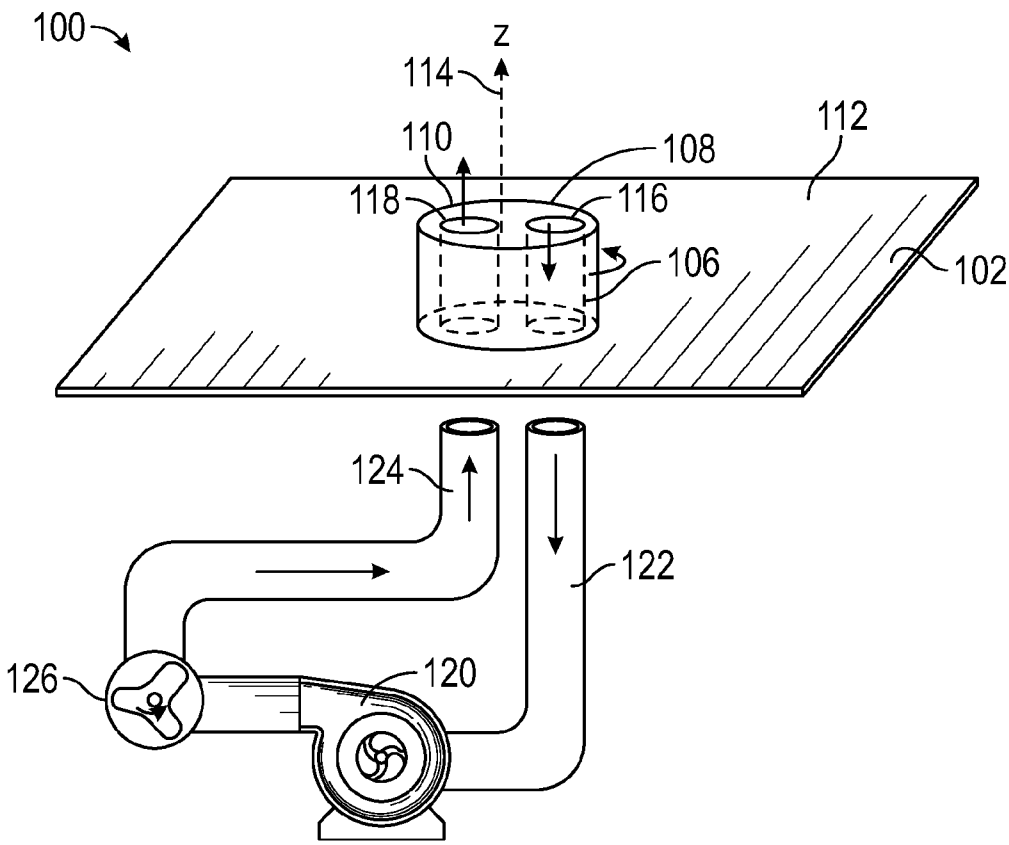

100
z
114
110
108
112
118
116
106
102
124
122
126
120

FIG. 2

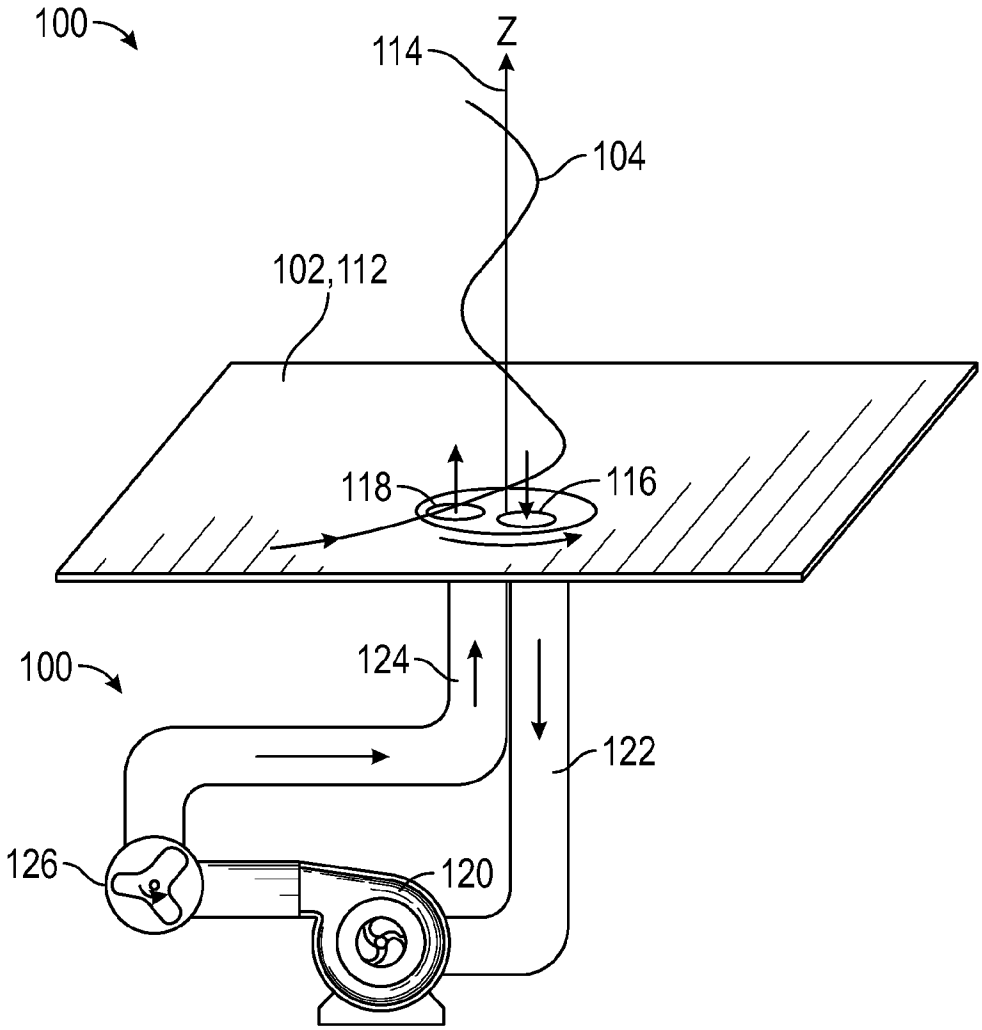

100
Z
114
104
102,112
118
116
100
124
122
126
120

FIG. 3

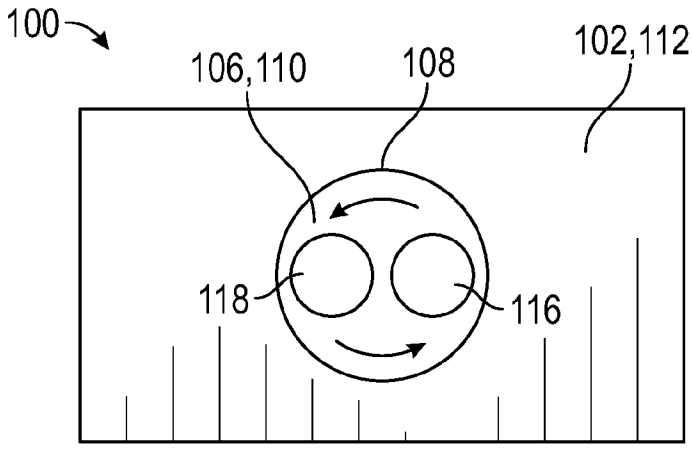

100
106,110
108
102,112
118
116

FIG. 4

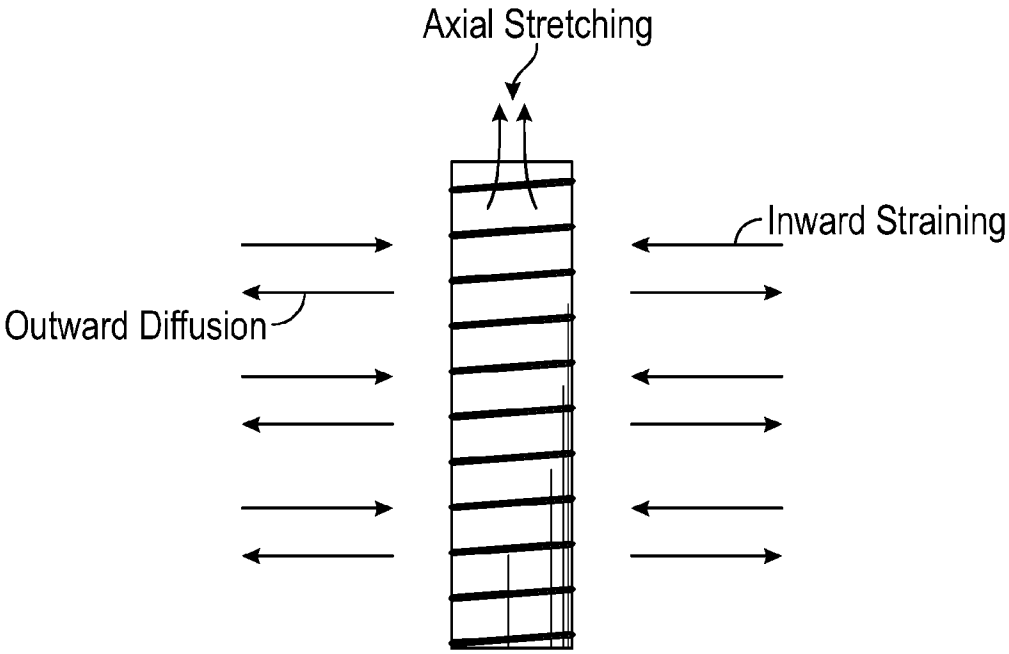

Axial Stretching
Inward Straining
Outward Diffusion

FIG. 5

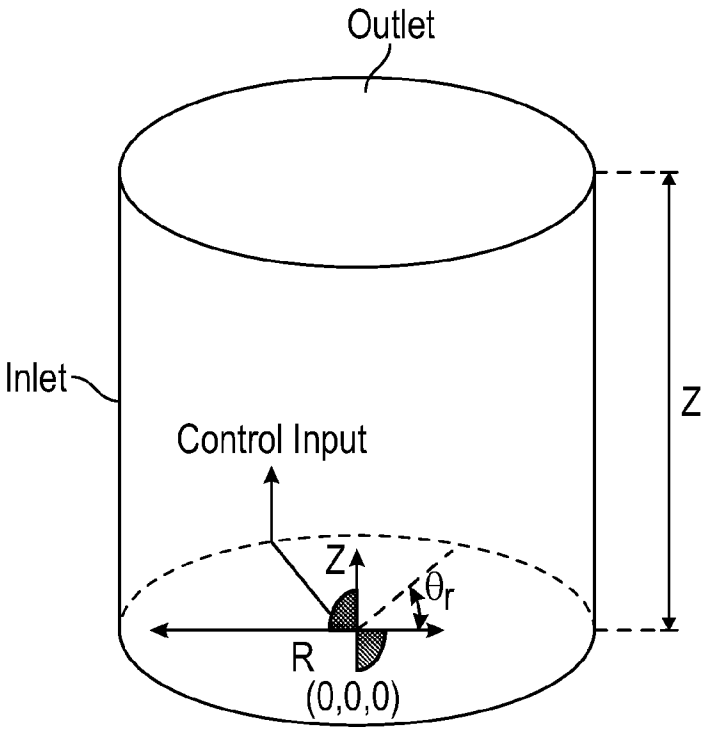

Outlet
Inlet
Control Input
Z
Z
θr
R
(0,0,0)

FIG. 6

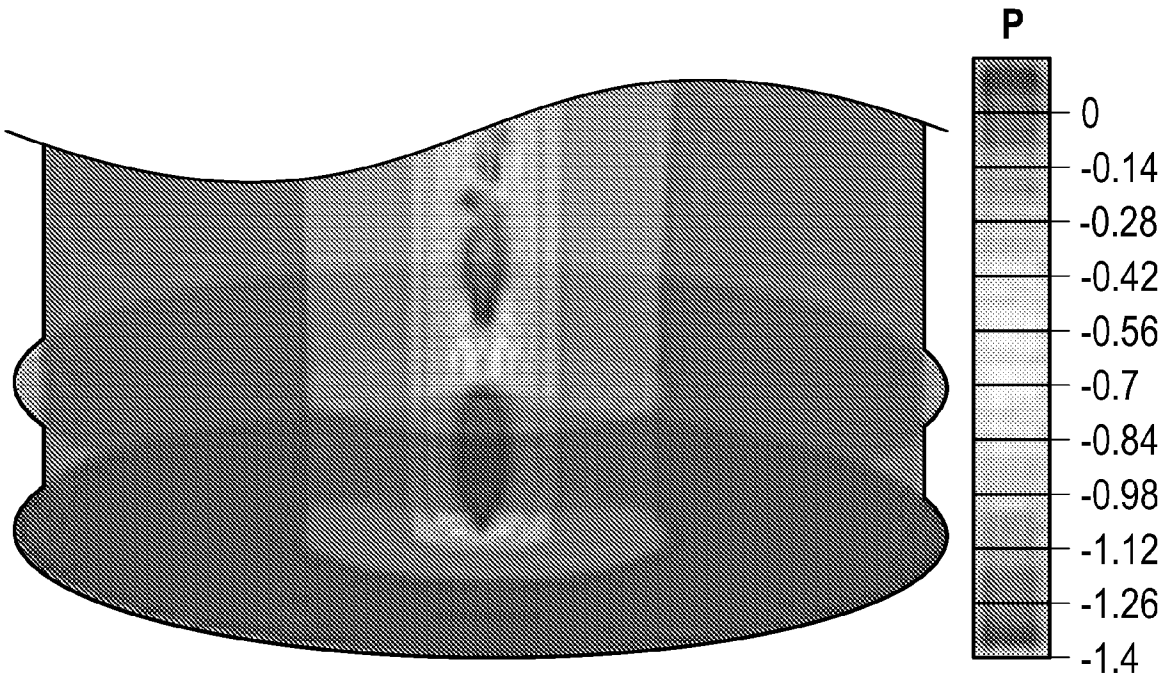

P
0
-0.14
-0.28
-0.42
-0.56
-0.7
-0.84
-0.98
-1.12
-1.26
-1.4

FIG. 7A

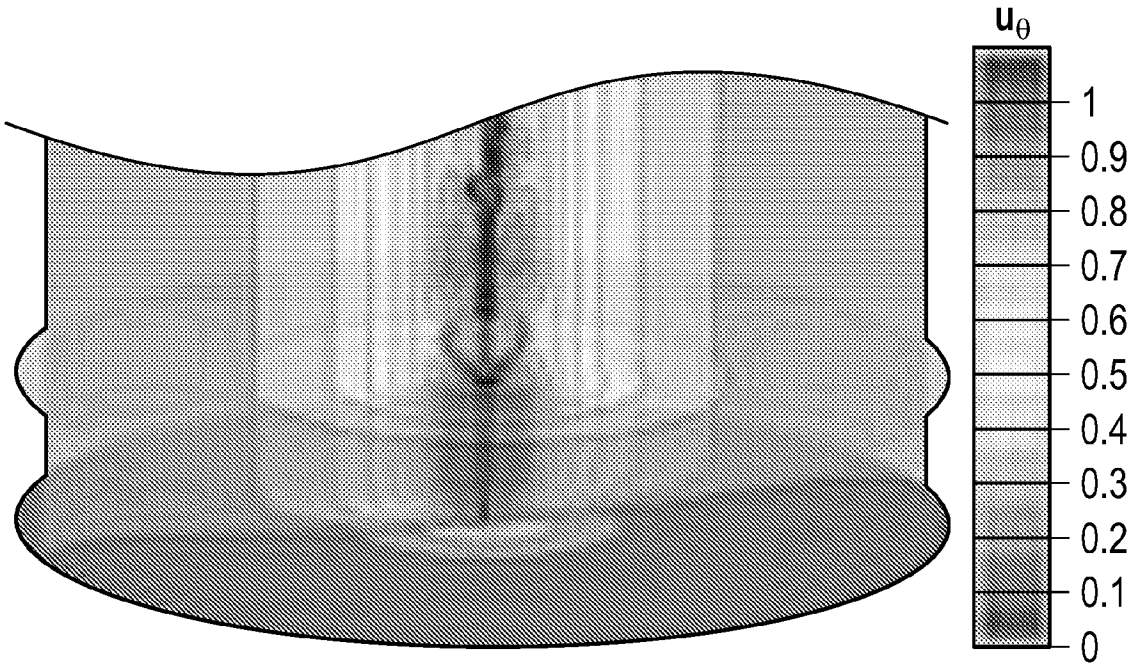

u_θ
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

FIG. 7B

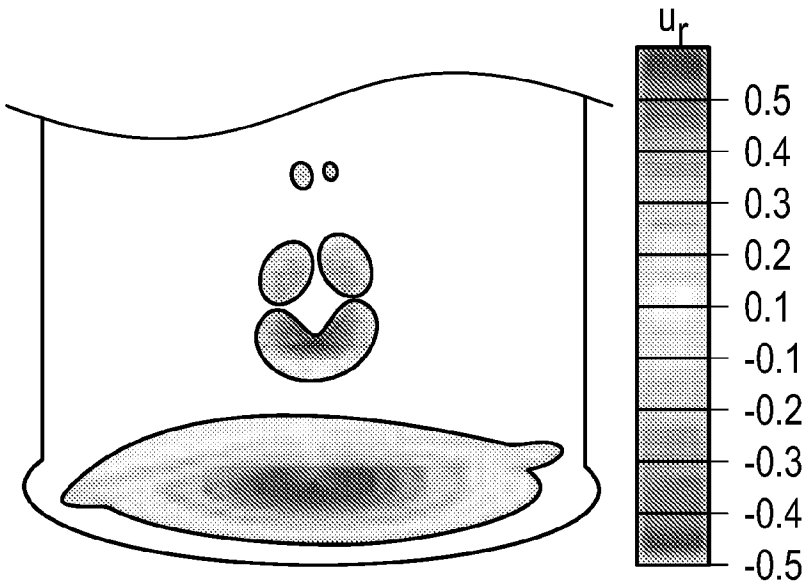

u_r
0.5
0.4
0.3
0.2
0.1
-0.1
-0.2
-0.3
-0.4
-0.5

FIG. 7C

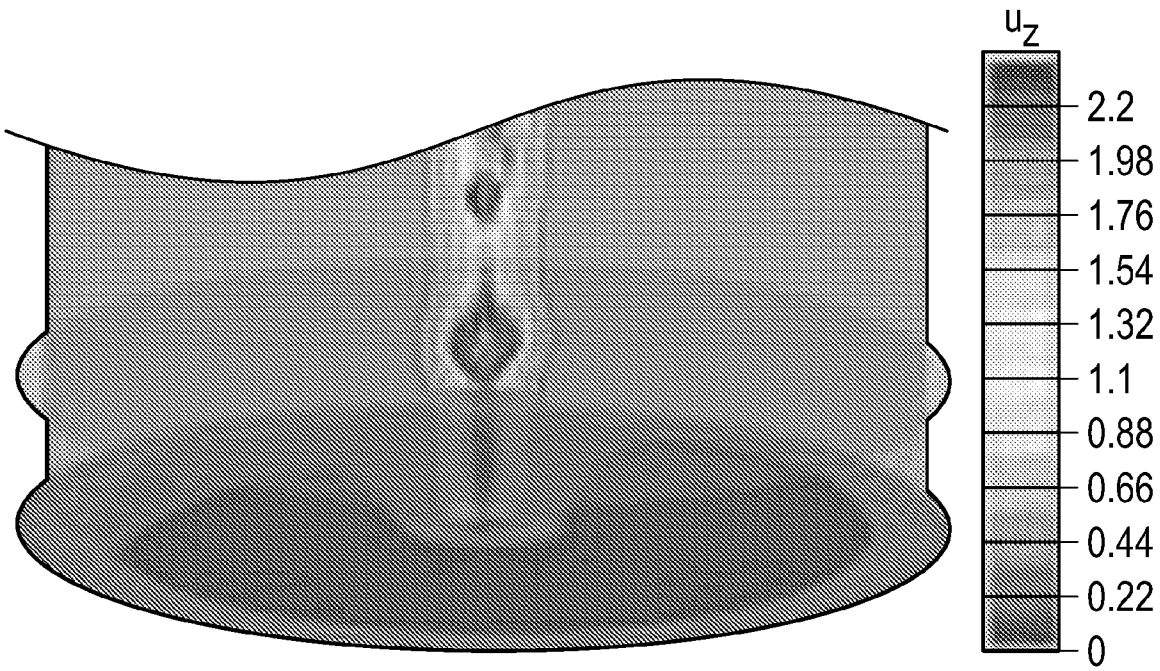
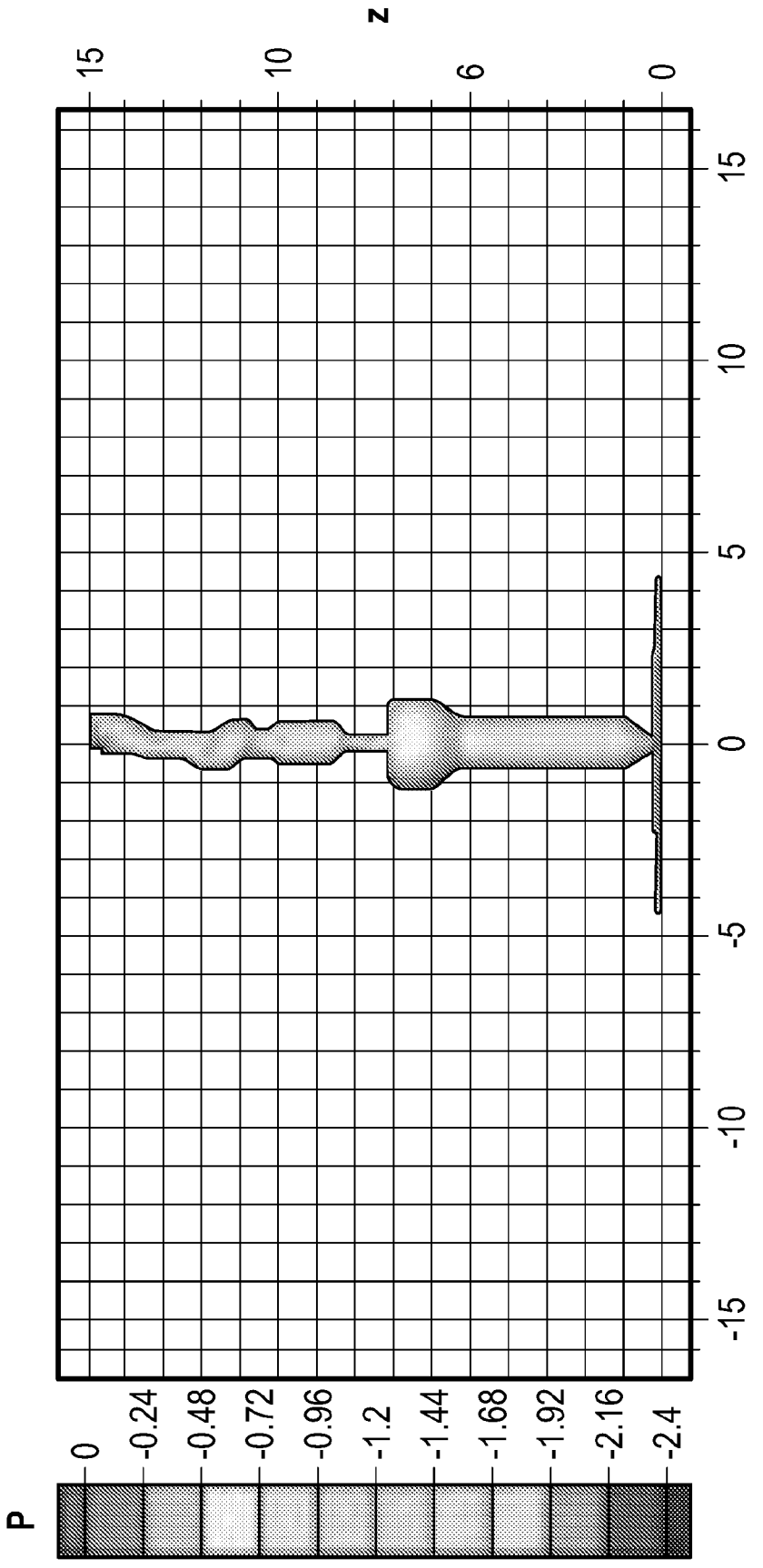

u_z
2.2
1.98
1.76
1.54
1.32
1.1
0.88
0.66
0.44
0.22
0

FIG. 7D



Vorticity Magnitude Visualization ω=2
(Shaded by Instantaneous Pressure)

FIG. 8

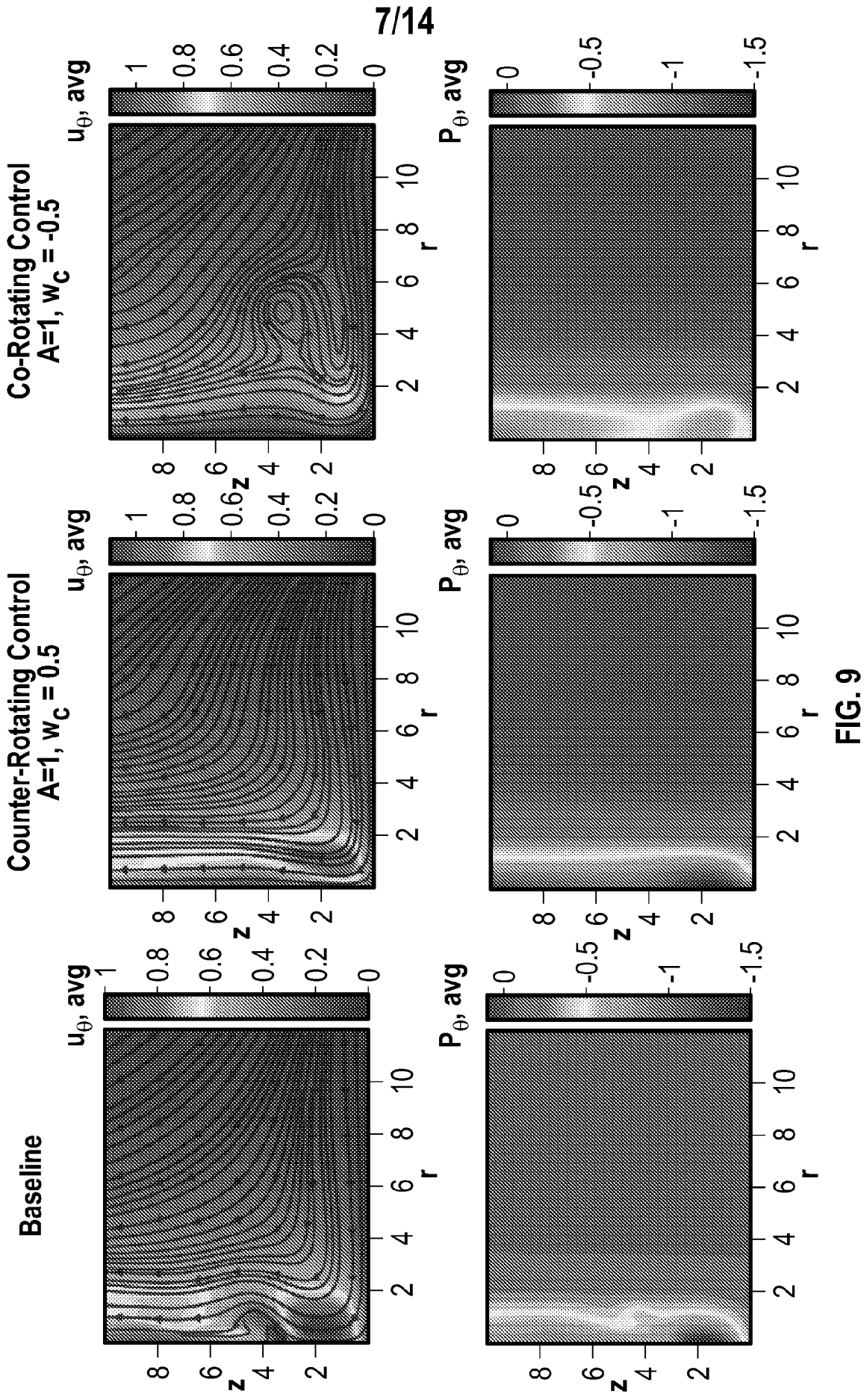

Baseline
Counter-Rotating Control
A=1, w_c = 0.5
Co-Rotating Control
A=1, w_c = -0.5
u_θ, avg
P_θ, avg
r
z

FIG. 9

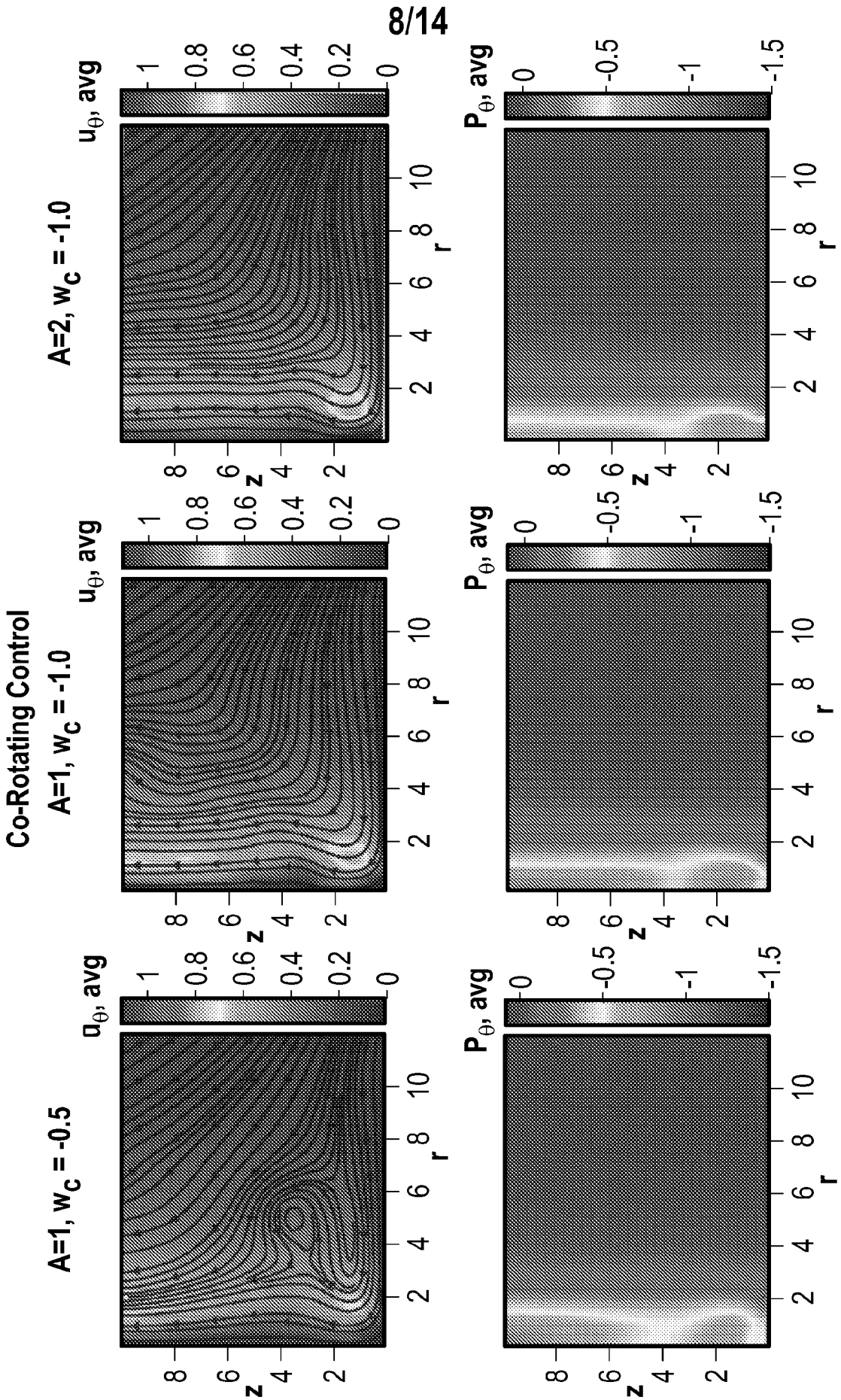

Co-Rotating Control
A=1, w_c = -0.5
A=1, w_c = -1.0
A=2, w_c = -1.0
u_θ, avg
P_θ, avg
z
r

FIG. 10

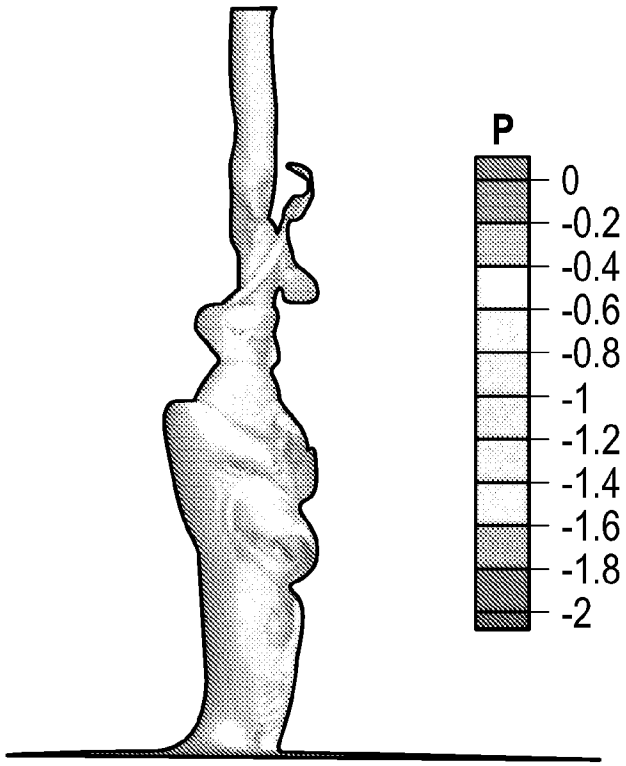


FIG. 11A

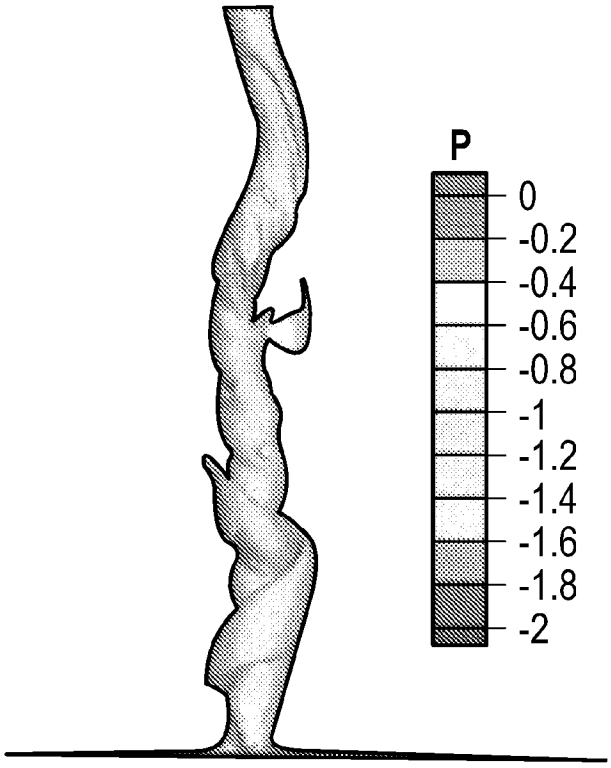


FIG. 11B

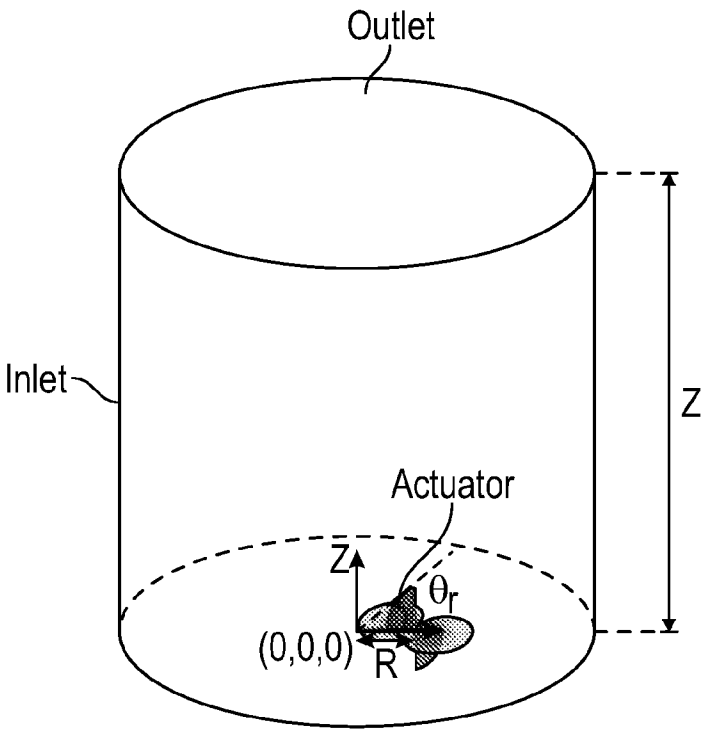


FIG. 12

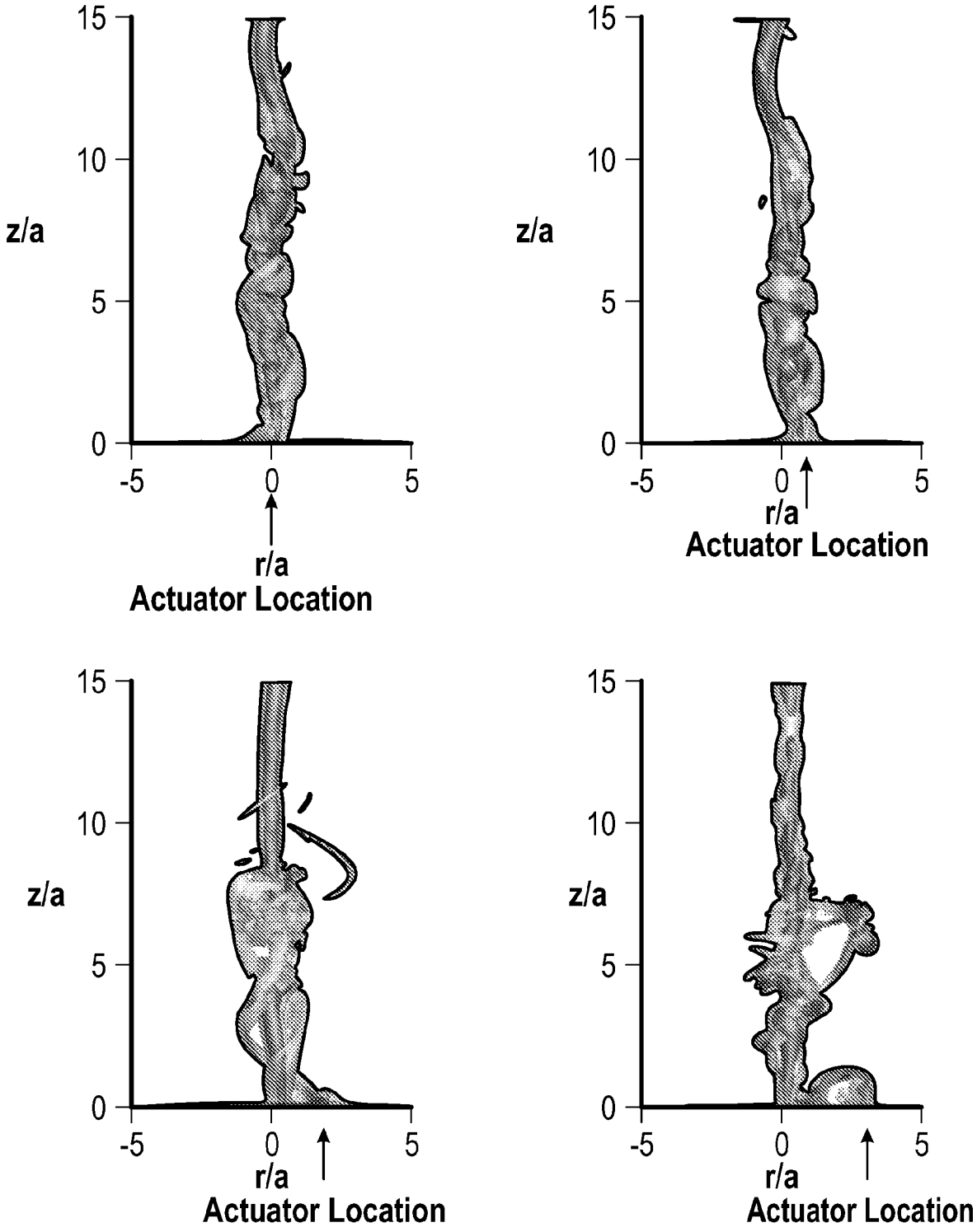

15
10
5
0
z/a
-5
0
5
r/a
Actuator Location
15
10
5
0
z/a
-5
0
5
r/a
Actuator Location
15
10
5
0
z/a
-5
0
5
r/a
Actuator Location
15
10
5
0
z/a
-5
0
5
r/a
Actuator Location

FIG. 13A

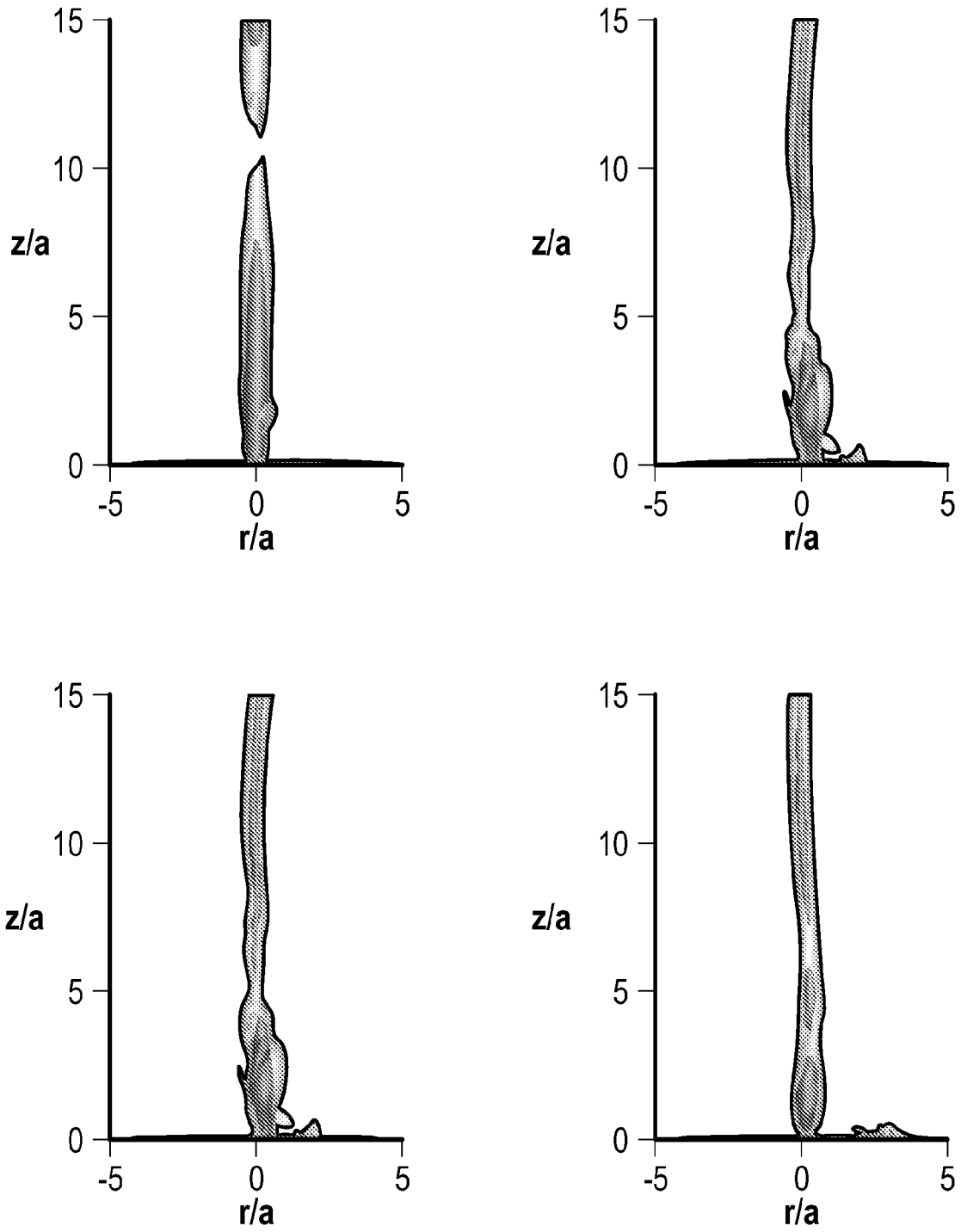

15
10
5
0
z/a
-5
0
5
r/a
15
10
5
0
z/a
-5
0
5
r/a
15
10
5
0
z/a
-5
0
5
r/a
15
10
5
0
z/a
-5
0
5
r/a

FIG. 13B

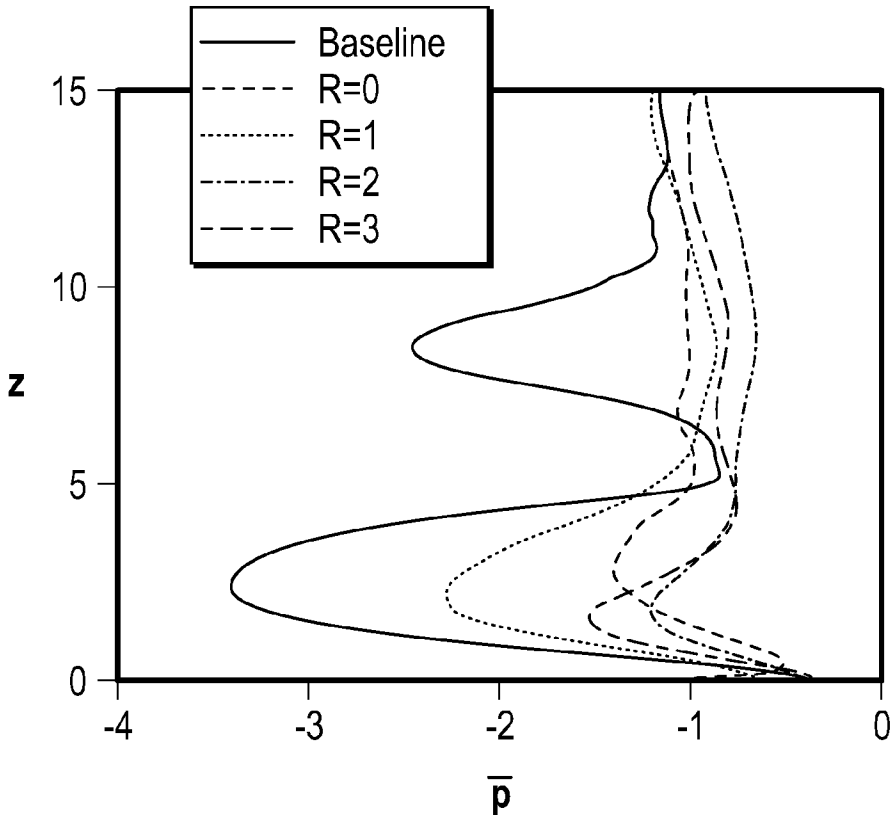


FIG. 14A

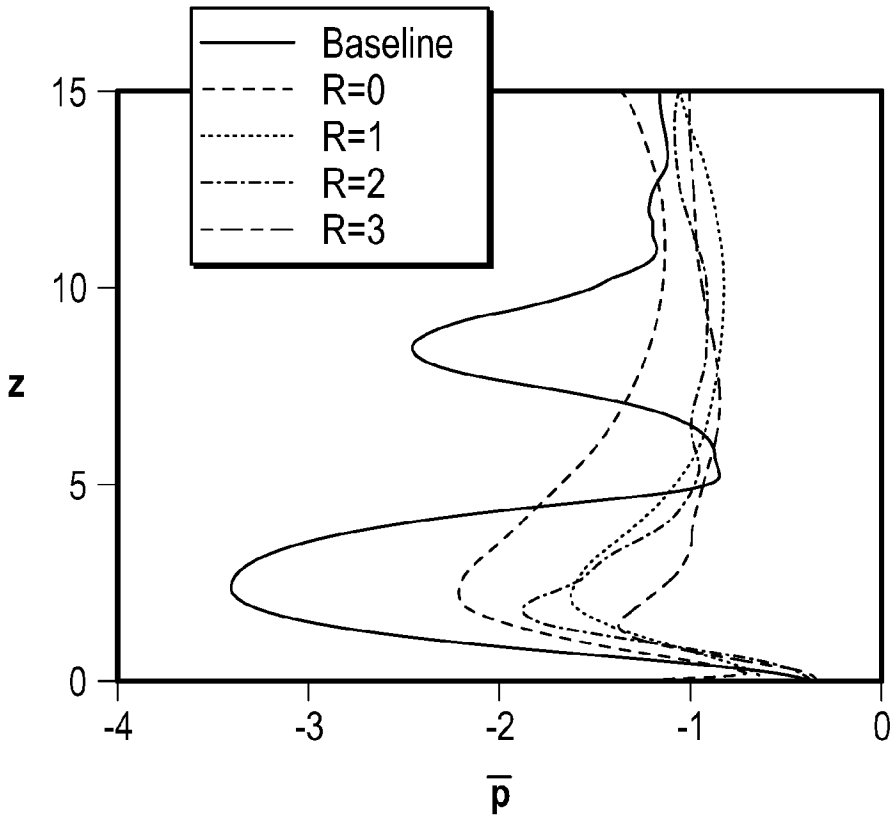


FIG. 14B

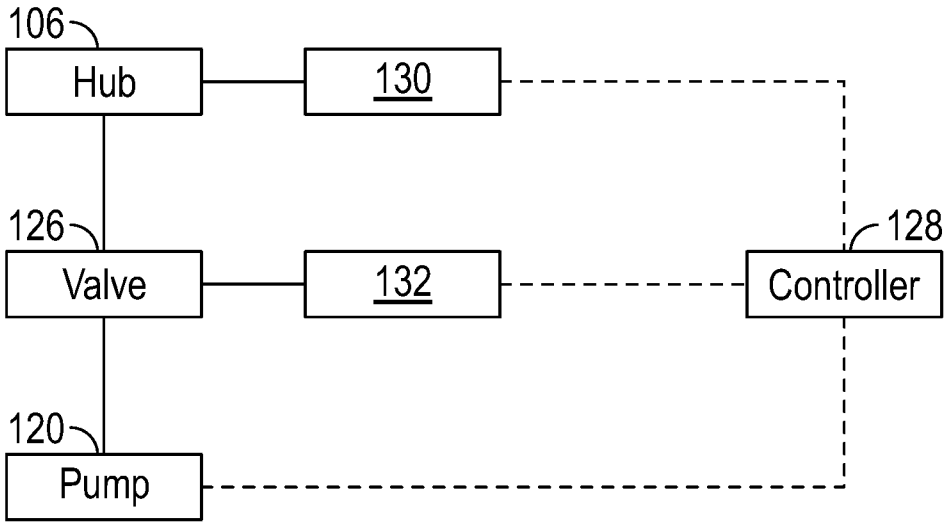


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/059980

A. CLASSIFICATION OF SUBJECT MATTER
INV. F04D29/70 F15D1/00
ADD.

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

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F04D F15D

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 6 119 987 A (KIKNADZE GENNADY IRAKLEVICH [RU] ET AL) 19 September 2000 (2000-09-19)	12,16,17
A	column 3, lines 3, 4, 12, 13, 29-31 column 4, lines 18-32 column 6, lines 40-51 column 8, lines 41-55 figures 2, 9-11	1-11, 13-15, 18-27

X	JP 2006 194100 A (TORISHIMA PUMP MFG CO LTD) 27 July 2006 (2006-07-27)	12,16,17
A	paragraphs [0006], [0023] - [0030] figures 1-10	1-11, 13-15, 18-27

	-/--	

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

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"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
7 February 2019	18/02/2019

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	De Tobel, David

1

Form PCT/ISA/210 (second sheet) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2018/059980

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	JP 2017 036717 A (EBARA CORP) 16 February 2017 (2017-02-16) paragraph [0016] figures 1-3	1-27
A	JP S60 67798 A (EBARA MFG) 18 April 1985 (1985-04-18) figures 9, 12	1-27
A	US 7 108 457 B1 (BROWN NEAL A [US] ET AL) 19 September 2006 (2006-09-19) figures 2A, 2B, 14A, 15C, 16B	1-27

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2018/059980

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 6119987 A	19-09-2000	AU 6701596 A	18-02-1997
		CN 1196790 A	21-10-1998
		DE 69620185 D1	02-05-2002
		DE 69620185 T2	07-11-2002
		EP 0839309 A1	06-05-1998
		ES 2172673 T3	01-10-2002
		US 6119987 A	19-09-2000
		WO 9704280 A1	06-02-1997
JP 2006194100 A	27-07-2006	NONE	
JP 2017036717 A	16-02-2017	NONE	
JP S6067798 A	18-04-1985	NONE	
US 7108457 B1	19-09-2006	NONE	