Provisional Application for United States Patent

TITLE: MANIPULATION OF FLUID

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BRIEF DESCRIPTION OF THE DRAWINGS

[0001] FIG. **22** is a cross-sectional view of an embodiment of the invention.

[0002] FIG. **24** is a cross-sectional view of another embodiment of the invention.

[0003] FIG. **25** is a cross-sectional view of the embodiment shown in FIG. **24**.

[0004] FIG. **26** is a cross-sectional view of the embodiment shown in FIG. **24**.

[0005] FIG. **27** is a cross-sectional view of the embodiment shown in FIG. **24**.

[0006] FIG. **28** is a cross-sectional view of the embodiment shown in FIG. **24**.

[0007] FIG. **29** is a cross-sectional view of the embodiment shown in FIG. **24**.

[0008] FIG. **30** is a cross-sectional view of another embodiment of the invention.

[0009] FIG. **31** is a cross-sectional view of the embodiment shown in FIG. **30** for a different mode of operation.

[00010] FIG. **32** is a cross-sectional view of the embodiment shown in FIG. **30** for a different mode of operation.

DETAILED DESCRIPTION OF THE INVENTION

[00011] The term “fluid” used herein encompasses all types of materials that exhibit the properties of a fluid. One such property is the ability of constituent particles to move relative to each other. It can refer to a liquid such as water, or a gas such as air, nitrogen, or carbon dioxide, for example. Note that a fluid can comprise several different types and species of fluid simultaneously, such as air, which consists of several types of gas. Unless specified, the assembly of different fluids will still be referred to as “the fluid” for simplicity.

[00012] The term “free stream flow” is the theoretical flow relative to a specified point which would occur if the entire assembly of apparatuses did not interact with the fluid. It can thus also be referred to as a global free stream flow. An assembly of apparatuses can be a vehicle, such as an aircraft or a ship, or a different type of fluid manipulation apparatus, such as a wind turbine, for example. The free stream flow can comprise contributions from the motion of a specified point in inertial space, such as the motion of a vehicle in inertial space. It can also comprise contributions from the motion of the fluid in inertial space, such as wind or currents. Different specified points can experience different free stream flows. For example, an apparatus could rotate, such that different points on the apparatus move at different velocities in inertial space and experience different free stream flow velocities in a fluid which is theoretically stationary in inertial space.

[00013] The term "local free stream flow" is the theoretical flow relative to a specified apparatus which would occur if only the specified apparatus did not interact with the fluid. The local free stream flow comprises a contribution of the free stream flow as well as a contribution due to other apparatuses, such as those of the remainder of an assembly, interacting with the fluid. For example, the downwash created by a horizontal fixed wing could affect the local free stream flow velocity magnitude and direction relative to a horizontal stabilizer mounted downstream of the wing.

[00014] A "fluid manipulation apparatus", or FMA, is an apparatus which manipulates the properties of a fluid. For example, an FMA could change the magnitude of the flow velocity of a fluid element relative to the magnitude of a free stream flow velocity for a specified scenario or boundary condition. In another example, an FMA could change the direction of the fluid flow velocity of a fluid element relative to a free stream flow velocity direction for a specified scenario. This effect on the fluid flow can be intentional or unintentional. When at least some of the effect on the fluid is intentional, the FMA can be further classified as an "intentional fluid manipulation apparatus", or IFMA. The intentional effect on the fluid flow can only be localized for some IFMAs, as in the case of an "intentional momentum carrying apparatus", or IMCA, defined below. For other IFMAs, the intentional effect on the fluid flow can also occur in the far wake, as can be the case for an "intentional momentum shedding apparatus", or IMSA. These definitions will be clarified in the following paragraphs.

[00015] Due to the intentional nature of the momentum shedding, and IMSA can also be referred to as a "thrust apparatus", or TA. A TA is any apparatus which is configured to impart an intentional rate of change of momentum to a fluid during nominal operation. An example of a TA is a conventional propeller or a helicopter main rotor. The wing of a fixed wing aircraft that provides lift during nominal constant speed cruise can also be regarded a thrust apparatus. There are many other possible types of TAs available. For example, the rate of change of momentum could be applied to the fluid by a TA via electromagnetic forces. For example, the TA can be a Hall-effect thruster, or a magnetohydrodynamic (MHD) drive. A Voith Schneider thruster, a cyclogyro, or a similar device are also examples of a TA.

[00016] In the aforementioned definition of a thrust apparatus, the requirement of imparting an intentional rate of change of momentum to a fluid can be described in several ways. For example, consider a thrust apparatus in isolation from other fluid manipulation apparatuses in an assembly of apparatuses. For instance, consider a wing in isolation from the remainder of a fixed wing aircraft. Or consider a helicopter main rotor in isolation from the remainder of a conventional helicopter. In a theoretical scenario, denoted the “isolated scenario”, a thrust apparatus is considered in isolation and defined or characterized by the fact that there is an intentional, non-zero induced flow in the far wake relative to the thrust apparatus during a nominal operating condition. The nominal operating condition can, in some instances, involve a free stream flow velocity magnitude and direction which is uniform in space and time. In some examples, the operating conditions during constant velocity cruise can be described as a nominal operating condition. The far wake is located an infinite distance from the thrust apparatus in this nominal operating condition. In other words, the thrust apparatus has an intentional, non-negligible effect on the flow field an infinite distance from the thrust apparatus compared to the free stream flow field. The term “intentional” refers to the requirement that the rate of change of momentum be useful or deliberate. For example, a useful rate of change of momentum can contribute to an average induced velocity of a fluid element in the far wake in the aforementioned isolated scenario, where the velocity has a non-zero component in a direction opposite to the direction of the intended thrust or lift. For some thrust apparatuses, the average induced velocity of a fluid element in the far wake has a substantial component in a direction opposite to the direction of the intended thrust or lift. The far wake induced flow of a fixed wing or a helicopter main rotor which is associated with the production of lift or thrust is considered intentional. The associated rate of change of momentum of the fluid in the proximity of the thrust apparatus is also considered intentional. An intentional effect of a thrust apparatus on the far wake is distinguished from unintentional, not useful, or counter-productive effects on the fluid flow field in the far wake, which can be associated with profile drag, pressure drag acting on some elements of the thrust apparatus, for instance. These unintentional effects increase the power consumption unnecessarily, i.e. compared to a theoretical situation in which these effects are mathematically removed, ceteris paribus.

[00017] The requirement of imparting an intentional rate of change of momentum to a fluid can also be described in another way. For example, a thrust apparatus can also be defined as any apparatus which can be considered to intentionally shed vortices in the simplified framework of Prandtl lifting-line theory. A thrust apparatus, or TA, or IMSA, can therefore also be described as an “intentional vortex shedding apparatus”, or IVSA. Note that the framework of lifting-line theory should only be considered as a reference or a guide, since it relies on simplified assumptions, such as inviscid and incompressible flow. The vortices which are intentionally or deliberately shed by a thrust apparatus contribute to the lift or thrust force acting on the thrust apparatus by imparting a rate of change of momentum to a fluid. When a thrust apparatus is considered in the aforementioned isolated scenario during nominal operating conditions, the intentionally shed vortices are also present an infinite distance from the thrust apparatus, where they generate an intentional induced flow. In other words, there is a non-zero, intentional, far wake induced flow velocity on account of, or produced by, the thrust apparatus. Note that a thrust apparatus can also be considered to shed vortices unintentionally in some models, such as mathematical models taking into account viscous drag or boundary layer effects in the form of theoretical shed vortices. Unintentional vortex shedding refers to any vortices which are not shed deliberately, i.e. any vortices which do not perform, or contribute to, a useful function such as the generation of lift or thrust.

[00018] An intentional momentum carrying apparatus, or IMCA, is a fluid manipulation apparatus which, when considered in an isolated scenario, does not intentionally shed momentum into the far wake. An example of an IMCA is a duct or a conventional tubular, or cigar shaped, axially symmetric fuselage. A fuselage modifies the free stream flow by intentionally deflecting the flow around the fuselage, which also increases the magnitude of the velocity of the flow in the proximity of the fuselage for the isolated scenario in which the fuselage is considered in isolation of any other fluid manipulation apparatuses, such as wings, for a nominal operating condition, such as constant velocity cruise. The aforementioned intentional deflection of the flow is localized to the vicinity of the fuselage. Thus, a fluid element in the proximity of a fuselage experiences an intentional, localized rate of change of momentum. In the ideal case, there is no effect on the fluid flow at an infinite distance from the fuselage. In other words, there is no intentional far wake effect on the fluid flow due to the fuselage. There can be an unintentional rate of change of momentum of the fluid in the proximity of the fuselage, which can also be associated with an unintentional change of momentum of a fluid element an infinite distance from the fuselage in the isolated scenario compared to the free stream flow. Such an unintentional change in the fluid flow in the far wake can arise from profile drag effects, for example.

[00019] Similarly, a duct modifies the free stream flow by intentionally modifying the magnitude of the flow velocity in the proximity of the duct. For example, a duct can be configured to reduce the magnitude of the flow velocity of a fluid element at the center of the circular duct relative to the free stream flow for an isolated scenario during nominal operating conditions. In this case the nominal operating conditions can refer to a constant and uniform free stream flow velocity parallel to the central axis of symmetry of the duct. This intentional modification is only localized in the proximity of the duct, and converges to a negligible value an infinite distance from the center of the duct. Thus, there is no intentional far wake effect on the fluid flow due to the duct, i.e. there is no far wake intentional induced flow velocity of a fluid element due to the interaction of the duct with the fluid. As before, there can be an unintentional modification of the fluid flow in the far wake, and associated unintentional rate of change of momentum of the fluid in the proximity of the duct, due to drag forces or transient effects.

[00020] An IMCA can also be described in the simplified framework of lifting-line theory. An IMCA can be considered to carry an enclosed or bound vorticity. As such, an IMCA can also be considered to be an “intentional vortex carrying apparatus”, or IVCA. For example, the intentional effect of a circular, axially symmetric duct on the fluid can be modelled as a circular vortex ring, or a two- or three-dimensional continuous distribution of vorticity, or incrementally small, discrete vortex rings. Note that no intentional vorticity is shed into the fluid during a nominal operating condition, in which the magnitude of the vorticity is constant in time and uniform along the circumference of the vortex ring. Similarly, the intentional effect of a fuselage on the fluid flow can also be modelled as a three-dimensional continuous distribution of vorticity contained within the fuselage or located on the surface of the fuselage, i.e. the interface between the fuselage and the fluid.

[00021] The “induced power” of an IMSA is the rate of change of energy of the fluid that is associated with the intentional rate of change of momentum of the fluid. Any other power consumption is accounted for in “zero-lift power”, or “profile power”. Note that the term “lift” also encompasses thrust in this context. Note that an IMCA does not consume any induced power. Any power losses associated with a pure IMCA are considered profile power losses. An IMSA is able to consume induced power, in which case intentional work is done by the fluid manipulation apparatus on the fluid. For example, a propeller of an aircraft or a ship, or the fixed wing of a conventional fixed wing aircraft, results in, or is associated with, an induced power consumption. An IMSA is also able to recover induced power, in which case work is done by the fluid on the fluid manipulation apparatus intentionally. For example, the power generated by a wind turbine can be considered to be induced power.

[00022] In the process of applying a rate of change of momentum to a fluid, a fluid manipulation apparatus can change the flow velocity relative to the local free stream velocity. This change in velocity is the “downwash”, or “induced velocity”. Note that the induced velocity can be directed downstream or upstream, or perpendicularly to the stream, for example. An induced velocity can be generated by an IMSA or an IMCA. In the latter case, the induced velocity is localized, i.e. confined to the vicinity of the IMCA. In these terms, an IMSA can also be characterized as an apparatus, which contributes an intentional induced velocity to the far wake in an isolated scenario. Note that an induced velocity contribution by one IMSA can be cancelled by another IMSA when both are IMSAs are considered together.

[00023] FIG. **22** is a cross-sectional view of an embodiment of the invention. Some features of the apparatus shown in FIG. 22, as well as some of the principles of operation of the apparatus share similarities with the apparatus shown in the other figures, and will therefore not be described in the same detail in the context of FIG. 22, and vice versa.

[00024] Embodiment 700 comprises a duct apparatus 702 which encloses a fuselage apparatus 719.

[00025] In the embodiment shown, duct apparatus 702 is circular in cross-section when viewed along the X-axis and axially symmetric about an axis parallel to the X-axis. Duct apparatus 702 can be considered to be an IMCA. Duct apparatus 702 comprises an outside surface 717 and a channel 703 with an inside surface 718 located between first opening 704 and second opening 712, where the channel comprises a first contraction 705, a first expansion 706, a region of substantially constant cross-sectional area 707 of channel 703 when viewed in the X-direction, a second expansion 708, a second contraction 710, and a third expansion 711. Note that the terms "contraction" and "expansion" refer to the magnitude of the radius of the axially symmetric channel.

[00026] The duct apparatus comprises a first compartment 730 and a second compartment 732. These compartments can fulfill a number of purposes. In some embodiments, they can be used to store landing gear, fuel, cargo, or components of other lifting or thrusting mechanisms.

[00027] Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions. In other embodiments, there need not be a third expansion 711, i.e. the second opening can be located at the end of second contraction 710. In other embodiments the cross-sectional geometry of channel 703 or outside surface 717 can be square, rectangular, or elliptical. In some embodiments, the cross-sectional geometry of channel 703 can change from square to circular in the positive X-direction, for example.

[00028] For some embodiments, the cross-sectional area of the circular or annular channel 703 can vary with time. For example, the radius of the channel at station 739 can be modified for different operating conditions. The radius can be increased or decreased depending on the free stream flow velocity magnitude. In this manner, the properties of the flow through duct 703 can be modified and controlled such that the principles of the invention can be applied at different free stream flow conditions. For example, the existence, or the location, of a shock wave within the first expansion 706 or second expansion 708 can be regulated by controlling the cross-sectional area of the channel 703 at station 739. A wide variety of methods for changing the cross-sectional area of a channel as a function of time are available. For example, a ramp connected to the duct apparatus 702 can be hydraulically extended into the channel, thus reducing the cross-sectional area of the channel. In another example, a spike located within channel 703 can be moved along the length of the channel, i.e. axially along the X-direction, towards or away from a contraction of the channel, thus decreasing or increasing the annular cross-sectional area of the channel, respectively.

[00029] Bulk material 701 can comprise a metal such as aluminium, steel, or titanium. In some embodiments, bulk material 701 comprises composites, such as carbon fiber or fiberglass.

[00030] Fuselage apparatus 719 comprises a leading point 720, a trailing point 721, an inside surface 723, an outside surface 722, and first fuselage compartment 724 separated from a second fuselage compartment 725 by a bulkhead 728. The fuselage apparatus 719 is rigidly connected to the duct apparatus by several support struts, such as support strut 727. The support struts reduce the cross-sectional area of channel 703 at the location of the support struts by only a small amount in this embodiment. In some embodiments, the fuselage can be configured to carry cargo, passengers, or fuel, for example.

[00031] Embodiments of the invention are at least partially enveloped by a fluid, as defined earlier. Note that different types of fluids can envelop at least a portion of an embodiment of the invention at the same time. For example, in the case in which an embodiment of the invention is a ship, the embodiment is enveloped by both water and air, i.e. a liquid fluid and a gaseous fluid. In FIG. 22, the fluid is compressible. For example, the fluid can be a gas such as air.

[00032] The operating condition depicted in FIG. 22 can be described as nominal, level cruise. In the depicted, simplified scenario, the free stream flow relative to the center of mass of embodiment 700 is constant in time and spatially uniform in magnitude and direction, where the direction is parallel to the X-axis. In the depicted operating condition, the free stream flow velocity magnitude relative to the embodiment 700 is larger than the speed of sound in the fluid. Since the wind velocity is assumed to be negligible in this scenario, this is equivalent to embodiment 700 moving relative to the fluid at a speed faster than the speed of sound in the fluid in an inertial reference frame. In FIG. 22, the free stream flow velocity relative to embodiment 700 is aligned with and parallel to the X-axis, i.e. from the left of the page to the right of the page.

[00033] Dashed lines 715 and 716 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of embodiment 700. Streamlines 715 and 716 are therefore part of a streamsurface, or streamtube, which separate fluid flowing around embodiment 700 from fluid flowing through channel 703 of embodiment 700. In this embodiment, the steamtube is circular when viewed along the X-direction.

[00034] The fluid upstream of embodiment 700, such as at station 734, is moving faster relative to embodiment 700 than the speed of sound in the fluid in the configuration shown in FIG. 22. The first contraction 705, the first expansion 706 and the second expansion 708 of channel 703 are configured to compress the fluid flowing through channel 703 in the positive X-direction. The first throat is defined to be the portion of channel 703 with the smallest cross-sectional area of channel 703 between first contraction 705 and first expansion 706 when viewed along the X-direction. The average speed of the fluid relative to embodiment 700 at the first throat, i.e. station 735, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 734, the average relative speed is larger than the speed of sound, and further downstream, such as at station 737 or 738, the average relative speed is smaller than the speed of sound within the fluid in this embodiment. In the depicted embodiment, the flow through channel 703 is substantially adiabatic and isentropic when neglecting friction. In other embodiments, there can be a shock wave located between the first throat and station 738. In other words, the relative flow speed of the fluid downstream of the first throat can be faster than the speed of sound within the fluid, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave, resulting in a relative flow speed at station 738 which is slower than the speed of sound, as in the ideal scenario in which there is an infinitely weak shock at the first throat..

[00035] Both the second contraction 710 and the third expansion 711 of channel 703 are configured to expand the fluid flowing through channel 703 in the positive X-direction. The second throat is defined to be the portion of channel 703 with the smallest cross-sectional area of channel 703 between second contraction 710 and third expansion 711 when viewed along the X-direction. The average speed of the fluid relative to embodiment 700 at the second throat, i.e. station 739, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 738, the average relative speed is smaller than the speed of sound, and downstream, such as at station 740, the average relative speed is larger than the speed of sound within the fluid in this embodiment.

[00036] Note that in other embodiments, the fuselage can be incorporated into the duct apparatus. For example, the first compartment 730 or the second compartment 732 can be considered to be, and configured as, a fuselage. In another example, the axially symmetric fuselage apparatus 719 need not be arranged concentrically with the axially symmetric duct apparatus 702. In other words, the central axis of fuselage apparatus 719 need not be coincident with the central axis of duct apparatus 702. For instance, the fuselage apparatus can be arranged flush with inside surface 718 of duct apparatus 702, similar to first compartment 730, instead of being located centrally within channel 703 as shown in FIG. 22. In this case, the fuselage outside surface 722 is identical to the inside surface 718 of channel 703, and channel 703 only passes through the center of the fuselage. This can reduce the wetted area and the viscous drag compared to configurations similar to the embodiment shown in FIG. 22. For some embodiments, the first compartment 730 can be considered to be joined to the second compartment 732 by an annular fuselage segment embedded within duct apparatus 702 in a similar manner as first compartment 730. In some embodiments, the first compartment 730 and the second compartment 732 can be considered to be coincident. Note that the angle subtended by the cross-section of the fuselage relative to the central axis of duct apparatus 702 when viewed along the X-direction need not be 360 degrees as in the circumferential case exemplified by annular fist compartment 730, but can be 200 degrees, or 100 degrees, or 60 degrees, for example. In other embodiments, the fuselage apparatus 719 can be elliptical or rectangular in cross-section when viewed along the X-direction.

[00037] A disturbance moving through a fluid at a speed greater than the wave speed in the fluid will typically induce wave drag. The wave drag is a measure of the energy of the waves produced by the disturbance. There are several ways to quantify the wave drag. For example, the wave drag can be calculated from the wave power produced by a specified disturbance divided by the average free stream flow velocity magnitude.

[00038] A disturbance can be caused by a volume which is configured to displace fluid. The volume can be the hull of a ship, which produces gravity waves, or the fuselage or wing of a supersonic aircraft, which produces shock waves. A disturbance can also be caused by a device configured to modify fluid flow properties at a specified location, where the modification can comprise a change in the flow direction, or a change in the flow velocity magnitude in an inertial space, or a change in the temperature of the fluid, for example. Such a device can be an electric or magnetic field generating apparatus, or a laser, for instance.

[00039] In accordance with some embodiments of the invention, a duct apparatus can be employed to manipulate the fluid flow in the vicinity of the disturbance in a manner in which the wave drag associated with the disturbance is reduced.

[00040] For example, for embodiments traveling through an incompressible fluid such as water, the drag due to surface waves can be reduced by a duct apparatus configured as follows. After entering the duct apparatus through an inlet, the fluid is accelerated by a first contraction, where the first contraction can be configured in a similar manner as first contraction 705 in some embodiments, and the inlet can be configured in a similar manner as first opening 704. Note that the acceleration of the fluid in the first contraction in this case is in contrast to the deceleration of the fluid in the embodiment shown in FIG. 22. After having been accelerated in a first contraction, the fluid flows through a section of substantially constant cross-sectional area in some embodiments. For example, the fluid can flow through a pipe or a channel with a circular cross-sectional area. In other embodiments the pipe has an annular cross-sectional area, such as the annular portion of channel 703 at station 737 in FIG. 22. With a reduced wetted area for a given cross-sectional area, a circular cross-section can be favorable to an annular cross-section. In some embodiments, said pipe is substantially straight. In some embodiments, this pipe comprises curves or bends. For instance, the pipe can guide the fluid flow around a cargo-hold of a container ship. Following the section with a substantially constant cross-sectional area, the fluid flow subsequently enters a first expansion, where the fluid is decelerated before exiting through an outlet or second opening. In some embodiments, the velocity of the fluid exiting the outlet is substantially equal to the free stream flow velocity. In some embodiments, the exit velocity can be larger or smaller than the free stream flow velocity. In the case in which the duct apparatus is employed on ships, the leading edge of the duct apparatus forms the bow of the ship, and the outside surface of the duct apparatus, such as outside surface 717 of duct apparatus 702, forms the outside hull of the ship, and the trailing edge of the duct apparatus forms the stern of the ship. The volume within the outside surface of the duct apparatus which is not occupied by the fluid flowing through the channel (comprising the first contraction, the pipe of substantially constant streamwise cross-sectional area, and the first expansion) can be considered to be the useful volume of the ship, which can comprise the cargo or the passenger compartments, for example. The duct apparatus can have a circular cross-section when viewed in the streamwise direction. In other embodiments, the duct apparatus can have a semi-circular cross-section, similar to the hull of a conventional ship. To reduce the wave drag associated with gravity waves in water, only the portion of a ship which is in contact with water can be encompassed by, embedded within, or configured as said duct apparatus.

[00041] During nominal operations, the duct apparatus can be configured to reduce the wave drag associated with moving a useful volume or other disturbance through a fluid. The fluid with which the duct apparatus interacts can be distinguished in terms of the fluid which flows through the interior channel of the duct apparatus, denoted the "interior flow", and the fluid which doesn't flow through the interior channel and instead flows around the duct apparatus, on the side of the outside surface of the duct apparatus, denoted the "exterior flow". The duct apparatus is configured to reduce the disturbance imparted on the exterior flow. In this embodiment this is accomplished by an outside surface which is parallel to the free stream flow. The outside surface of duct apparatus 702 is cylindrical in shape and parallel to the free stream flow, for example. The disturbance imparted by the outside surface is thus reduced. In some embodiments, the circular streamwise cross-section of the outside surface of a duct apparatus can decrease in diameter in a downstream direction, for example. This can reduce the disturbance of the boundary layer on the portion of the exterior flow which lies outside the boundary layer of the outside surface. In some embodiments, when ignoring friction, the wave drag associated with the outside surface of the duct apparatus is negligible.

[00042] The duct apparatus can also be configured to reduce the wave drag associated with the interior flow. In some embodiments, during nominal operations, the cross-sectional area and shape of the steamtube associated with the interior flow upstream of the inlet is substantially equal to the cross-sectional area and shape of the inlet. In other embodiments, the cross-sectional area of the former can be larger or smaller of the cross-sectional area of the latter. In other embodiments, the shape of the cross-sectional area of the former can be larger than the cross-sectional area of the latter, for example. Since the objective can be to minimize the total drag as opposed to just the wave drag, some embodiments can have a reduced, but non-zero wave drag compared to embodiments in the prior art. In some embodiments, during nominal operations, the cross-sectional area and shape of the steamtube associated with the interior flow downstream of the outlet is substantially equal to the cross-sectional area and shape of the outlet. In other embodiments, the cross-sectional area of the former can be larger than the cross-sectional area of the latter, for example. In other embodiments, the shape of the cross-sectional area of the former can be larger or smaller than the cross-sectional area of the latter. In some embodiments, the disturbances imparted on the interior flow impart a negligible disturbance or a negligible wave drag on the exterior flow. In some embodiments, the wave drag imparted by disturbances on the interior flow to the exterior flow is reduced compared to embodiments in the prior art. Generally speaking, the magnitude of disturbance imparted to a fluid due to an initial deflection around a finite volume, such as the disturbance applied within a first contraction, can be reduced by containing the disturbance within the interior of a duct apparatus until it can be cancelled or mitigated by a second disturbance, such as the disturbance applied by a first expansion prior to the second opening of the duct apparatus.

[00043] In some embodiments, a propulsion unit is located within the channel of the duct apparatus, where the propulsion unit can comprise at least one propeller configured to accelerate the fluid, similar to maritime pump jet propulsion. For instance, a propeller can be located in the first contraction section, where the thrust of the propeller is directed in the upstream direction. In some embodiments, the propeller can be employed to reduce or avoid a localized pressure increase near the interior walls of the first contraction and ensure a uniform flow within the first contraction. The first contraction is configured to accelerate the fluid within the first contraction in a manner in which the wave drag of the duct apparatus is reduced compared to other configurations. To that end, the variance of the fluid flow velocity magnitude for a given cross-sectional area of the first contraction when viewed in a direction parallel to the free stream, i.e. in a streamwise direction, can be reduced. This can be accomplished by a propulsion unit, or annular foils located within the first contraction, for example. Such fluid flow manipulation apparatuses can ensure that the reduction in the cross-sectional area of the first contraction is accompanied by a corresponding increase in the fluid flow velocity magnitude in the first contraction, and a corresponding reduction in pressure of the fluid in the first contraction. The first expansion can be configured in a similar manner.

[00044] In some embodiments, a propeller can be located in the first expansion section, where the thrust of the propeller is directed in the downstream direction, and where at least a portion of the energy extracted from the fluid is recovered mechanically or electrically and stored for later use or used to do useful work, such as powering an upstream propeller in the first contraction. A propeller in the expansion section can be used to regulate the flow rate of fluid through the channel. Such a propeller can also be used to avoid or reduce flow separation in the first expansion section, which can reduce the streamwise length of the expansion section. In other embodiments, annular foils or ducts can be placed within the expansion section to avoid or reduce drag due to flow separation. In some embodiments, the propulsion unit can be placed between the first expansion and the first contraction. Such a propulsion unit can be employed to at least offset the reduction in the fluid flow velocity through the duct apparatus due to friction, for instance.

[00045] In another example, for disturbances traveling through a compressible fluid at a speed greater than the wave speed in the fluid, the wave drag associated with a disturbance can be reduced by a duct apparatus configured as shown in FIG. 22. The waves in question can be sound waves or shock waves, for instance, although the principles of the invention can be applied to other types of waves. In such embodiments, the duct apparatus can be configured to artificially reduce the fluid flow velocity in the vicinity of the disturbance. In FIG. 22, the disturbance in question can be considered to be fuselage 719, although the duct apparatus per se also imparts a disturbance to the fluid flow. In the case of the duct apparatus, at least a portion of the disturbances, such as the disturbances associated with deflecting or decelerating or accelerating the fluid, are configured to cancel each other or to be cancelled in the vicinity of the duct apparatus. In this particular embodiments, a portion of the disturbances associated with the fuselage apparatus 719, such as the disturbances associated with deflecting or decelerating or accelerating the fluid, are also configured to cancel each other or be cancelled in the vicinity of the duct apparatus. In other embodiments, at least one type of disturbance imparted to the fluid by the fuselage apparatus need not be cancelled, but can manifest itself in the far wake, downstream of the duct apparatus and the fuselage apparatus, as will be discussed in the context of the embodiment shown in FIG. 24.

[00046] In FIG. 22, the flow located outside of streamtube 715 does not experience any disturbances when viscous drag is assumed to be zero. This is due to the cylindrical outside surface 717 which is parallel to the free stream flow. Thus the flow in the vicinity of the outside surface 717 is deflected by only a minimal amount. The deflection can be due to the boundary layer associated with outside surface 717, for example. In other embodiments, the exterior flow can experience localized disturbances. The outside surface of the duct apparatus need not be parallel to the free stream flow velocity. For instance, the streamwise cross-sectional area of the outside surface can increase or decrease in a downstream direction. For example, the exterior flow can be deflected by a small amount, as shown in FIG. 23. The deflection in FIG. 23 is in a radially outward direction. In some embodiments, the deflection can be in a radially inward direction. The duct apparatus can be configured in a manner in which the total drag associated with the motion of the embodiment relative to the fluid is minimized. In addition to an outside surface of duct apparatus being configured to reduce the disturbance imparted on the exterior flow by said surface, the size and shape of the upstream streamtube 715 and downstream streamtube 716 of the duct apparatus is configured to not change in this idealized frictionless scenario. In other words, any disturbances caused by the duct apparatus are not communicated to the exterior flow in the form of a change in the shape or size of the streamtube, resulting in a negligible wave drag associated with the duct apparatus in the exterior flow. The uniform, cylindrical shape of the streamtube 715 upstream of the duct apparatus is a consequence of the duct apparatus traveling faster than the wave speed in the fluid and the geometry of the duct apparatus, which is configured to prevent a bow shock from forming during nominal operations.

[00047] As discussed in the previous example, at least a portion of the disturbances imparted on the interior flow at the entrance of duct apparatus 702, i.e. the compression of the fluid in the first contraction 705 and the first expansion 706, are configured to be contained within the duct apparatus 702, such as the region of substantially constant cross-sectional area 707 or the second expansion 708, until they are cancelled at the exit, i.e. the expansion of the fluid in second contraction 710 and the third expansion 711. The compression inside the first contraction 705 is configured to be isentropic and adiabatic when assuming inviscid flow for simplicity. This can be accomplished by a gradual compression of the fluid flowing through first contraction 705. The individual compression characteristics produced by elements of the interior surface 718 within first contraction 705 merge with the corresponding characteristics of circumferentially adjacent elements before the compression characteristics produced by streamwise downstream adjacent elements can merge and coalesce with, or catch up to, upstream characteristics to form a shock wave. In such embodiments, the first contraction 705 can be considered to comprise a fan of infinitesimally weak compressive shock waves. In other embodiments, shock waves of finite size can be formed within the first contraction 705. This can be a consequence of a more practical finite leading edge angle of first inside surface 718 at first opening 704, for example. The expansion through second contraction 710 and third expansion 711 can also be assumed to be isentropic and adiabatic when ignoring wall friction and heat transfer effects. The fluid velocity at second opening 712 and first opening 704 is spatially uniform in magnitude and direction, and equal to the free stream flow velocity vector in the simplified, ideal scenario depicted in FIG. 22.

[00048] Due to the reduction of the fluid flow velocity to subsonic speeds prior to the fluid encountering the fuselage apparatus 719, there are no shock waves produced by the fuselage apparatus 719 within duct apparatus 702 in the simplified, depicted embodiment. In other embodiments, shock waves can form within channel 703. These can be due to localized transonic flow, for example. For example, the fluid flow around an IMSA, such as IMSA 817 in FIG. 24, can reach supersonic velocities locally. IMSA 817 can be a transonic airfoil, for example. In another example, shock waves can also be located within the first expansion 706, as mentioned. This can avoid an unstarting of the flow through the channel 703 due to free stream flow variations, resulting in a bow shock. Such variations can be caused by wind in the atmosphere, for instance. In another example, the flow velocity within a channel can be supersonic throughout the channel, or in the vicinity of a disturbance generating apparatus. In such embodiments, shock waves will form within the channel. At least a portion of these shock waves can be configured to cancel, similar to the shock waves in Busemann's biplane. In configurations in which these shock waves do not cancel, the wave drag associated with disturbance generating apparatuses within the channel of a duct apparatus, or in the vicinity of a fluid manipulation apparatus configured in accordance with the invention, the combined wave drag associated with the disturbance generating apparatuses and the fluid manipulation apparatus can nevertheless be lower than the wave drag associated with an equivalent disturbance generating apparatus for which the fluid flow is not modified by a fluid manipulation apparatus configured in accordance with the invention. The reduction in the local free stream flow of said disturbance generating apparatus relative to the free stream flow by a fluid manipulation apparatus can reduce the wave drag of the disturbance generating apparatus, even when the local free stream flow is still supersonic.

[00049] Note that a body such as fuselage 719 traveling at supersonic speeds through a fluid such as air will produce shock waves. Due to the manipulation of the fluid flow by duct apparatus 702, however, the wave drag associated with fuselage 719 can be reduced. The combined wave drag of duct apparatus 702 and fuselage apparatus 719 can be lower than the theoretical wave drag of the fuselage 719 alone, i.e. in the "reference scenario" without being encompassed or embedded within a fluid manipulation apparatus, such as duct apparatus 702, configured in accordance with the invention. In other embodiments, a different type of disturbance generating apparatus can be positioned at the location of, i.e. in place of, fuselage apparatus 719, as shown in FIG. 24. In some embodiments, the total drag of said combined apparatus can be lower than the theoretical total drag of the disturbance generating apparatus, or a suitable equivalent, traveling through the fluid alone, i.e. in the reference scenario. The reduction in wave drag can be larger in magnitude than any increase in viscous drag associated with the additional duct apparatus, for instance. In other embodiments, the total drag can be larger than the total drag in the reference scenario. This can be due to the increased viscous drag associated with added or increased wetted area of the duct apparatus combined with the fuselage apparatus, for instance. In some such embodiments, the benefit derived from the reduction in the noise associated with the waves produced by the disturbance generating apparatus can nevertheless offset any cost increase associated with an increase in the total drag. Note that the reduction in the fluid flow velocity within channel 703 can also help reduce the viscous drag of duct apparatus 702.

[00050] The purpose of the duct apparatus 702 can be considered to be in part the deceleration and increase in pressure of the compressible fluid in the vicinity of an arbitrary disturbance generating apparatus, which, in this case, is fuselage apparatus 719, in order to reduce the wave drag associated with the disturbance generating apparatus. The disturbance generating apparatus can also comprise a propeller, a fan of a turbofan engine, a wing, or horizontal or vertical control surfaces, or types of IMCA, or types of IMSA, for example.

[00051] In FIG. 22 the fuselage apparatus 719 is shown as a structure which is connected to, but easily distinguishable from, duct apparatus 702. In other embodiments, the fuselage can be embedded within the duct apparatus 702 in a manner in which the fuselage is contained within the interior surface 718 and the outside surface 717 of the duct apparatus 702. In some such embodiments, the fuselage is configured in an annular, cylindrical fashion, similar to first compartment 730 or second compartment 732. In other words, channel 703 can be configured to pass through the center of the fuselage, with the outside surface of the fuselage being identical to the outside surface 717 of duct apparatus 702. In other embodiments, the fuselage need not fully enclose channel 703, and channel 703 need not fully enclose the fuselage, as shown in FIG. 22. For example, the channel can have a circular streamwise cross-section, a portion of which is bounded by the fuselage portion of the duct apparatus, and another portion of which is bounded by the outside wall of the duct apparatus. Instead of being annular in cross-section, the fuselage can be semi-circular or semi-annular in streamwise cross-section. The circumferential extent of the fuselage, or the angle subtended by the fuselage about the central axis of the cylindrical duct apparatus need not be 360 degrees as in the annular or circular case, but can be 300 degrees, 200 degrees, 100 degrees, or 60 degrees, for example. In other words, the fuselage can be configured to be a continuous volume, i.e. a volume which does not fully enclose the channel 703, and the channel can be a circular or semi-circular shape. Note that a channel with a closed shape, such as a closed circular cross-sectional shape, can serve to reduce the wetted area of the duct apparatus compared to an annular channel, such as the annular channel shown in FIG. 22.

[00052] FIG. **24** is a cross-sectional view of another embodiment of the invention. Some features of the embodiment shown in FIG. 24 as well as some of the principles of operation of the embodiment share similarities with features and principles of operation described by the other figures, and will therefore not be described in the same detail in the context of FIG. 24, and vice versa.

[00053] Note that the apparatus contained within inside surface 816 and outside surface 815 does not have to be a solid material, but can contain open spaces in order to not unnecessarily increase the mass or cost of embodiment 800. For example, the duct apparatus 802 can comprise compartments similar to first compartment 730 or second compartment 732 shown in FIG. 22.

[00054] Embodiment 800 comprises a duct apparatus 802 which encloses an IMSA 817.

[00055] In the embodiment shown, duct apparatus 802 is circular in cross-section when viewed along the X-axis and axially symmetric about an axis parallel to the X-axis. Duct apparatus 802 can be considered to be an IMCA. Duct apparatus 802 comprises an outside surface 815 and a channel 803 with an inside surface 816 located between first opening 804 and second opening 810, where the channel comprises a first contraction 805, a first expansion 806, a region of substantially constant cross-sectional area 807 of channel 803 when viewed in the X-direction, a second contraction 808, and a second expansion 809. Note that the terms “contraction” and “expansion” refer to the magnitude of the radius of the axially symmetric channel.

[00056] In some embodiments, the cross-sectional area of channel 803 is elliptical or rectangular in shape. In some such embodiments, the long axis of the shape is parallel to the Z-axis during nominal operations. Such a duct apparatus can be configured to harbor or enclose, and manipulate the local free stream flow for, a wing with a long axis which is also parallel to the Z-axis.

[00057] Bulk material 801 can comprise a metal such as aluminium, steel, or titanium. In some embodiments, bulk material 801 comprises composites, such as carbon fiber or fiberglass.

[00058] IMSA 817 can be described as a wing. The cross-sectional view in FIG. 24 shows the airfoil profile of IMSA 817 with trailing edge 819 and outside surface 820. IMSA 817 is rigidly connected to the duct apparatus by support strut 824. The stagnation streamline of IMSA 817, i.e. the streamline incident on the leading edge stagnation point of the right wingtip of IMSA 817 and the streamline originating at the trailing edge stagnation point of the right wingtip of IMSA 817, is indicated by dotted line 841. The lift vector of IMSA 817 has a substantial component parallel to the Y-axis. Note that the shape and size of wing 817 is shown in an exaggerated from for clarity, and is not intended to be practical in the depicted form.

[00059] Embodiments of the invention are at least partially enveloped by a fluid, as defined earlier. In FIG. 24, the fluid is compressible. For example, the fluid can be a gas such as air.

[00060] The operating condition depicted in FIG. 24 can be described as nominal, level cruise. In the depicted, simplified scenario, the free stream flow relative to the center of mass of embodiment 800 is constant in time and spatially uniform in magnitude and direction, where the direction is parallel to the X-axis. In the depicted operating condition, the free stream flow velocity magnitude relative to the embodiment 800 is larger than the speed of sound in the fluid. Since the wind velocity is assumed to be negligible in this scenario, this is equivalent to embodiment 800 moving relative to the fluid at a speed faster than the speed of sound in the fluid which is at rest in an inertial reference frame. In FIG. 24, the free stream flow velocity relative to embodiment 800 is aligned with and parallel to the X-axis, i.e. from the left of the page to the right of the page.

[00061] Dashed lines 813 and 814 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of embodiment 800. Streamlines 813 and 814 are therefore part of a streamsurface, or streamtube, which separate fluid flowing around embodiment 800 from fluid flowing through channel 803 of embodiment 800. In this embodiment, the steamtube is circular when viewed along the X-direction.

[00062] The fluid upstream of embodiment 800, such as at station 834, is moving faster relative to embodiment 800 than the speed of sound in the fluid in the configuration shown in FIG. 24. The first contraction 805, and the first expansion 806 of channel 803 are configured to compress the fluid flowing through channel 803 in the positive X-direction. The first throat is defined to be the portion of channel 803 with the smallest cross-sectional area of channel 803 between first contraction 805 and first expansion 806 when viewed along the X-direction. The average speed of the fluid relative to embodiment 800 at the first throat, i.e. station 835, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 834, the average relative speed is larger than the speed of sound, and further downstream, such as at station 837, the average relative speed is smaller than the speed of sound within the fluid in this embodiment. In the depicted embodiment, the flow through channel 803 is substantially adiabatic and isentropic when neglecting friction. In other embodiments, there can be a shock wave located between the first throat and station 837. In other words, the relative flow speed of the fluid downstream of the first throat can be faster than the speed of sound within the fluid, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave, resulting in a relative flow speed at station 837 which is slower than the speed of sound, as in the ideal scenario in which there is an infinitely weak shock at the first throat..

[00063] Both the second contraction 808 and the second expansion 809 of channel 803 are configured to expand the fluid flowing through channel 803 in the positive X-direction. The second throat is defined to be the portion of channel 803 with the smallest cross-sectional area of channel 803 between second contraction 808 and second expansion 809 when viewed along the X-direction.

The average speed of the fluid relative to embodiment 800 at the second throat, i.e. station 839, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 837, the average relative speed is smaller than the speed of sound, and downstream, such as at station 840, the average relative speed is larger than the speed of sound within the fluid in this embodiment.

[00064] Duct apparatus 802 is configured to decelerate the fluid flow in the vicinity of a disturbance generating apparatus, which in this case can be considered to be the IMSA 817, such that the local free stream flow of IMSA 817 is smaller than the free stream flow velocity magnitude. As a result of the duct apparatus, the wave drag associated with IMSA 817 is reduced compared to the reference scenario in which the local free stream flow of IMSA 817, or an equivalent IMSA or lifting apparatus, is substantially equal to the free stream flow. Note that the local free stream flow can still be faster than the wave speed within said fluid. In such embodiments, the resulting wave drag is greater than zero, but reduced by a small amount. In the depicted embodiment, the reduction in the local free stream flow compared to the free stream flow is sufficiently large, that the magnitude of the local free stream flow of IMSA 817 by virtue of the fluid manipulation of an appropriately configured duct apparatus is lower than the speed of sound of the fluid at IMSA 817. In such embodiments, the resulting wave drag can be reduced substantially. In the reference scenario IMSA 817, or an equivalent IMSA, is traveling faster than the speed of sound relative to a surrounding fluid during nominal operations, since the local free stream flow is larger than the speed of sound at the location of IMSA 817. Therefore, IMSA 817 or an equivalent IMSA would be associated with a wave drag in the reference scenario. An equivalent IMSA in a reference scenario can be configured to produce the same amount of lift as IMSA 817 with the same planform area and/or geometry, for example. It is this wave drag associated with a disturbance generating apparatus which can be reduced by a fluid manipulation apparatus configured in accordance with the invention.

[00065] Note that the principles of the invention can also be applied to reduce the wave drag associated with transonic flow. In other words, the free stream flow velocity magnitude can be smaller than the speed of sound in the free stream, and a fluid manipulation apparatus can be configured in accordance with the invention to reduce the local free stream flow velocity of an IMSA, IMCA, or other disturbance generating apparatus to a magnitude which is smaller than the free stream flow velocity magnitude, such that the combined wave drag associated with the disturbance generating apparatus and the fluid manipulation apparatus can be lower than the wave drag associated with an equivalent disturbance generating apparatus of the prior art. The latter wave drag can be the wave drag associated with an equivalent disturbance generating apparatus in the reference scenario in which the local free stream flow velocity magnitude is substantially equal to the free stream flow velocity magnitude, for example.

[00066] As mentioned, for the embodiment shown in FIG. 22, the reference scenario can be that of fuselage apparatus 719 alone traveling at the same free stream velocity as embodiment 700. For the embodiment shown in FIG. 24, the reference scenario can be that of IMSA 817 alone traveling at the same free stream velocity as embodiment 800. Another reference scenario for embodiment 800 can be that of a theoretical supersonic aircraft traveling at the same free stream velocity as embodiment 800, where the weight of the aircraft is equal to the lift of IMSA 817, and the geometry of the aircraft, such as the length of the aircraft or the volume of the fuselage, shares common features with the geometry of embodiment 800, such as the length or the volume of the internal compartments.

[00067] Note that the fuselage of a conventional supersonic aircraft can be considered to be a fluid manipulation apparatus for the main wing of the aircraft, since the shock wave produced by the fuselage can modify the local free stream flow of the main wing. This modification which can reduce the local free stream flow, and reduce the wave drag of wing alone. Note that in this framework, the fuselage can be considered to be a duct apparatus, although such a duct apparatus is not configured in accordance with the invention.

[00068] Duct apparatus 802 is configured to reduce the local free stream flow in the vicinity of a disturbance generating apparatus, such as IMSA 817, in a manner in which the wave drag associated with duct apparatus 802 is reduced compared to fluid manipulation apparatuses in the prior at. This can be accomplished by configuring the fluid manipulation apparatus in a manner in which only a negligible or small disturbance is imparted on the exterior flow, outside of duct apparatus 802, as mentioned, as well as a gradual compression and deceleration of the interior flow entering duct apparatus 802, a containment of the pressure increase by outside walls of the duct apparatus, and a gradual expansion and acceleration of the interior flow exiting duct apparatus 802. Note that the containment of the pressure increase associate with the deceleration of the interior flow serves to prevent or mitigate the disturbance imparted by the duct apparatus on the interior flow from being communicated or transferred to the exterior flow. The disturbances imparted on the interior flow during the compression are configured to be at least partially cancelled during the expansion or prior to exiting the channel.

[00069] Note that, in general, embodiments of the invention need not comprise a duct apparatus. Other embodiments can comprise a fluid manipulation apparatus configured to perform at least a portion of the aforementioned function of the duct apparatus 802. Embodiments of the invention comprise a fluid manipulation apparatus configured to reduce the local free stream flow of a specified disturbance generating apparatus, where the resulting local free stream flow can be larger or smaller than the speed of sound, and where the disturbance generating apparatus can be an IMSA, or IMCA, such as a wing, propeller, control surface, or fuselage. The fluid manipulation apparatus is furthermore configured to artificially contain the pressure increase in the vicinity of the disturbance generating apparatus. This can reduce the wave drag of the disturbance generating apparatus as well as mitigate the wave drag associated with the fluid manipulation apparatus.

[00070] For example, a fluid manipulation apparatus can be configured to impart a body force per unit mass on the fluid in the vicinity of the specified disturbance generating apparatus. The magnitude and the direction of this body force per unit mass can be configured to decelerate the fluid upstream of the disturbance generating apparatus, to contain or confine the resulting pressure increase in the vicinity of the disturbance generating apparatus, and to accelerate the fluid downstream of the disturbance generating apparatus. Recall that, in the case in which the fluid is a liquid such as water, the flow can instead be accelerated upstream and decelerated downstream of a disturbance generating apparatus by said fluid manipulation apparatus. In the vicinity of the disturbance generating apparatus, the flow can be considered to be protected from the higher pressure "exterior" flow, i.e. the exterior flow can be considered to be confined or contained. Note that in such embodiments there need not be a channel through a fluid manipulation apparatus. Instead, a body force per unit mass generating field can be generated exterior to a fluid manipulation apparatus, where the streamlines which pass in the vicinity of the disturbance generating apparatus being referred to the "interior flow" and the remaining flow being denoted the "exterior flow", although both flows can be exterior to the fluid manipulation apparatus.

[00071] There are a wide variety of body force per unit mass generating apparatuses and methods known in the art. For example, the fluid upstream of the disturbance generating apparatus can be ionized in the upstream portion of the fluid manipulation apparatus and subsequently subjected to an electric field which is configured to decelerate, confine, and accelerate the ionized fluid in the vicinity of a disturbance generating apparatus, prior to being deionized or neutralized once more in the downstream portion of the fluid manipulation apparatus. Alternatively or concurrently, magnetic fields can be used. The fluid can also be electrically or magnetically polarized in some embodiments.

[00072] A body force can arise from the existence of a potential field gradient. One such example is the force which arises from the gradient of an electric potential. For example, the elements of a fluid can be configured to be electrically charged. In the context of a fluid, the term “elements” refers to the constituent parts of the fluid, such as molecules, for example. In the case of a gas, the molecules could be positively or negatively ionized, for instance. By applying an electric field, body forces per unit mass can be applied to the electrically charged elements of the fluid by a fluid manipulation apparatus.

[00073] For other embodiments it can be impossible or inconvenient to use, procure, or create a fluid with mobile electrical charges. In this case, elements of the fluid can be polarized by applying an electric field, or these elements can already have an intrinsic polarization, as in the case of polar molecules, such as water. When placed in an electric field gradient, these polarized elements can experience a body force. Note that the magnitude of said force depends on the orientation of the polarization axis relative to the electric field, amongst other parameters. Thus an electric field can be configured to generate body forces per unit mass on the polar elements in the fluid, as well as polarize elements in the fluid, if necessary. The electric field can be applied in a myriad of ways known in the art.

[00074] Magnetism can also be employed to generate body forces. The fluid can comprise diamagnetic, paramagnetic, or ferromagnetic elements. When magnetized, the individual elements in the fluid can form magnetic dipoles, or these elements can already have an intrinsic magnetic dipole, such as an electron. When these magnetic dipoles are placed in a magnetic field with a non-zero curl or gradient, they can experience a body force. Note that the magnitude of the body force is a function of the orientation of the magnetic dipole relative to the local magnetic field, amongst other parameters. Thus an external magnetic field can be configured to generate body forces per unit mass on the magnetized elements in the fluid, as well as magnetize the elements in the fluid, if necessary. The magnetic field can be generated by ferromagnets other at least instantaneously magnetized elements, or by an electrical current flowing through the wires of an electromagnet, amongst other methods known in the art.

[00075] In FIG. 24, the duct apparatus is configured in a manner in which only a small amount of vorticity is shed by duct apparatus 802 compared to the vorticity shed by IMSA 817. This is accomplished in part by ensuring IMSA 817 is located sufficiently far from the inside surface 816, such that the induced flow velocity of IMSA 817 and the associated wake at the inside surface 816 is sufficiently small. Note that the vorticity shed by duct apparatus 802, or any induced flow velocity within the supersonic exterior flow can incur a wave drag on the exterior flow. Thus, it can be advantageous for the duct apparatus 802 to be sufficiently large that the bound vortex of IMSA 817 as well as any vorticity shed by IMSA 817 does not impart a theoretical induced flow velocity, i.e. an induced local free stream flow velocity, at inside surface 816. Such a theoretical induced velocity can give rise to a theoretical bound vortex associated with duct apparatus 802, or vortex shedding by duct apparatus 802, due to the theoretical constraint preventing fluid from passing through inside surface 816. These shed vortices at the tailing edge of duct apparatus 802, i.e. at second opening 810, can give rise to shock waves and wave drag. The magnitude of this wave drag can be reduced by reducing the interference of IMSA 817 as well as the interference of the wake of IMSA 817 on duct apparatus 802. This can be accomplished by appropriately configuring parameters such as the size of duct apparatus 802, which can be measured in terms of the diameter or cross-sectional area at station 837 or the length of the duct apparatus 802 downstream of IMSA 817, for example, the location and size of IMSA 817 within duct apparatus 802, where the size can be measured in terms of wingspan chord length or reference area, the magnitude of the lift produced by IMSA 817, as well as the properties of the fluid at station 837, where the properties can refer to the local free stream flow velocity or density. Note that duct apparatus 802 can and does impart a substantial amount of interference on IMSA 817 and the wake of IMSA 817 by changing the local free stream flow of IMSA 817 and its wake.

[00076] In the second contraction 808 and the second expansion 809 the vortex sheet of IMSA 817, as indicated by streamline 841, is accelerated together with the interior flow, i.e. the bulk flow within channel 803, in the positive X-direction. In the depicted embodiment, at second opening 810, the velocity of the vortices in vortex sheet of IMSA 817 are moving in the positive X-direction at a speed which is greater than the speed of sound, as is the case for the interior flow at that location. Downstream of second opening 810, the vortex sheet of IMSA 817 does not move at a speed faster than the speed of sound relative to the bulk flow. Therefore, the vortex sheet can traverse from the interior flow to the exterior flow without incurring a shock wave at the interface. Note that this is true even when there is a slip velocity or a velocity difference or velocity gradient between the interior flow and the exterior flow.

[00077] In some embodiments, the wave drag associated with the acceleration of the vortex sheet of IMSA 817 from a speed which smaller than the speed of sound relative to the duct apparatus 802 within the region of substantially constant cross-sectional area within duct apparatus 802, to a speed which is greater than the speed of sound relative to the duct apparatus 802 at station 840 can be small or negligible in some embodiments when compared to the wave drag associated with an equivalent IMSA in the prior art. This is due to the acceleration of the free vortices of the vortex sheet together with the acceleration of the bulk of the interior flow, such that the vortices don't move faster than the surrounding fluid. By virtue of a fluid manipulation apparatus such as duct apparatus 802, a given vortex of IMSA 817, bound or free, is prevented from or hindered in, incurring a significant induced velocity to, or imparting a disturbance on, flow which is moving supersonically relative to said vortex source. The gradual acceleration of the fluid in the second contraction 808 and the second expansion 809 can serve to reduce the strength of any shock waves associated with the vortex sheet of IMSA 817.

[00078] FIG. **25** is a cross-sectional view of the embodiment shown in FIG. **24** viewed in the positive X-direction at the location indicated in FIG. 24.

[00079] Streamline 841 is shown. The stagnation streamline of IMSA 817, i.e. the streamline incident on the leading edge stagnation point of the left wingtip of IMSA 817 and the streamline originating at the trailing edge stagnation point of the left wingtip of IMSA 817, is indicated by dotted line 842. The interior surface 823 of IMSA 817 is shown.

[00080] FIG. **26** is a cross-sectional view of the embodiment shown in FIG. **24** viewed in the positive X-direction at the location indicated in FIG. 24.

[00081] The cross-section of the theoretical shed vortex sheet of IMSA 817 at this location is indicated by dashed line 843. The roll-up of the vortex sheet is represented schematically.

[00082] FIG. **27** is a cross-sectional view of the embodiment shown in FIG. **24**.viewed in the positive X-direction at the location indicated in FIG. 24.

[00083] The cross-section of the theoretical shed vortex sheet of IMSA 817 at station 839 is indicated by dashed line 844. The roll-up of the vortex sheet has progressed further.

[00084] FIG. **28** is a cross-sectional view of the embodiment shown in FIG. **24** viewed in the positive X-direction at the location indicated in FIG. 24.

[00085] The cross-section of the theoretical shed vortex sheet of IMSA 817 at that location is indicated by dashed line 845. The roll-up of the vortex sheet has progressed further.

[00086] Dashed dotted line 846 illustrates the projection of the outside surface 815 on a plane parallel to the YZ-plane downstream of said cross-sectional view.

[00087] FIG. **29** is a cross-sectional view of the embodiment shown in FIG. **24** viewed in the negative X-direction at the location indicated in FIG. 24.

[00088] FIG. **30** is a cross-sectional view of another embodiment of the invention. Some features of the embodiment shown in FIG. 30 as well as some of the principles of operation of the embodiment share similarities with features and principles of operation described by the other figures, and will therefore not be described in the same detail in the context of FIG. 30, and vice versa.

[00089] Embodiment 850 comprises a duct apparatus 852 which encloses an IMSA 892 which can be described as a wing, am upstream IMSA 908, a fuselage apparatus 869, a downstream IMSA 919, and an engine 925.

[00090] In the depicted embodiment, engine 925 can be described as a turbofan engine. In some embodiments, a driveshaft of engine 925 can be coupled to a gearbox. In some such embodiments, engine 925 can be described as a turboshaft engine.

[00091] In the embodiment shown, duct apparatus 852 is circular in cross-section when viewed along the X-axis and axially symmetric about an axis parallel to the X-axis. Duct apparatus 852 can be considered to be an IMCA. Duct apparatus 852 comprises an outside surface 867 and a channel 853 with an inside surface 868 located between first opening 854 and second opening 862, where the channel comprises a first contraction 855, a first expansion 856, a region of gradually increasing cross-sectional area 857 of channel 853 when viewed in the X-direction, a second expansion 858, a second contraction 860, and a third expansion 861. Note that the terms “contraction” and “expansion” refer to the magnitude of the radius of the axially symmetric channel.

[00092] Fuselage apparatus 869 comprises a leading point 870, a trailing point 871, an inside surface 873, an outside surface 872, and fuselage compartment 874 schematically separated from the remaining fuselage by dashed line 875. The fuselage apparatus 869 is rigidly connected to the duct apparatus by several support struts. In the embodiment shown, individual stator blades, such as stator blade 913, can also be considered to be support struts, and vice versa. In some embodiments, the fuselage can be configured to carry cargo, passengers, or fuel, for example.

[00093] The duct apparatus comprises a first compartment 880 within the upstream constriction, or duct element 951, and a second compartment 882 within the downstream constriction, or duct element 952. These compartments can fulfill a number of purposes. In some embodiments, they can be used to store landing gear, fuel, or cargo.

[00094] Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions. In other embodiments the cross-sectional geometry of channel 853 or outside surface 867 can be square, rectangular, or elliptical when viewed along the X-direction. In some embodiments, the cross-sectional geometry of channel 853 can change from square to circular in the positive X-direction, for example.

[00095] For some embodiments, the cross-sectional area of the circular channel 853 can vary with time. For example, the radius of the channel at station 890 can be modified for different operating conditions. The radius can be increased or decreased depending on the free stream flow velocity. In this manner, the properties of the flow through duct 853 can be modified and controlled such that the principles of the invention can be applied at different free stream flow conditions. For example, the existence, or the location, of a shock wave within the first expansion 856 can be regulated by controlling the cross-sectional area of the channel 853 at station 890. A wide variety of methods for changing the cross-sectional area of a channel as a function of time are available. For example, a ramp connected to the duct apparatus 852 can be hydraulically extended into the channel, thus reducing the cross-sectional area of the channel. In another example, a spike located within channel 853 can be moved along the length of the channel, i.e. axially along the X-direction, towards or away from a contraction of the channel, thus decreasing or increasing the annular cross-sectional area of the channel, respectively.

[00096] Similarly, the cross-sectional area of the channel 853 at station 885 can be modified in order to ensure the desired flow profile within channel 853 as well as upstream and downstream of channel 853.

[00097] Bulk material 851 can comprise a metal such as aluminium, steel, or titanium. In some embodiments, bulk material 851 comprises composites, such as carbon fiber or fiberglass.

[00098] IMSA 892 can be described as a wing. The cross-sectional view in FIG. 30 shows the airfoil profile 893 of IMSA 892 with trailing edge 895, inside surface 899, and outside surface 896. IMSA 892 is rigidly connected to the duct apparatus by support strut 900. The stagnation streamline of IMSA 892, i.e. the streamline incident on the leading edge stagnation point of the right wingtip of IMSA 892 and the streamline originating at the trailing edge stagnation point of the right wingtip of IMSA 892, is indicated by dotted line 901. During the supersonic, nominal, constant velocity, level cruise configuration shown in FIG. 30, IMSA 892 is configured to generate lift, as indicated by lift vector 941, which has a substantial component parallel to the Y-axis.

[00099] There is an upstream IMSA 908 comprising a propeller or a fan disc with fan blades or propeller blades, such as blade 911, mounted to a central hub 909 with leading point 870. Stator blades, such as stator blade 913, are located downstream of the propeller. In other embodiments, there are no dedicated stator blades, with upstream IMSA 908 consisting only of a single fan disc or propeller. In another example, the upstream IMSA can consist of two coaxial and counter-rotating propellers. In the depicted embodiment, the propeller blades and the stator blades are configured to be able to be rotated about their long axis. In other words, the blade pitch angle can be regulated for the stator blades and the rotor blades of upstream IMSA 908. During the supersonic, nominal, level cruise configuration shown in FIG. 30, the fan blades and the stator blades of upstream IMSA 908 are feathered, i.e. in a low drag configuration. For some embodiments, the rotor of upstream IMSA 908 is stationary, i.e. does not rotate relative to the duct apparatus 852, in this configuration. In other embodiments, the rotor of upstream IMSA 908 can rotate in this configuration.

[000100] There is a downstream IMSA 919 comprising a propeller or a fan disc with fan blades or propeller blades, such as blade 922, mounted to a central shaft. Stator blades, such as stator blade 924, are located downstream of the propeller. In other embodiments, there are no dedicated stator blades, with downstream IMSA 919 consisting only of a single fan disc or propeller. In another example, the downstream IMSA can consist of two coaxial and counter-rotating propellers. In the depicted embodiment, the rotor of downstream IMSA 919 is rotating in the same direction as the rotor of upstream IMSA 908. In other embodiments, the direction of rotation of the downstream IMSA 919 can be opposite to the direction of rotation of the upstream IMSA 908. This can serve to reduce the torque acting on embodiment 850 about an axis parallel to the axis of rotation of the upstream and downstream IMSAs due to the drag acting on both As explained in the context of upstream IMSA 908, the propeller blades and the stator blades of downstream IMSA 919 are configured to be able to be rotated about their long axis. In other words, the blade pitch angle can be regulated for the stator blades and the rotor blades of downstream IMSA 919. During the supersonic, nominal, level cruise configuration shown in FIG. 30, the fan blades and the stator blades of downstream IMSA 919 are feathered, i.e. in a low drag configuration. For some embodiments, the rotor of downstream IMSA 919 is stationary, i.e. does not rotate relative to the duct apparatus 852, in this configuration. In other embodiments, the rotor of downstream IMSA 919 can rotate in this configuration.

[000101] Engine 925 can be described as a jet engine comprising a compressor 928, combustion chamber 940, and turbine 932 within nacelle 931. The first stage of turbine 932 consists of a rotor disc with rotor blades, such as rotor blade 934, and a stator with stator blades, such as stator blade 935. The second stage of turbine 932 consists of a rotor disc with rotor blades, such as rotor blade 936, and a stator with stator blades, such as stator blade 937. Engine 925 is of a twin spool architecture, with the rotor disc of the first stage of turbine 932 driving the first spool 926 which drives the rotor discs of the compressor 928. Compressor 928 comprises three stages, each consisting of a rotor disc with rotor blades, such as rotor blade 929 of the third stage, and a stator with stator blades, such as stator blade 930 of the third stage. The rotor disc of the second stage of turbine 932 drives a second spool, which drives the rotors of both the upstream IMSA 908 and the downstream IMSA 919 via drive shaft 927, drive shaft 915, and drive shaft 916, for example. Fairing 933 is configured to reduce the drag of engine 925 by reducing or avoiding flow separation at the exit of turbine 932. The trailing point 871 of fairing 933 is indicated.

[000102] In the depicted embodiment, an inlet ramp or door 938 can be configured to prevent a large portion of the interior flow from entering engine 925. The inlet door 938 can be configured to close-off the inlet of engine 925. Exit door 939 can be configured to provide an aerodynamic or hydrodynamic fairing to nacelle 931. During the supersonic, nominal, level cruise configuration shown in FIG. 30, the inlet door 938 and exit door 939 are shown in a fully closed configuration. During this operating condition, the thrust is provided by the injection and combustion of fuel by the flame holders, such as flame holder 724, within channel 853. Engine 925 can be considered to be turned off during this operating mode. In other embodiments, engine 925 can remain turned on during supersonic, nominal, level cruise. For example, engine 925 can drive an electric generator in order to provide electrical power for auxiliary systems on vehicle 850. The power can be used to charge batteries, or be consumed by electrical equipment such as flight computers or air-conditioning units. The inlet door 938 and exit door 939 are shown in a fully open configuration in FIG. 31 and FIG. 32. In this configuration, a portion of the fluid moving through channel 853 can be ingested by, or flow through, engine 925, which can produce power via the combustion of fuel, for example.

[000103] The power generated by engine 925 is transmitted to upstream IMSA 908 and to downstream IMSA 919 via a drive train, as mentioned. In some embodiments, the drive train can comprise clutches, drive shafts, gears, or gear boxes, for example. In other embodiments, the power generated by engine 925 can be transferred to upstream IMSA 908 and to downstream IMSA 919 electrically. Engine 925 can power an electric generator, at least a portion of the electricity produced by which can be transferred to an electric motor via electrical conductors, where the electric motor can be configured to power upstream IMSA 908 and/or downstream IMSA 919. A portion of said electricity can also be used to power auxiliary electrical systems of embodiment 850.

In some embodiments, the rotor disc of downstream IMSA 919 can be connected to drive shaft 927, as shown in FIG. 30, which in turn can be configured to drive an electric generator, the electrical power of which can be transferred via electrical conductors around fuselage compartment 874 to an electric motor driving the rotor disc of upstream IMSA 908.

[000104] In the depicted embodiment, the drive train which mechanically transmits the power from drive shaft 927 to upstream IMSA 908, is directed around fuselage compartment 874 by universal joints. In embodiment 850 the universal joints are constant velocity joints, or CV joints, such as CV joint 907 connecting drive shaft 915 to drive shaft 916.

[000105] In the depicted embodiment, the stator blades of downstream IMSA 919 are configured to be able to inject fuel into the adjacent fluid flow, as well as hold the flame during combustion of said fuel. The stator of IMSA 919 can thus be considered to be a flame holder. During the supersonic, nominal, level cruise configuration shown in FIG. 30, the flame holder is configured to inject fuel into channel 853 and stabilize a flame during the combustion of said fuel. In such embodiments and during this mode of operation, channel 853 can be operated in the same manner as a ramjet. The thrust imparted by the fluid on the embodiment 850 is schematically represented by thrust vectors, such as thrust vector 943. Note that the thrust is the result of pressure of the fluid acting on embodiment 850. In other words, the thrust arises from the integration of the pressure acting on the wetted surfaces of embodiment 850. As a result, the flow velocity magnitude of the interior flow at station 891 is greater than the free stream flow velocity magnitude, i.e. the flow velocity magnitude of the interior flow at station 884.

[000106] Any surplus torque imparted by the combination of the upstream and downstream IMSAs on the remaining portion of embodiment 850 can be cancelled by adjusting the pitch angle or the orientation of the stator blades of the downstream and/or upstream IMSAs relative to the fluid. The stator blades can also be used for roll, pitch, and yaw control of embodiment 850 in some embodiments. In other embodiments, dedicated IMSAs, similar to IMSA 892, can be located within the region of channel 853 in which the fluid is flowing subsonically relative to the duct apparatus, where the dedicated IMSAs are configured to maintain roll, pitch, and/or yaw control. In yet other embodiments, control surfaces can be located in the regions within channel 853 in which the fluid is moving supersonically relative to the duct apparatus. In some such embodiments, the control surfaces can be located at the trailing edge of the duct apparatus, i.e. at the second opening 862. Pitch and yaw control can be accomplished by thrust vectoring, for example, where the thrust is produced by the acceleration of the interior flow. In some embodiments, tail surfaces, such as a vertical or horizontal tail, can be mounted on the outside surface 867 and be configured to interact with the exterior flow, i.e. the flow outside of cylindrical streamtube 865 or 866.

[000107] Embodiments of the invention are at least partially enveloped by a fluid, as defined earlier. In FIG. 30, the fluid is compressible. For example, the fluid can be a gas such as air.

[000108] The operating condition depicted in FIG. 30 can be described as nominal, level cruise. In the depicted, simplified scenario, the free stream flow relative to the center of mass of embodiment 850 is constant in time and spatially uniform in magnitude and direction, where the direction is parallel to the X-axis. In the depicted operating condition, the free stream flow velocity magnitude relative to the embodiment 850 is larger than the speed of sound in the fluid. Since the wind velocity is assumed to be negligible in this scenario, this is equivalent to embodiment 850 moving relative to the fluid at a speed faster than the speed of sound in the fluid which is at rest in an inertial reference frame. In FIG. 30, the free stream flow velocity relative to embodiment 850 is aligned with and parallel to the X-axis, i.e. from the left of the page to the right of the page, as indicated by arrow 944.

[000109] Dashed lines 865 and 866 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of embodiment 850. Streamlines 865 and 866 are therefore part of a streamsurface, or streamtube, which separate fluid flowing around embodiment 850 from fluid flowing through channel 853 of embodiment 850. In this embodiment, the steamtube is circular when viewed along the X-direction.

[000110] The fluid upstream of embodiment 850, such as at station 884, is moving faster relative to embodiment 850 than the speed of sound in the fluid in the configuration shown in FIG. 30. The first contraction 855, and the first expansion 856 of channel 853 are configured to compress the fluid flowing through channel 853 in the positive X-direction. The first throat is defined to be the portion of channel 853 with the smallest cross-sectional area of channel 853 between first contraction 855 and first expansion 856 when viewed along the X-direction. The average speed of the fluid relative to embodiment 850 at the first throat, i.e. station 885, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 884, the average relative speed is larger than the speed of sound, and further downstream, such as at stations 887, 888 or 889, the average relative speed is smaller than the speed of sound within the fluid in this embodiment. In the depicted embodiment, the flow through channel 853 is substantially adiabatic and isentropic when neglecting friction. In other embodiments, there can be a shock wave located between the first throat and station 887. In other words, the relative flow speed of the fluid immediately downstream of the first throat can be faster than the speed of sound within the fluid, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave, resulting in a relative flow speed at station 887 which is slower than the speed of sound, as in the ideal scenario in which there is an infinitely weak shock at the first throat. In the preferred embodiment, such a shock wave is configured to be located upstream of upstream IMSA 908.

[000111] Both the second contraction 860 and the third expansion 861 of channel 853 are configured to expand the fluid flowing through channel 853 in the positive X-direction. The second throat is defined to be the portion of channel 853 with the smallest cross-sectional area of channel 853 between second contraction 860 and third expansion 861 when viewed along the X-direction. The average speed of the fluid relative to embodiment 850 at the second throat, i.e. station 890, is approximately equal to the speed of sound within fluid at that location. Upstream, such as at station 887, the average relative speed is smaller than the speed of sound, and downstream, such as at station 891, the average relative speed is larger than the speed of sound within the fluid in this embodiment.

[000112] During the supersonic, nominal, level cruise configuration shown in FIG. 30, duct apparatus 852 is configured to reduce the local free stream flow of the disturbance generating apparatuses, such as upstream IMSA 908, fuselage apparatus 869, IMSA 892, downstream IMSA 919, the fuel injector and flame holder 924, or engine 925. Duct apparatus 852 is furthermore configured to accomplish said reduction in the local free stream flow without incurring an unnecessarily large wave drag of its own. This can be accomplished by configuring the duct apparatus as described previously. For instance, the change in the diameter of the circular outside surface 867 of duct apparatus 852 in the downstream direction can be configured to be small, and gradual. The disturbance imparted by the duct apparatus on the interior flow during the deceleration of the interior flow can be shielded from the exterior flow by the outside wall of the duct apparatus, and at least a portion of said disturbance on the interior flow can be cancelled prior to the interior flow exiting through the second opening 862. Any vortex shedding, such as the vortices shed by IMSA 892 or upstream IMSA 908, can be configured to occur within duct apparatus 852 at a reduced local free stream flow velocity compared to the free stream flow velocity, such that the wave drag associated with the shedding process is reduced or negligible compared to a reference scenario. The same principle can be applied to other disturbances, such as bound vortices or IMCAs, or engines, or the combustion of fuel, as mentioned. The interference, or local free stream flow velocity modification, imparted by the bound or free vortices within the duct apparatus, such as between stations 885 and 890, on the duct apparatus 852, such as the interior surface 868 of the duct apparatus 852, is low, such that duct apparatus 852 does not incur an unnecessarily large wave drag, where the associated waves can be in the interior flow or the exterior flow. This can be accomplished by ensuring the diameter of the channel 853 is large enough in relation to the strength and the location of the vortices. The strength of a bound or free vortex filament as well as the distance to the interior or outside surface of the duct apparatus are some of the parameters which determine the strength of said interference. Note that, while not all disturbances carry or shed vortices, such as the disturbances created by the combustion of fuel, the principles of the invention apply to such disturbances as well.

[000113] During supersonic, nominal, level cruise, the majority of the weight of the depicted embodiment 850 is carried by the lift force 941 produced by IMSA 892, and the majority of the thrust is produced by channel 853 being configured as a ramjet. Embodiment 850 can be described as a supersonic aircraft, for example. In FIG. 30, embodiment 850 is moving relative to the stationary free stream fluid in the negative X-direction, parallel to the X-axis, at a supersonic speed.

[000114] FIG. **31** is a cross-sectional view of the embodiment shown in FIG. **30** for a different mode of operation. In FIG. 31, embodiment 850 is moving relative to the stationary free stream fluid in the negative X-direction, parallel to the X-axis, at a subsonic speed. The direction of the free stream flow relative to embodiment 850 is indicated by arrow 950. In this configuration, a portion of the weight of embodiment 850 is carried by the lift force 945 acting on duct apparatus 852. The longitudinal symmetry axis of duct apparatus 852 is rotated in a negative direction about the Z-axis. The resulting angle of attack of duct apparatus 852 results in the deflection of interior flow and exterior flow in the negative Y-direction, which gives rise to a lift force and drag force acting on duct apparatus 852. Duct apparatus 852 can be considered to be a closed wing, or an annular wing, during this mode of operation.

[000115] In order to reduce the interference between IMSA 892 and the downstream IMSA 919, IMSA 892 is feathered during this mode of operation. Interference can lead to a distortion of the flow field at downstream IMSA 919, which can lead to unnecessary drag, noise, and vibrations. To that end, the shape of IMSA 892 is changed in a manner in which no vortices are shed by IMSA 892 in a simplified, frictionless scenario. In some embodiments, the IMSA 892 can be morphed such that the camber and angle of attack of each airfoil section of IMSA 892 is zero. In other embodiments, IMSA 892 can be retracted into a fairing or mounted flush against an inside surface, such as interior surface 868 or fuselage outside surface 872. This can reduce the wetted area of embodiment 850 while also minimizing or reducing any interference between IMSA 892 and downstream IMSA 919.

[000116] Upstream IMSA 908 is configured to produce thrust directed in the upstream direction, as indicated by thrust vector 946, and downstream IMSA 919 is configured to produce thrust directed in the downstream direction, as indicated by thrust vector 949. This can increase the mass flow rate through the channel 853 and reduce the induced drag associated with the production of lift and thrust. Note that upstream IMSA 908 and downstream IMSA 919 produce a net thrust directed in the upstream direction, which cancels the drag acting on embodiment 850 and contributes to the net lift of embodiment 850.

[000117] The power consumed by the upstream IMSA 908 is provided by the power extracted by the downstream IMSA 919 from the interior flow, as well as engine 925.

[000118] In FIG. 31, there is no fuel flow via the flame holder into the interior flow and no combustion of fuel in the interior flow apart from within the combustion chamber 940 engine 925 during subsonic, nominal, level cruise. In other modes of operation, flame holder can inject and combust fuel in channel 853, similar to the operation of an afterburner. Similarly, fuel can also be injected and combusted immediately downstream of turbine 932 in engine 925.

[000119] Dashed lines 959 and 960 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of duct apparatus 852. Streamlines 959 and 960 are therefore part of a streamsurface, or streamtube, which separate the exterior flow, i.e. the fluid flowing around duct apparatus 852, from the interior flow, i.e. fluid flowing through channel 853. In this embodiment, the steamtube is circular when viewed along the X-direction.

[000120] As the free stream velocity is increased for the operating mode shown in FIG. 31, the magnitude of the thrust of downstream IMSA 919 can be reduced. The purpose of the downstream IMSA 919 during the operating modes shown in FIG. 31 and FIG. 32 is the increase of the mass flow rate through channel 853. As the free stream velocity magnitude is increased, the services of the downstream IMSA 919 are only required to a lesser extent. Thus the magnitude of the thrust of downstream IMSA 919 can be reduced. Depending on the net thrust requirement, the thrust of upstream IMSA 908 can be reduced or increased as the free stream velocity increases. At low free stream flow velocities, the thrust produced by upstream IMSA 908 can be limited by structural constraints or power limits of engine 925. As the free stream flow velocity is increased, or at the aforementioned low free stream flow velocities, the thrust produced by upstream 908 can also be limited by an increase in the wave drag, compressibility drag, or noise of the rotor blades of upstream IMSA 908. The wave drag can arise from the tip velocity of the rotor or fan of upstream IMSA 908 relative to the fluid exceeding the speed of sound at that location. Portions of the rotor blades of upstream 908 can also encounter compressibility drag at large speeds relative to the surrounding fluid. As the thrust of upstream IMSA 908 is reduced, the magnitude of the thrust of downstream IMSA 919 is reduced in order to meet a given net thrust requirement. At sufficiently large free stream flow velocities, the magnitude of the thrust of the downstream IMSA 919 is so small, that it is more advantageous to feather downstream IMSA 919. To that end, downstream IMSA 919 can be uncoupled from the drive train via a clutch and feathered, while upstream IMSA 908 continues to provide thrust. In this configuration, upstream IMSA 908 and engine 925 can be considered to operate as a conventional turbofan engine, with the fan being represented by upstream IMSA 908 and the core being represented by engine 925.

[000121] As the speed is increased further, the thrust and the rate of rotation of the rotor of upstream IMSA 919 can be reduced to avoid or reduce the wave drag and/or compressibility drag associated with the rotor blades of upstream IMSA 919. As before, upstream IMSA 908 and engine 925 can be considered to operate as a conventional turbofan engine, albeit with a reduced percentage of thrust produced by the fan, i.e. upstream IMSA 919. The remaining portion of the required thrust can be provided by the acceleration of fluid through engine 925, which per se can be considered to operate as a turbojet engine.

[000122] As the free stream flow velocity approaches and exceeds Mach 1, an afterburner of engine 925 can be optionally engaged to compensate for the reduction of the thrust and rate of rotation of upstream IMSA 908 in the vicinity of Mach 1 and aid engine 925 in meeting the net thrust requirement. Alternatively or concurrently, fuel can be injected and combusted within channel 853 at station 889 by the flame holder and fuel injector. As the speed is increased beyond Mach 1, the local free stream flow velocity of upstream IMSA 908 reduces, allowing the rate of rotation, and the thrust produced by upstream IMSA 908 to increase once more. At a sufficiently large speed, any fuel flow into the afterburner of engine 925 or into the interior flow at station 889 can be reduced, or stopped completely, in order to improve fuel efficiency. At such speeds, upstream IMSA 908 and engine 925 can be considered to be a turbofan engine at supercruise. During some modes of operation, this reduction of fuel flow need not occur in order to aid in the acceleration of embodiment 850. As the speed is increased further, any fuel flow into the afterburner of engine 925 or into the interior flow at station 889 can be increased. Fuel can be injected into the channel 853 by the flame holder and injector, such as flame holder 924, and combusted. The portion of channel 853 within which the interior flow remains exterior to engine 925 can thus be considered to be operated as a ramjet in this mode of operation. As the speed is increased further, the thrust produced by upstream IMSA 908 can be reduced, and upstream IMSA 908 can be feathered as well, corresponding to the configuration shown in FIG. 30.

[000123] In the aforementioned description, the acceleration from low subsonic speeds to supersonic speeds is described. Note that the wave drag associated with embodiment 850 during this acceleration is comparatively low. Not that there are other ways in which this acceleration can be carried out. For example, a shock can be allowed to form upstream of first opening 854. This shock wave can be produced by a separate, dedicated shock body such as a separate fuselage, for example. The shock wave can also be produced by appropriately reducing the cross-sectional area of channel 853 at station 890 or station 885, for example. This can reduce the mass flow rate through channel 853 and increase the thrust and rate of rotation of the rotor of upstream IMSA 919 in the vicinity of Mach 1 and at supersonic speeds compared to the scenario described above. This can incur wave drag and can contribute to noise pollution, however. The reduction in the mass flow rate through channel 853 can also increase the induced drag or induced power of embodiment 850.

[000124] FIG. **32** is a cross-sectional view of the embodiment shown in FIG. **30** for a different mode of operation. This mode of operation can be described as constant velocity climb. Note that the configuration of embodiment 850 during hovering flight is similar to the configuration shown in FIG. 32. Embodiment 850 can be described as a vertical takeoff and landing (VTOL) vehicle capable of supersonic flight.

[000125] In FIG. 32, embodiment 850 is moving relative to the stationary free stream fluid in the positive Y-direction, parallel to the Y-axis, at a subsonic speed. The direction of the free stream flow relative to embodiment 850 is indicated by arrow 958.

[000126] Dashed lines 961 and 962 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of duct apparatus 852. Streamlines 961 and 962 are therefore part of a streamsurface, or streamtube, which separate the exterior flow, i.e. the fluid flowing around duct apparatus 852, from the interior flow, i.e. fluid flowing through channel 853. In this embodiment, the steamtube is circular when viewed along the X-direction.

[000127] Upstream IMSA 908 is configured to produce thrust directed in the upstream direction, as indicated by thrust vector 955, and downstream IMSA 919 is configured to produce thrust directed in the downstream direction, as indicated by thrust vector 841. As mentioned, this can increase the mass flow rate through the channel 853 and reduce the induced drag associated with the production of thrust. Note that upstream IMSA 908 and downstream IMSA 919 produce a net thrust directed in the upstream direction, which cancels the drag force and the weight force acting on embodiment 850 during constant velocity climb.

[000128] The power consumed by the upstream IMSA 908 is provided by the power extracted by the downstream IMSA 919 from the interior flow, as well as engine 925. Said power is in this embodiment mechanically transferred to upstream IMSA 908 via the drive train comprising the drive shafts, such as drive shaft 915.

[000129] In FIG. 32, there is no fuel flow via the flame holder into the interior flow and no combustion of fuel in the interior flow apart from within the combustion chamber 940 engine 925 during subsonic, nominal, constant velocity, vertical climb. In other modes of operation, flame holder can inject and combust fuel in channel 853, similar to the operation of an afterburner. Similarly, fuel can also be injected and combusted immediately downstream of turbine 932 in engine 925.

[000130] For the mode of operation shown in FIG. 32, IMSA 892 is feathered, as described in the context of FIG. 31. Note that the IMSA 892 can be used as a control surface, or the control surface of IMSA 892 can remain active during configurations in which IMSA 892 is feathered.

[000131] During landing, embodiment 850 can deploy landing gear, and approach the ground vertically in a configuration similar to the configuration shown in FIG. 32. Takeoff and hovering flight can follow the same principles. Following takeoff, embodiment 850 can transition from the operating mode shown in FIG. 32 to the operating mode shown in FIG. 31, and subsequently to the operating mode shown in FIG. 30. The transition can be accomplished by the same mechanism used for pitch control, for instance. As mentioned, this can be carried out by control surfaces or thrust vectoring, for instance.

[000132] In some embodiments, duct apparatus 852 can comprise slots which allow flow to pass through outside surface 867 and through interior surface 868. These slots can be located downstream of constriction 951, i.e. downstream of first contraction 855 and downstream of first expansion 856, and upstream of upstream IMSA 908. In some embodiments, the slots can also pass through constriction 951, i.e. through a portion of the first compartment 880. Slots can be located upstream of constriction 952, i.e. upstream of second contraction 860 and downstream of downstream IMSA 919. In some embodiments, the slots can also pass through constriction 952, i.e. through a portion of the second compartment 882. The slots can be arranged circumferentially around the cylindrical or circular duct apparatus 852. Doors or ramps can be configured to close the slots or open the slots. These slots can be similar to the slots at the inlet of the jet engine of a Hawker Siddeley Harrier, for example. During operations at subsonic speeds, such as subsonic cruise or climb, the slots can be in an open position, allowing fluid to flow into channel 853 upstream of upstream IMSA 908, and out of channel 853 downstream of downstream IMSA 919. This can increase the mass flow rate of fluid through the upstream and downstream IMSAs. The slots can also serve to reduce flow separation at the first opening 854 and/or the second opening 862 or the first constriction 951 or the second constriction 952 by allowing flow to bypass first constriction 951 or the second constriction 952. This reduces the strength of the bound vortices associated with first constriction 951 or second constriction 952 and can reduce the amount of flow separation. At larger free stream flow velocities, such as at supersonic speeds, the slots can be closed, resulting in a configuration similar to the configuration shown in FIG. 30.

[000133] In other embodiments, other types of disturbance generating apparatuses, or a different arrangement of disturbance generating apparatuses, such as IMCAs, IMSAs, or apparatuses configured to increase or decrease the temperature of the fluid, within channel 853 can be used or employed.

[000134] For example, in other embodiments, the fuselage of embodiment 850 can be replaced by engine 925, the bulk of which can be located upstream of downstream IMSA 919 instead of downstream. Such embodiments need not comprise a wing, such as IMSA 892 of embodiment 850, and the drive train can comprise a single, straight shaft, as opposed to a series of shafts connected by universal joints, or constant velocity joints. Such embodiments can be considered to be, and operated as, a turbofan jet engines, for example.

[000135] Engine 925 can also be embedded within fuselage apparatus 869 in other variations of embodiment 850. In other words, engine 925 can be located within or enclosed by the outside surface 872 of fuselage apparatus 869, and upstream of downstream IMSA 919 and downstream of upstream IMSA 908. Engine 925 can be supplied with air via ducts which enter fuselage apparatus 869 from channel 853. Other variations of embodiment 850 don’t feature a downstream IMSA similar to downstream IMSA 919. In some embodiments, the rotors of upstream IMSA 919 can be powered by at least one electric motor, which in turn can be powered by batteries, for example.

[000136] In other embodiments, the vehicle can be configured to be able to remain substantially horizontal during takeoff, hover, or landing. In other words, the long axis can be substantially parallel to the X-axis, as shown in FIG. 30, during VTOL operations. To that end, an embodiment configured in a similar manner as embodiment 850 can feature the following modifications compared to embodiment 850.

[000137] The outside wall of the duct apparatus can feature slots which run circumferentially around duct apparatus, as described previously. The slots can be located between IMSA 908 and IMSA 919, i.e. in the vicinity of station 887. Note that the slots need to be sufficiently large to allow a sufficient fluid flow through the duct apparatus to support the weight of the duct apparatus. In other embodiments, the slots can also be described as doors to the interior or the channel 853 of the duct apparatus. In some embodiments, the slots are only located on the top portion of the duct apparatus, i.e. the portion located in the positive Y-direction, in order to prevent or reduce vortex ring state and the re-ingestion of engine exhaust by engine 925.

[000138] The direction of rotation of IMSAs 908 and 919 can be reversed compared to nominal, subsonic cruise shown in FIG. 31. This can be accomplished by a gearbox and a clutch, which are configured to be able to change the direction of rotation of the drive shafts driving IMSAs 908 and 919. If IMSA 908 or 919 is driven by an electric motor, the direction of rotation of the motor can be reversed. Furthermore, the individual blades of IMSA 908 and IMSA 919 are configured to be able to rotate about their long axis, i.e. the radially outward axis, by approximately 180 degrees. In other embodiments, the direction of rotation of the rotors of IMSA 908 and IMSA 919 does not need to be reversed during VTOL operations compared to subsonic, nominal, level cruise. For example, the airfoils of the rotors of IMSA 908 and IMSA 919 can be symmetric, or they can feature a sufficiently small camber or twist, such that the direction of the thrust vector can be reversed without changing the direction of rotation of the rotors of IMSA 908 and IMSA 919. Note that the stator vanes of each IMSA can be used to mitigate any loss of efficiency associated with operating the rotors in a manner in which the thrust is reversed compared to subsonic, nominal, level cruise.

[000139] In addition, the portion of the duct prior to the second opening 862 can be curved, and, in some cases, extended, on the order of 90 degrees. Similarly, the portion of the duct in the vicinity of the first opening 654 can be curved, and, in some cases, extended, by approximately 90 degrees. The portion of the duct in the vicinity of the first opening 854 and the portion of the duct in the vicinity of the second opening 862 can be swiveled about the roll axis of the vehicle, as well as the pitch axis of the vehicle. These swiveling portions of the duct apparatus can be configured in a similar manner as the swiveling duct downstream of the main engine of the Lockheed F-35, for example. In a different embodiment, the curving or turning portion of the wall of the nominally straight duct can be provided by the extension of ramps or buckets into the flow in order to turn or redirect the flow, similar to the buckets being used in conventional thrust reversers of jet engines. Alternatively or concurrently, flow deflecting vanes can be used to deflect the flow in the downward direction, i.e. the negative Y-direction, during nominal VTOL operations. These vanes can be reconfigured to redirect the flow in the desired direction, where the direction can have two degrees of freedom, or “DOF”, relative to the bulk of the duct apparatus, for example. These DOF can comprise a rotation of the flow exiting the duct apparatus about the pitch or roll axis of the vehicle.

[000140] During nominal hover, i.e. in the absence of disturbances, the flow enters the duct apparatus through the slots in the vicinity of station 887. The flow subsequently bifurcates and moves either towards IMSA 908 or IMSA 919. The thrust produced by IMSA 908 is directed in the positive X-direction in a scenario similar to the scene shown in FIG. 30, i.e. in an upstream direction for this hovering scenario, and the thrust produced by IMSA 919 is directed in the negative X-direction, i.e. also in an upstream direction for this hovering scenario. Subsequently to being accelerated by IMSA 919 or IMSA 908, the flow is deflected by 90 degrees from a direction substantially parallel to the X-axis to a direction substantially parallel to the Y-axis, and directed in the negative Y-direction. The plane of the second opening 862 and the first opening 854 is now no longer parallel to the YZ-plane, but parallel to the XZ-plane during nominal hover.

[000141] The power consumed during hovering is provided by engine 925 in the aforementioned embodiment. Note that such an embodiment of the invention can be capable of both vertical and horizontal VTOL operations, as described.

[000142] During hover, roll control can be provided by the stator blades of IMSA 908 or IMSA 919. Roll control can also be provided by thrust vectoring when the line of action of the net thrust vector does not pass through the center of mass. Pitch and yaw control can be provided by the swiveling of the planes of the first or second opening of the duct apparatus, i.e. by thrust vectoring, as well as the regulation of the magnitude of the thrust of IMSA 908 or IMSA 919. Position control can be provided by the net thrust of IMSA 908 and IMSA 919 as well as the thrust vectoring. Recall that the individual rotor blades of IMSA 908 and IMSA 919 can be rotated about their long axis in order to facilitate thrust control at sufficient amplitude within a sufficient time.

[000143] In other embodiments capable of horizontal VTOL operations, the flow direction compared to the aforementioned scenario can be reversed. Instead of ingesting fluid through the central slots, i.e. the slots in the vicinity of station 887, the fluid can be expelled through a series of central slots. The direction of thrust of IMSA 908 is in the negative X-direction, and the thrust of IMSA 919 is directed in the positive X-direction, which is identical to the direction of thrust during subsonic, nominal, level cruise shown in FIG. 31. This simplifies the design of IMSA 908 and IMSA 919. The slots can comprise thrust vectoring apparatuses, which can be employed to ensure stability and control of the vehicle. For example, the slots can comprise guide vanes, which a configured to control the direction of the fluid exiting the slots. The slots can be located sufficiently far apart from each other along the wall of the duct apparatus, such that sufficient pitch and yaw control authority can be facilitated. Note that such an embodiment ingests the fluid through the first opening 854 and the second opening 862, which do not require the aforementioned bends of, nominally, 90 degrees. Such bends can improve the controllability of the vehicle, however. IMSA 908 and IMSA 919 serve to increase the pressure or energize the flow at station 887, where the flow enters the inlets to the slots before exiting through the outlet of the slots in the direction determined by the guide vanes in the proximity of the outlets, where the guide vanes are controlled by the flight control computer, for example.

[000144] In some of these other embodiments, the inlet of engine 925 is located downstream of IMSA 908, but upstream of the inlets to the slots on inside surface 868. In this manner the engine does not re-ingest its own exhaust during horizontal VTOL operations.

[000145] In some of these other embodiments, the inlet of a slot is one of several openings located circumferentially on the inside surface 868 of channel 853 between IMSA 908 and IMSA 919, while the outlet of the same slot is located at one of four locations on the exterior surface 867 of the duct apparatus. The outlet of a slot is connected to the corresponding inlet via a pipe, channel, or duct which passes through the wall of the duct apparatus. Two outlets can be located at the location of the first compartment 880, and two can be located at the location of the second compartment 882. The outlets can be offset from one another in the Z-direction, and facing in the negative Y-direction in general, for the scene shown in FIG. 30. Guide vanes can be located immediately upstream of the outlets, where the guide vanes can be configured to control the flow direction of the flow exiting through the outlet. Valves within the pipes can regulate the mass flow rate of fluid through a given outlet. The inlet and the outlet of a slot can be closed by a door to ensure a smooth outside surface 867 and inside surface 868 during non-VTOL operations.

[000146] The benefit of horizontal VTOL operations can be, amongst others, the comfortable transportation of patients as well as the reduction of the wind disturbances in proximity of the ground. Such wind disturbances are often directed parallel to the ground, and the amount of drag the vehicle is subjected to due to a disturbance can be reduced by turning the vehicle into the primary direction of such wind disturbances.

[000147] In some embodiments a combustion chamber or flame holder can be located upstream of downstream IMSA 919 and downstream of upstream IMSA 908. The combustion chamber can be located at station 887, for example. In some modes of operation, channel 853 can thus be considered to be, and operated as, a turbojet engine. An additional flame holder can be located downstream of IMSA 919 and operated as an afterburner to said turbojet engine.

[000148] In some embodiments, a portion of engine 925 can be located in the section of channel 853 corresponding to the third expansion 861. This can reduce the overall length of embodiment 850, i.e. the extent of embodiment 850 along the central axis, which can reduce the overall wetted area and viscous drag. In some embodiments, this can increase the wave drag, however.

[000149] Unless specified or clear from context, the term "or" is equivalent to "and/or" throughout this paper.

[000150] The embodiments and methods described in this paper are only meant to exemplify and illustrate the principles of the invention. This invention can be carried out in several different ways and is not limited to the examples, embodiments, arrangements, configurations, or methods of operation described in this paper or depicted in the drawings. This also applies to cases where just one embodiments is described or depicted. Those skilled in the art will be able to devise numerous alternative examples, embodiments, arrangements, configurations, or methods of operation, that, while not shown or described herein, embody the principles of the invention and thus are within its spirit and scope.