

Channel Wing as a Potential VTOL/STOL Aero-Vehicle Concept

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Abstract: Low-cost, high efficiency, multi-purpose and compact aircraft capable of Vertical Takeoff and Landing (VTOL) or Short Takeoff and Landing (STOL) flight have long been desired by the aerospace community. The channel wing concept, first proposed by Willard Custer in the late 1940s', is a promising candidate for efficient V/STOL performance. A channel wing has an upwardly opening semi-cylindrical channel placed near the aircraft fuselage. A propulsion unit is mounted in the channel; usually a propeller located towards the rear. When the propeller is operated at static or low speed conditions, the speed of the air flowing through the channel is much higher than that of the air flowing below the wing. As a result, high lift is generated. The concept was brought to life in prototype airplanes manufactured by the Custer Channel Wing Corporation in the 1950s' and the 1960s', but these designs had a number of problems. The improvements in aerospace technology since then and recent developments in circulation control technology may facilitate the realization of a superior channel wing configuration. This paper presents a comprehensive review of the most significant patents on this subject and concludes with comments on possible future developments.

Keywords: Channel wing, circulation control, boundary layer removal, tilting channel & curved wing.

1. INTRODUCTION

Vertical Takeoff and Landing (VTOL) and Short Takeoff and Landing (STOL) flight has been one of the main interests of both the civilian and military aviation communities throughout the history of flight. Today, several aircraft capable of achieving V/STOL flight exist. The most common type of such aircraft is the helicopter. A fixed-wing V/STOL capable aircraft is the Harrier jet, and the V-22 is a fixed wing airplane with a turboshaft engine that can be tilted. However, despite the advantages they possess, all these aircraft have setbacks that result from their operating principles. Helicopters are limited to a certain maximum speed due to compressibility effects and drag on their rotor blades, the Harrier consumes huge amounts of fuel, and the V-22 is heavy due its mechanically complex engine arrangement. All these aircraft perform well, yet their setbacks and/or limitations result in the need for a more efficient, all-around V/STOL aircraft. One possible solution to this issue is the channel wing design, first conceived by Willard Custer during the 1940s'.

Custer proposed that it is the speed of the air flowing over the wing that creates lift, and not the speed of the wing through the air. Hence, he came up with the idea of the "channel wing". As the name implies, the channel wing contains a semi-cylindrical or U-shaped channel. The channel wing is formed by merging the channel and a fixed wing portion that extends from one side of the channel. Figure 1 shows the arrangement in Custer's final design. The channel surface is airfoiled, thus it can generate lift when air flows over it. With the placement of a propulsion system

within the channel, close to its trailing edge, air can be sucked over the channel surface. The reason for putting the propulsion system near the trailing edge is to use the maximum possible channel surface to generate lift. When the engine is running, and the aircraft is standing still or is moving with a low forward speed, the speed of the air flowing through the channel is high with respect to the speed of the air below the channel surface. Thus, a high pressure region below the channel and a low pressure region over the channel are created. Consequently, a high amount of lift is generated that could not normally be produced by a conventional wing arrangement. At high speeds, the benefit derived from using the channel is eliminated but the aircraft can continue to fly unimpeded since the projected areas of the channels and the fixed wing portions can generate enough lift.



Fig. (1). The CCW-5 channel wing aircraft designed by William Custer.

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If they achieve all the desired capabilities, channel wing airplanes could be beneficial for a number of applications. They could be used by civilians as a personal aircraft, since they require no runway or a very small one. In addition, they can fly at speeds similar to other commercial, small size aircraft like the Cessna 172. Their hovering capabilities would make them very useful for other civilian purposes like firefighting or rescue missions. Their properties described above would naturally render them quite useful to the military as well. They could be stored within a very small area, like a small pocket camouflaged by trees, and take off whenever needed. They could easily depart from carriers and conduct similar missions to the V-22, while costing much less since they would not have the mechanical complexity of said aircraft.

Custer took a number of patents on the channel wing concept. He and his company designed and produced prototype airplanes based on this design. The airplanes were effective at low speeds but a number of complications arose during cruise, high speed flight and landing. Recently, researchers from Georgia Tech proposed the idea of using pneumatic blowing slots to solve the problems of the basic channel wing design. Various modifications and solution methods have also been proposed by other inventors.

This paper analyzes the patents obtained by Custer as well as by other inventors. To the best of the authors' knowledge, the patents chosen for inclusion in this review represent the most significant patent studies related to the subject, starting with the pioneering work done by Custer, and continuing with patents that are considered worthy of mention due to their contributions to the evolution of the basic channel wing concept. To honor his historical and scientific precedence, the paper begins with patents obtained by Custer and continues with the patents of other researchers. Descriptions of each patent are provided to summarize the development of the channel wing design until our time; continued with a summary of previous articles on the subject and concluded with suggestions on possible further improvements. To the authors' knowledge, this paper is the first review article published on the subject.

2. PHYSICAL PRINCIPLE

The basic idea of the channel wing concept is to make use of the high speed of the air which flows over the channel when air is sucked over the channel via a propulsion unit. This situation is especially pronounced when the aircraft is static or it is moving at a low speed, because there is a large difference in the speed of the air which flows below and above the channel. As a result, a high amount of lift is produced, even when the aircraft is moving slowly.

3. CHANNEL WING PATENTS & ARTICLES

3.1. Patents by Custer

The aircraft design presented in Custer's first patent has a conventional fuselage with a conventional tail, and a channel wing superimposed on this structure [1]. The design can be seen in Fig. (2). A pair of propellers is located inside one channel; one fore and one aft. They're operated by the same

engine, and they have a variable pitch configuration so as to improve forward flight capabilities. The propellers could be placed behind or forward of the channel edges, as long as they are very close to the edge. This is done in order to reduce tip losses. It is also suggested that the leading edge propeller's blades feather so as to cut back on speed during landing. A way to control the feathering using the engine and/or other controls must be installed.

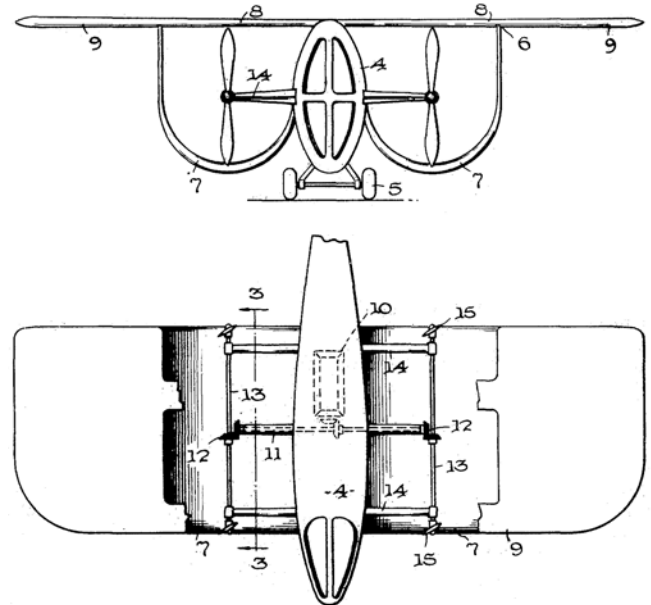


Fig. (2). Multiple propeller channel wing [1].

A design having a movable channel has also been proposed [2]. The channels are arranged such that they can be tilted (rotated about a lateral axis extending from one wing tip to the other). The channels are tilted up during take-off, and they're at a horizontal position during cruise. Vertical fins extend above the channel upper end and below the channel bottom surface. They isolate the stream within the channel (preventing outside air from entering the channel), and they contain rudders. Elevators are mounted behind the propeller discs so as to provide control and additional lift production. The propellers are located almost at the channel trailing edge; this is done in order to stop air flowing below the channel surface from entering the channel stream, and make maximum use of the lift generated by the channel. The aircraft's fuselage is rather short because the author believes sufficient control is attained using the tail rudder and the rudders situated on the fins. The control surfaces and tilting channels are controlled via conventional methods through the cockpit. It is stated that good results in terms of lift production have been obtained when the propellers are operated at 4000 revolutions per minute (rpms). This patent is the first to mention that the propellers on either side of the fuselage rotate in opposite directions.

A design based on a tailless fuselage employs the channel wing concept so as to increase the overall efficiency of the aircraft, as seen in Fig. (3) [3]. Experiments have proven that this type of construction is indeed beneficial. Further goals are to increase the static and in-flight lift. The best results in

lift production have been obtained with a channel chord smaller than the propeller radius, and when the propeller is placed very close to the rear end of the channel. This situation becomes more pronounced when the distance between the propeller disk and the rear end is about 1.27 centimeters. It is noted that a 50% increase in lift is obtained under static conditions and an important increase in in-flight lift is attained. The channel may merge with the wing at the leading edge, or extend beyond it if desired. Since there is no conventional tail on the airplane, in order to control it, it is suggested to add a rudder to the rear part of the engine, and to put ailerons and elevators on the wing.

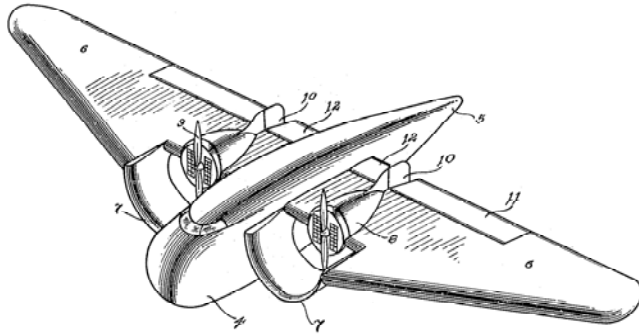


Fig. (3). Tailless channel wing design [3].

Custer obtained a patent for a modified version of the conventional fuselage, tail and channel wing combination in 1950 [4]. In this design, rudder-like devices can be attached to the fins that extend rearward from the side-walls of the channel. Two plates that connect the fuselage and the outboard wing portion extend over the channel, and they act as spars. The inner ailerons seen in Fig. (4), are used in moderate to low speed range operations, whereas the outboard ones are used when the aircraft is approaching the runway and is in need of excessive lift. As a modification to the previous conclusion about the propeller disk – trailing edge gap, it is noted that this distance should be less than 1/6 of the propeller diameter. The depth of the channel should be almost constant when viewed from the front to the rear edge. The thickness of the airfoil is high at the mid portion of the channel, and it gradually decreases towards the side walls.

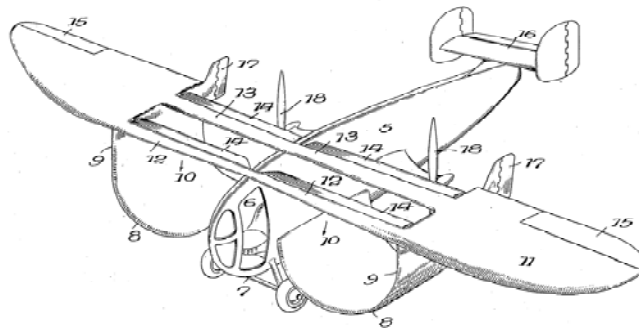


Fig. (4). Conventional fuselage, tail and channel wing combination [4].

Changing the tail arrangement to a single-vertical tail and modifying the channel setup so that the channel only extends up to 50% of the wing chord, Custer proposes another design as seen in Fig. (5) [5]. This is done in order improve the low-speed lift production capabilities of the aircraft without compromising forward flight performance. The chord of the channel is approximately equal to half of the propeller diameter. A different version of the design, seen in Fig. (6), uses a single channel located at the mid portion of the wings. An engine located inside the fuselage drives a propeller which is located at the rear edge of the fuselage. Fins which are similar in construction to the ones described in previous patents protrude upwards of the channel sides, and they extend backwards along the aircraft's longitudinal axis in order to support a boom-tail structure. The rest of the aircraft's operational principles are similar to the first design.

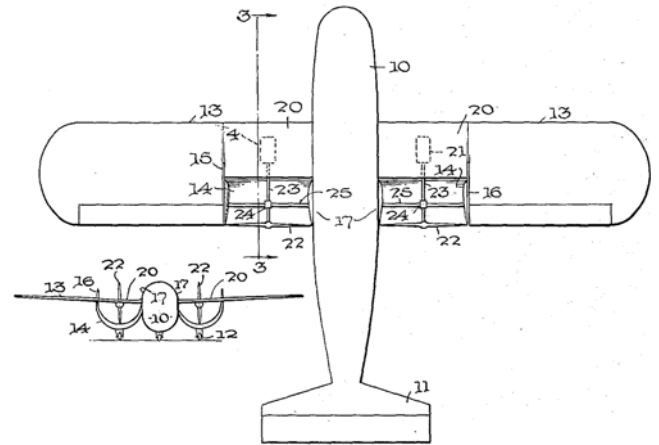


Fig. (5). Channel wing airplane [5].

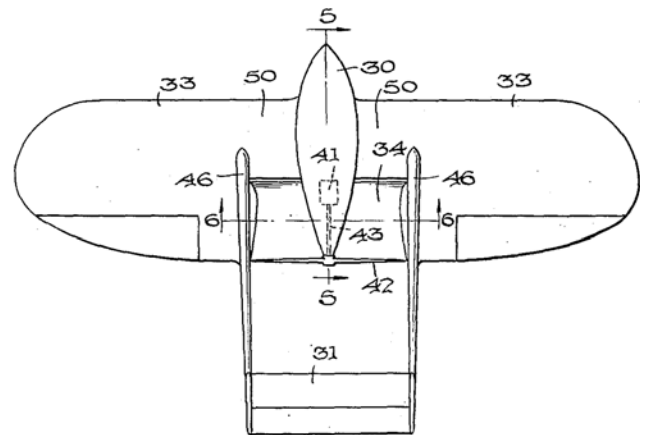


Fig. (6). Boom-tail arrangement [5].

Boundary layer removal (BLR) can be extremely beneficial for aircraft, especially if turbulent conditions occur over the aircraft's wings. Custer patented an interesting system that achieved this by using the flow conditions just before and after the propeller slipstream, as seen in Fig. (7) & Fig. (8) [6]. BLR slots are located behind the maximum thickness point of the airfoil. This helps the process because

air pressure increases over the airfoil surface when air proceeds rearwards of that point. Two such slots extend over the top of the wing. When the propeller is operated in the channel, a low-pressure zone which draws the air (or boundary layer) from the slots through the conduits is created. The air drawn is exhausted from openings located just in front of the propeller disc. The air which passes over the openings of the ducts which are radially positioned on the channel surface, behind the propeller disk, creates a low pressure at that region. As an additional BLR operation, air is drawn from the secondary slots located aft of the primary slots, into the conduits; then it is exhausted via the ducts. The openings of the ducts have a triangular cross-sectional shape which forces the flow to proceed rearward. The channels have the previously mentioned vertical fins installed at their sides so as to prevent the air flowing over the outboard wings to mix with the channel flow.

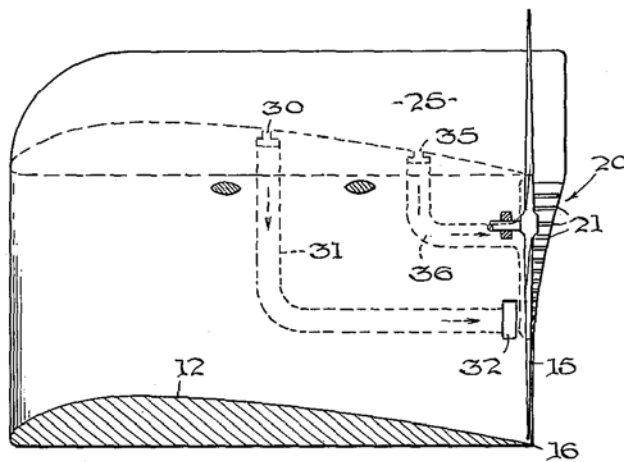


Fig. (7). Isometric view of the BLR system [6].

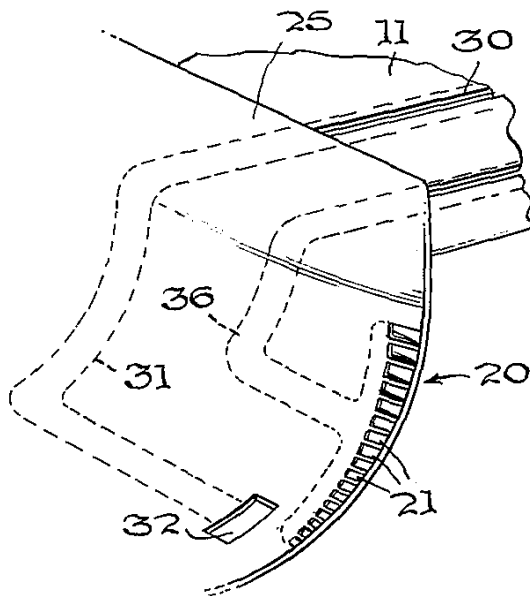


Fig. (8). Rear view of the BLR system [6].

Another idea developed by Custer is to use an aircraft having multiple channels placed in tandem on their wings, as seen in Fig. (9) & Fig. (10) [7]. This configuration produces large increases in lift production, when compared to the classical channel wing configuration with a single channel placed on either side of the fuselage. Custer mentions that this conclusion has been drawn from experiments. The design comprises of a fuselage and tail of conventional construction. The wings are also similar to previous Custer designs; however, this time there are multiple (a pair of) channels placed on either side of the fuselage. Ailerons are mounted on the fuselage between the channels to further increase the amount of lift produced by the channels. Additional control surfaces are placed on the tail and outboard wings. A pair of propellers is driven by a single engine mounted on the aircraft.

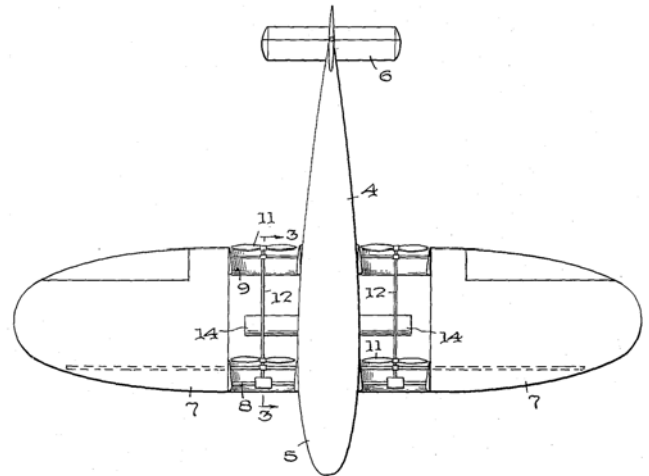


Fig. (9). Top view of the multiple channel wing design [7].

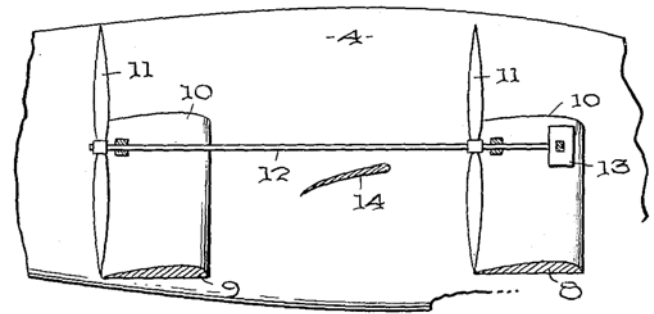


Fig. (10). Side/isometric view of the pair of channels [7].

Custer obtained a patent for a modified version of his basic design in which the fuselage, tail and channel wing arrangements are all the same; however, the outboard wing extending laterally from the channel outer wall is now made movable, for extended lift and control purposes [8]. Fig. (11) & Fig. (12) depict this concept. The movable wing is connected with a shaft which originates from inside the fuselage, continues through the channel and connects with the movable wing. The shaft supports the wing and controls its rotation. The control mechanism for the movable wing is a conventional one and it is situated inside the cockpit.

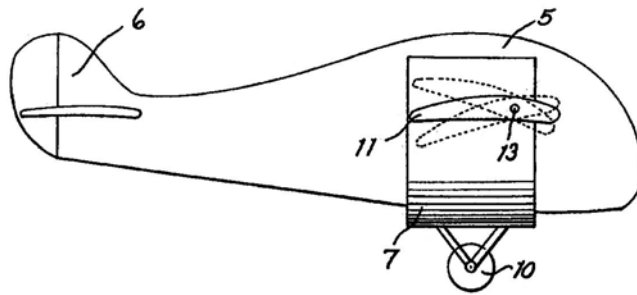


Fig. (11). Side view of the movable wing and the aircraft using such a system [8].

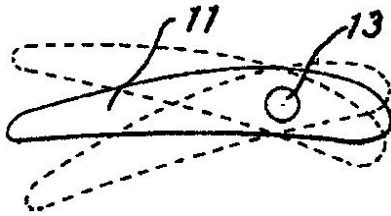


Fig. (12). Close-up view of the movable wing [8].

Custer's first channel wing patent which involves jet propulsion was obtained in 1952 [9]. Fig. (13) shows this jet aircraft design. The upwardly opening semi-cylindrical channel increases the take-off and landing stability of jet aircraft by making use of the increased lift capabilities of the channel wing. Decreasing the take-off/landing distance is also one of the goals of the design.

At takeoff, a jet aircraft which is of conventional design is oriented nose-up into the air, and it is not propelled in a direction parallel to the ground. As a result, the engine does not have sufficient mass inflow. This mass flow shortage results from the fact that most of the air travels over the engine nacelle (cowling), instead of flowing in through the inlet. By using a channel wing, more mass flow is directed into the engine and this liability is corrected. Furthermore, the conventional aircraft is unstable at takeoff & landing because it relies on the engine thrust for stability. That is to say, the engine must provide high thrust and make the aircraft reach a high speed in a short time period. The high speed is necessary for producing lift because the wings' airfoils are of thin design, in order to create low drag at high speeds. If it cannot attain the necessary speed, it might overshoot the runway or crash. The channel wing concept provides extra lift at low speeds which alleviates the issue just stated, because the aircraft can now generate high lift despite its thin airfoil.

The basic design consists of jet engines mounted on the middle of the channels, where the channels are similar to the ones used in previous patents. As before, wing portions that extend laterally outward from the channels are present. Three modifications to the basic setup are also presented: The first one has ducts placed at the middle of the channel. The duct extends from the fore end of the channel to its aft end. A motor is mounted inside each duct, and said motors provide mass inflow through the duct and channel. The second

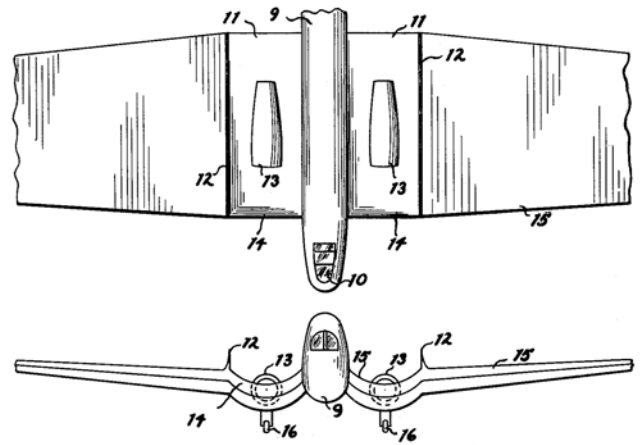


Fig. (13). Top and front views of the basic jet-propelled design [9].

design consists of a tubular fuselage having a channel inlet and channel exit. The jet tube contains a motor mounted inside. The third alternative has two tubes connected to the fuselage. The fore and aft portions of the tube are open so as to have the form of a channel. The jet tube has a motor mounted inside, and said tube has the classical curvature of a jet engine.

Another method is to place the jet engines near the leading edge [10]. This way, the high exit velocity of the jet engine flows over the entire channel surface and the aircraft makes maximum use of the channel wing concept. Fig. (14) depicts said concept.

Multiple ramjets or jets can be placed within the channel at the middle [10]. The jets could also be embedded in the channel structure, with their intakes located at the channel leading edge, as seen in Fig. (15). The multiple-jet concept can also be used with a flying-wing type arrangement. All these designs contain the vertical fins to isolate the channel flow. Note that the vertical plates designated as 42 seen in Fig. (14), form a rectangular channel which is the channel of the flying wing design.

The concept can be applied to missiles and rockets as well.

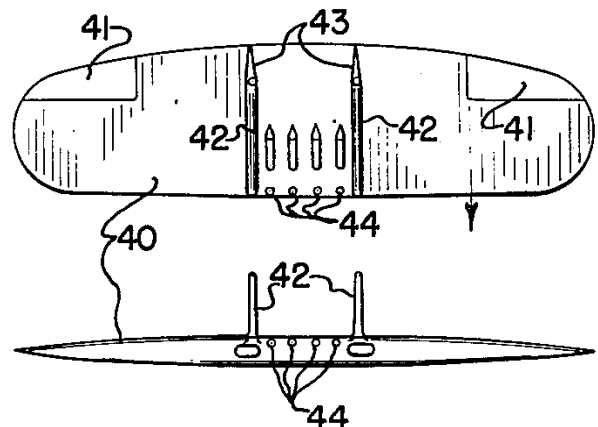


Fig. (14). Multiple jets used with a flying-wing like design [10].

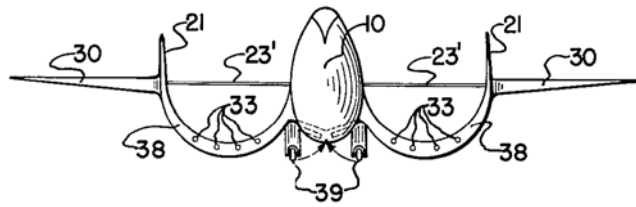


Fig. (15). Jets embedded within the channel airfoil [10].

Custer describes further details of his jet propelled channel designs in two additional patents [11, 12].

A very clever method to stabilize the channel wing aircraft if one of the channels undergoes a decrease in lift or total loss of power during flight is obtained by establishing communication between the channels [13]. This communication is achieved with the help of the tubes as shown in Fig. (16). The slots which are situated over the inner surface of the channel are connected with the tubes. When a pressure difference between the channels occurs, the valve designated as 14 which is placed inside the box designated as 12 in Fig. (17) shifts laterally so as to establish flow between the operational and non-operational channel. Thus, the aircraft can still be controlled and can still continue its lift production. When the balance is re-established, the valve returns to its original vertical position. The box is situated inside the fuselage midway between the channels. The valve is balanced by a spring.

This arrangement can also be used to generate unequal lift and/or thrust on either side of the aircraft. If the conventional control surfaces are not adequate to perform a move or to control the aircraft under a certain condition, the pressure balancing system can be used to perform these operations.

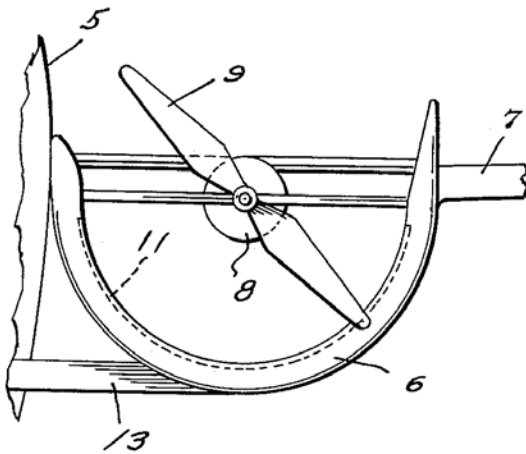


Fig. (16). The rear view of a connecting tube and channel [13].

Custer's 1964 patent focuses on a propeller tip spacing mechanism that will provide increased thrust and/or boundary layer control [14]. Custer has 3 alternative concepts that will deal with the issue at hand, which can be seen in Figs. (18), (19) & (20):

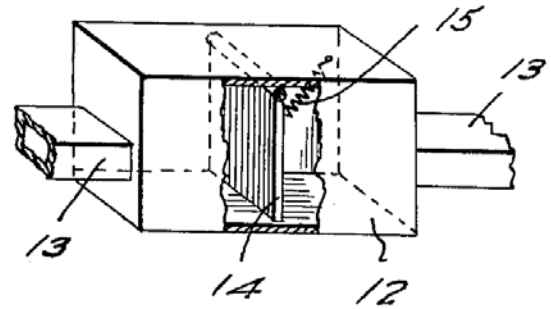


Fig. (17). The pressure balancing system [13].

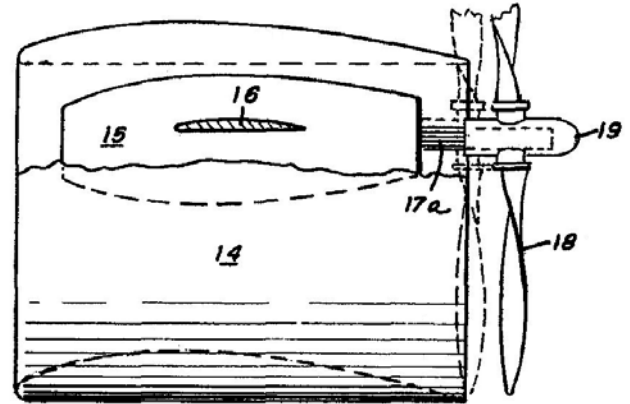


Fig. (18). The first concept [14].

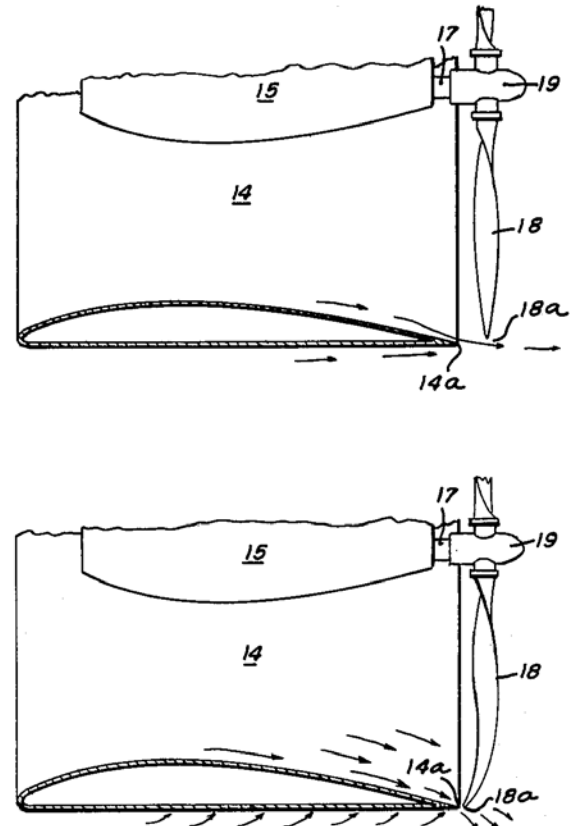


Fig. (19). The second concept [14].

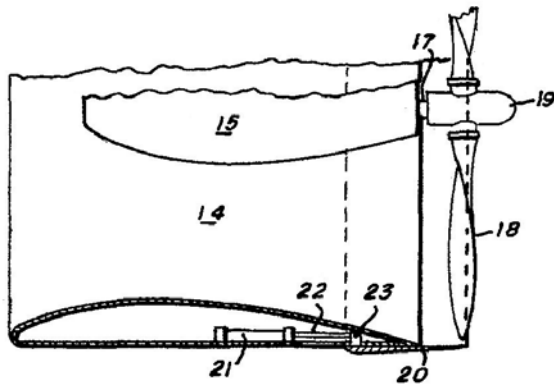


Fig. (20). The third concept [14].

The first one uses a shifting propeller design. That is to say, the propeller which is concentrically mounted on the shaft is shifted fore and aft by means of a mechanism (automatic or hydraulic control). When high thrust and lift are necessary, such as in take-off and landing, the gap between the propeller disk and channel trailing edge is very small and the propeller tip is kept very close to the trailing edge. During cruise, the propeller is shifted outwards to provide boundary layer control. The propeller is made up of stiff material.

The second and equally elaborate way of achieving this result is to employ a flexible propeller whose tips will approach the channel trailing edge at high lift requiring conditions. Since the suction is quite high at such conditions, the centrifugal force can not straighten out the tip of the propeller. As the rpm of the propeller is decreased, the tips gradually move away from the channel trailing edge. The flexible propeller should be constructed from flexible material like laminated wood or plastic. If this method is employed, the stiffness of the propeller should be scientifically arranged from 50% radius to the tip such that the flexibility just described could be achieved. Around 113 km/h, the tips usually assume their normal position with respect to the channel and propeller shaft. The propeller directs air flow effectively around 2400 rpm so as to provide boundary layer control. It is also noted that a gradual decrease in chord length as one proceeds from the 25% radius to the tip will help to prevent stall. In addition, the pitch of each section should decrease at a certain rate when one proceeds from the 25% station to the tip. The airfoil of each section should be chosen accordingly.

A third alternative is to use a mechanism mounted at the channel surface which is connected to the propeller tip. This mechanism will move the propeller tip longitudinally in order to deflect it; eventually, the flexibility principle previously described for the second alternative will be obtained.

Custer patented an exhaust stack addition/improvement to his designs in 1972, as seen in Fig. (21) & Fig. (22) [15]. The basic idea of the design is to close the gap between the exhaust of the jet engine and the channel surface in order to maximize the lift produced by the channel. This is done by placing the discharge side of the engine's contoured exhaust stack within that gap. The hot and fast exhaust air is being

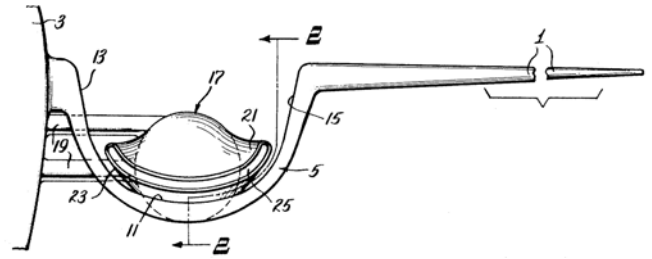


Fig. (21). Rear view of the contoured stack arrangement [15].

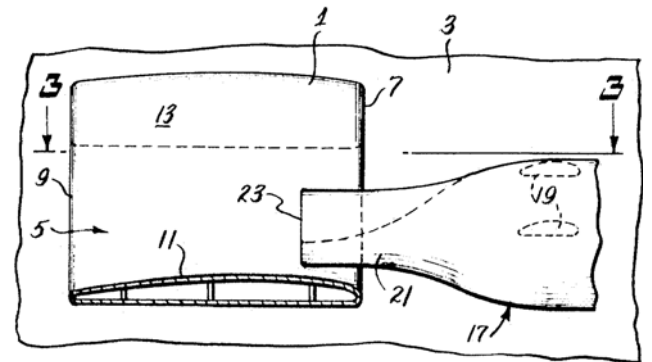


Fig. (22). Top/isometric view of the contoured stack arrangement [15].

directed in a parallel and flat manner over the channel-shaped exhaust stack, and then over the channel. Consequently, additional lift is generated.

The exhaust stack is contoured such that it is elongated, flattened and has the shape of a channel. It is placed slightly above the leading edge of the channel. In the case of a U-shaped channel, the exhaust stack and the channel surfaces trace the same curved path. In the case of a rectangular shaped channel, the contoured stack and channel bottom surface are not parallel, yet the plane passing from the bottom point of the stack and channel bottom surface are parallel.

The design has various configurations. The exhaust of the engine might be placed slightly after or slightly before (longitudinally) the channel leading edge. The exact location of the engine exhaust placement depends on the engine exhaust air and flame properties, as well as on aircraft size/mission requirements.

When the propeller is rotated at high speeds, during take-off and landing for example, very low pressure is created just ahead of the propeller tip. This causes a large amount of air spillback into the channel and a consequent decrease in lift production. Thus, using a small tip gap (distance between the propeller tip and channel surface) is essential. In his 1972 and final patent, Custer introduces the idea of using a film of water flowing over the channel surface in order to seal that gap when necessary, as seen in Fig. (23) [16]. Air compressors (most likely those belonging to the engines) induce compressed air into the water storage tank through connector lines (pipes). Then, water is discharged through discharge

lines which are situated at the bottom portion of the tank. A two-way valve is the junction point for the discharge lines and the lines leading to the discharge manifolds. This valve dictates the water flow. The manifolds, designated as 24 in Fig. (24), transmit the water to jet tubes which are situated near the leading edge of the channel. The jet tubes direct water flow over the channel surface. The water evaporates once it passes the propeller tip.

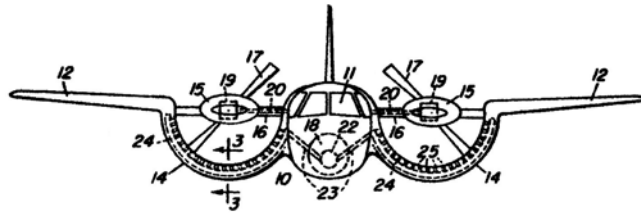


Fig. (23). Front view of a channel wing aircraft using the film of water jets to seal the tip gap [16].

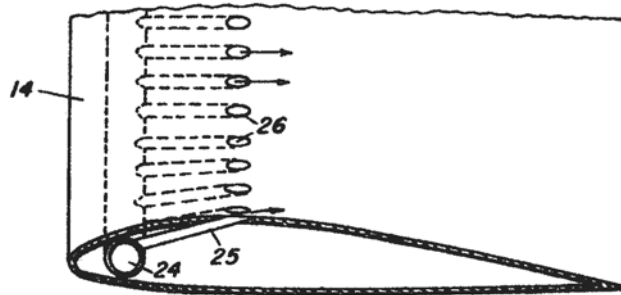


Fig. (24). Water jets placed near the leading edge [16].

3.2. Patents by other inventors

The first patent including the channel wing concept obtained by someone else than Custer is Taylor's 1954 patent, which is visualized by Fig. (25) & Fig. (26) [17]. This invention incorporates the channel wing concept with a movable system so as to change the direction of the lift/thrust vectors as well as the orientation of the aircraft. Two variations are presented, where the first one is an aircraft having a quasi-conventional fuselage mounted with a channel on top, and ailerons on the side of the channel. A rocker arm connects the control command and the propeller mount system. The propeller mount system's orientation can be modified with the use of the rocker arm, and this motion will help to modify the lift/thrust capabilities of the aircraft. The propeller mount can be tilted up and down, as well as right and left. Therefore, it can be rotated in a 2D sense. The aircraft relies almost solely on the channel for lifting purposes, with the addition of small contributions by the front portion of the fuselage and the ailerons. This design requires the careful arrangement of the aircraft's center of gravity in order to have a stable aircraft.

The second design has a conventional fuselage and wing combination. The wings are notched at their trailing edges. The notches house a channel plus propeller system which can be rotated in a 2D sense, so as to vector the thrust and modify the orientation of the aircraft.

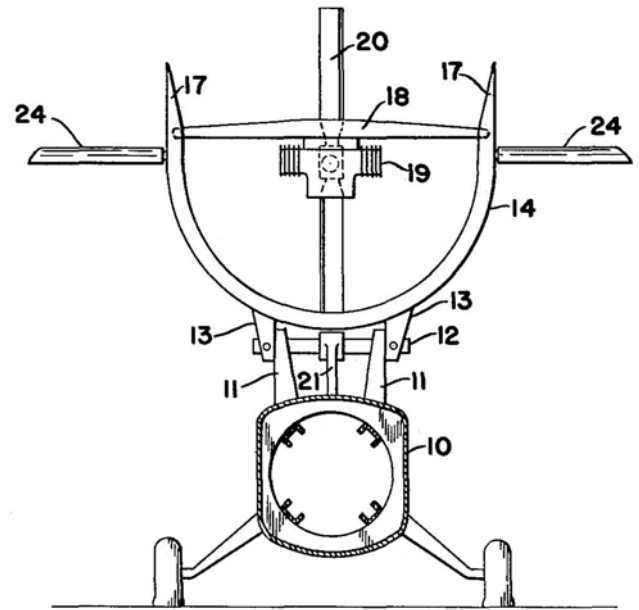


Fig. (25). Taylor's top mounted channel design [17].

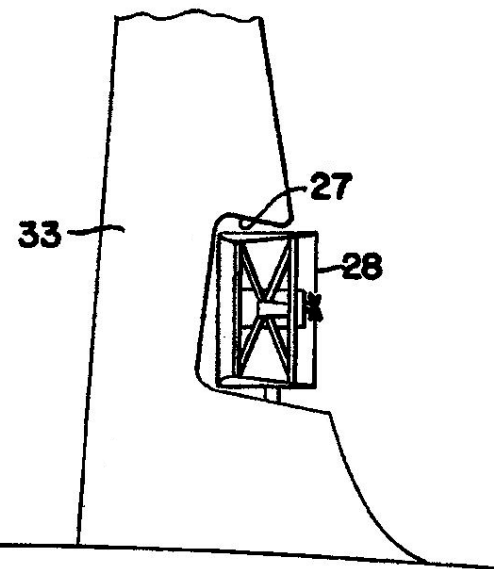


Fig. (26). Taylor's notched-channel design [17].

Fletcher's 1954 design consists of an aircraft having a conventional fuselage and a pair of wings, mounted with 4 tilting channels at the end of the wings, as seen in Fig. (27) & Fig. (28) [18]. This patent contains an effective merge of some of Custer and Taylor's ideas. The channels contain a turbo-prop engine. The channels are tilted in combination accordingly so that the lateral components of the lift and thrust vectors eliminate each other, and they provide a net force which points upward, for hover or vertical climb/descent situations. As the aircraft transits into forward flight, the channels are tilted increasingly forward. In other words, they have a near zero angle of attack. Note that the drag must also be accounted for while performing these maneuvers.

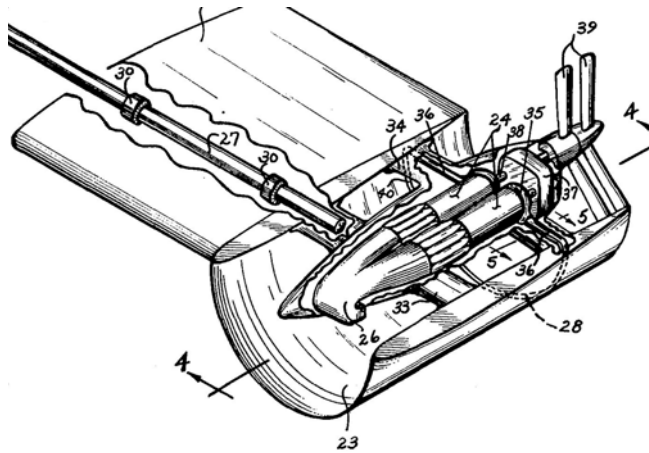


Fig. (27). Fletcher's BLR design [18].

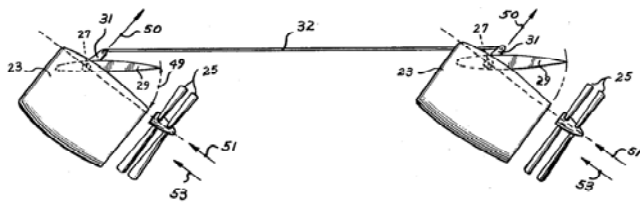


Fig. (28). The tilting channel arrangement used by Fletcher [18].

The novel issue that the inventor sets forth is to use the turbo-prop engine's compressor as a high pressure pump to suck the boundary layer air (BLR) from the surface of the channel. BLR ducts which are placed near the trailing edge are connected to conduits which transport the air flow to the compressor. This action not only increases efficiency by preventing boundary layer induced separation, but it also increases lift because mass flow rate through the engine is increased.

A modified version of the design has a second BLR stage, in addition to the system described for the basic design. The channel surface contains orifices near the trailing edge, and these are connected to a series of holes placed near the channel leading edge via a conduit. The engine exhaust gases are ejected towards the trailing edge orifices; the engine exhaust is bent so as to achieve this. These gases provide a low pressure zone while they pass over the orifices, and the boundary layer which forms over the holes are sucked through the conduit. Thus, a secondary BLR operation is conducted. Note that directing the engine exhaust within the channel increases the thrust.

Shew's 1960 patent incorporates two channels with a flying wing type surface [19]. The channels are placed at the front of the fuselage, as seen in Fig. (29). They are supported by side plates, which are placed on either side of the fuselage and extend along the entire length of the aircraft. The design has various control surfaces such as flaps and air brakes. There also are slots placed on the underside of the wing. These slots deflect the airflow to create high lift generating conditions. The plates also serve to constrain the high speed airflow over the wing.

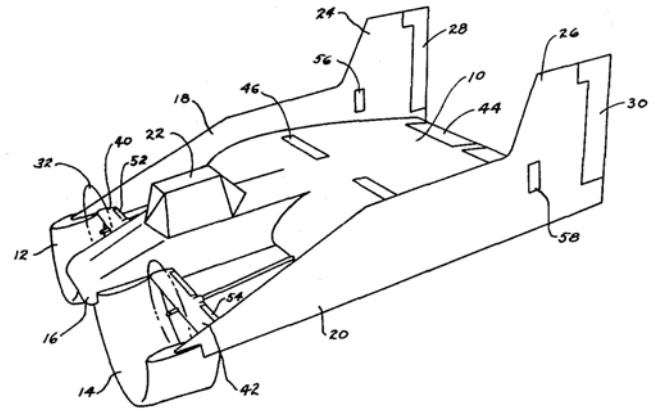


Fig. (29). Shew's design [19].

Taylor obtained a patent in 1960 which includes improvements to his previous patent as well as novel ideas [20]. Fig. (30), (31) & (32) contain details related to this patent. The basic aircraft design used has a cockpit/fuselage portion at the front; attached to the lower side of the nose is the frontal landing gear. A swept back conventional wing is superposed on the fuselage, towards the rear. A channel wing portion is mounted on the middle of the wing, towards the rear. The channel's lower surface smoothly blends with the airfoil structure of the wing. This provides an undisturbed lifting section. A propulsion means is mounted inside the channel. The aircraft described does not have a tail, therefore the center of gravity of the channel wing must be placed forward of the c.g. of the wing section in order to provide longitudinal stability to the aircraft. Vertical parts extend from the tips of the wings. The channel is of U shape, however rectangular channels are also proposed throughout the patent file. The wing might have a dihedral angle or it might be straight. The patent also describes various methods on how to increase the lift-production performance of the aircraft via several additions/modifications to the channel wing assembly. The channel could either be stationary, or it could be tilted upon will so as to increase lift to a further extent. In this case, the bottom portion of the channel will act as a flap. The author proposes 3 different flap designs: The first one is connected to the main wing via a linkage situated at the bottom of the wing section. The second one is connected at the mid-height of the airfoil. The third flap comprises a slot-type flap, which is more productive in terms of lift thanks to the smooth surface it provides after the tilting of the wing.

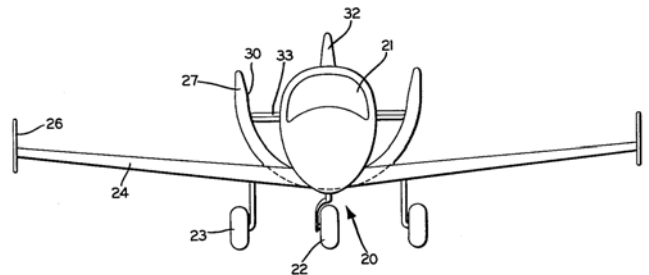


Fig. (30). Taylor's 1960 design [20].

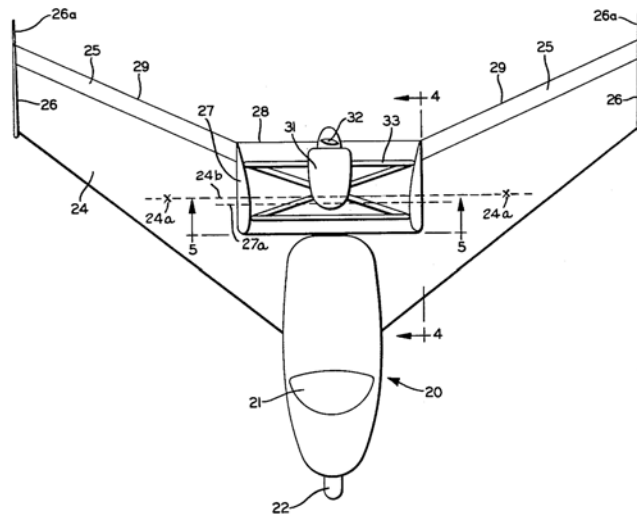


Fig. (31). Top view of the aircraft seen in Fig. (30). [20].

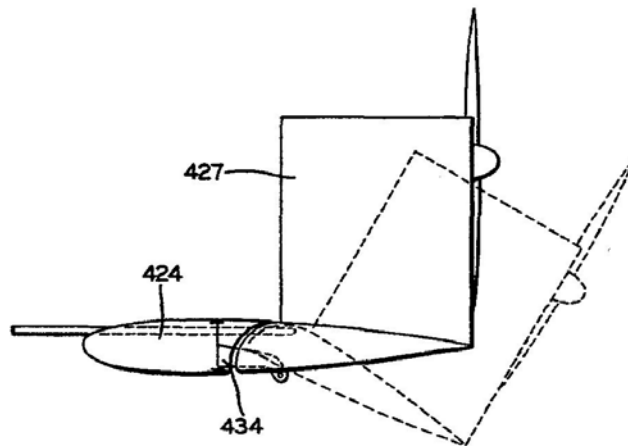


Fig. (32). One of Taylor's tilting channel arrangements [20].

Taylor proposes another design which comprises of a jet engine combined with a folding, rectangular channel wing. When extra lift is needed, parts on either side of a piece situated behind the wing section fold up, and form a rectangular channel combined with the lower portion. They can be folded back down when the extra lift is unnecessary. The rear end of the jet engine is of telescoping type so that it flexes and extends to maintain contact between the surface and the air flow.

Similar to his 1960 patent, Shew's 1963 patent comprises of two channel wing structures placed at the front of the aircraft, as seen in Fig. (33) [21]. Two wings making up a bi-plane combination are situated at the back of the cockpit. Two vertical plates, or booms, extend from the channel wing portions all the way to two vertical stabilizers at the back, and all the aircraft structure is confined in between these booms. The booms support the aircraft structurally and also prevent the airflow generated by the propellers from being propagated into the free-stream flow. The vertical stabilizers have airbrakes situated right in front of them. These airbrakes reverse the airflow so as to slow down the aircraft in situations where low speed is of the essence. The wings

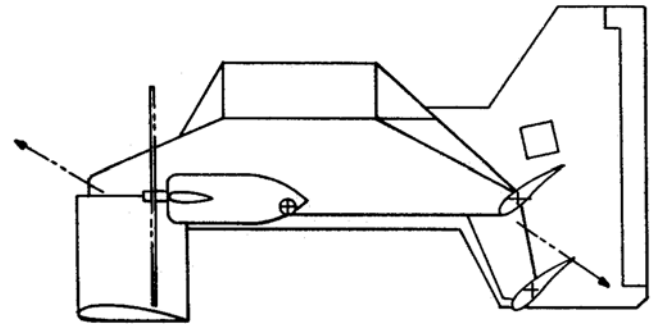


Fig. (33). The wings are tilted downwards to keep the tail at a low angle of attack [21].

can be rotated about a lateral axis so as to increase lift when necessary. If they're both tilted downwards at a positive angle of attack, the lower one is usually at a higher incidence than the upper one. Or they can both be tilted upwards to counteract the vector produced by the channels and airfoiled support struts, in order to take-off with a high angle of attack to create high lift during take-off.

Spence's 1970 invention consists of an improvement in the cross-sectional profile of curved wings, especially of a semi-circular wing like the Custer channel wing [22]. Fig. (34) depicts the proposed cross-section. The lift generated by the classical channel wing cross section creates induced drag, and the resultant of the forces generated by the channel has a drag component. This situation is especially significant near the vertical sections of the channel, because they contribute little to the lift and still produce drag, as opposed to the central sections of the channel. It is suggested to use a crescent-like thickness profile for the channel, unlike the regular channel wing design which has a less varying thickness profile as one proceeded towards the channel sides. Decreasing the thickness reduces the drag created by the vertical sections, and the author increases the incidence of the decreased-thickness sections in order to preserve the lift-production capabilities of the channel.

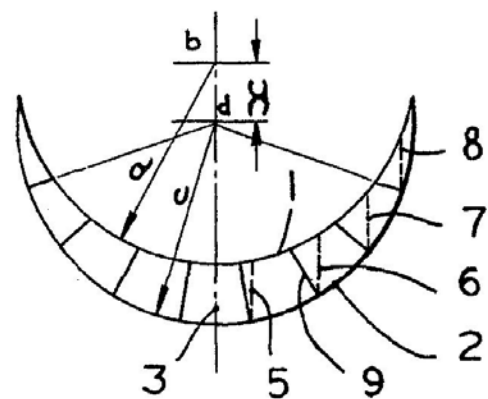


Fig. (34). Crescent shaped channel cross section [22].

De Angelis' 1988 patent comprises of an aircraft design which uses a semi-venturi shaped channel fuselage to generate lift, as seen in Fig. (35) & Fig. (36) [23]. It derives

its name from the varying the cross section of the channel in the longitudinal direction; that is to say, its shape changes as seen from the top and front. The inventor claims that the semi-venturi shaped channel accelerates the air more and creates better V/STOL flight conditions, compared to the classic channel wing configuration.

The surface of the channel is airfoiled. Air is sucked through the channel by means of a set of propellers. A propeller and engine combination is mounted at the rear, as well as a two propeller plus engine combination situated at the front. This setup has been described as the preferred type of the design; however, a single propeller or jet engine driven channel aircraft design is also proposed.

A canard system is attached to the front of the aircraft. It generates some amount of lift in addition to providing control with the flaps/ailerons situated on it. The cross section of the channel fuselage changes along the length of the fuselage. It decreases until the mid portion of the channel where it has a semi-circular profile, and then it increases until the end of the channel. Rudders are provided at the rear end of the channel side surfaces to provide yaw control.

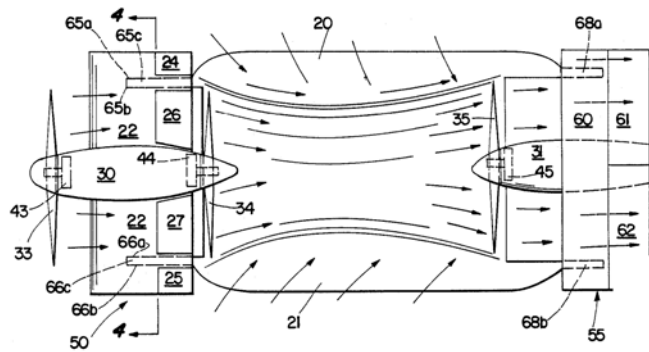


Fig. (35). Top view of the semi-venturi shaped channel [23].

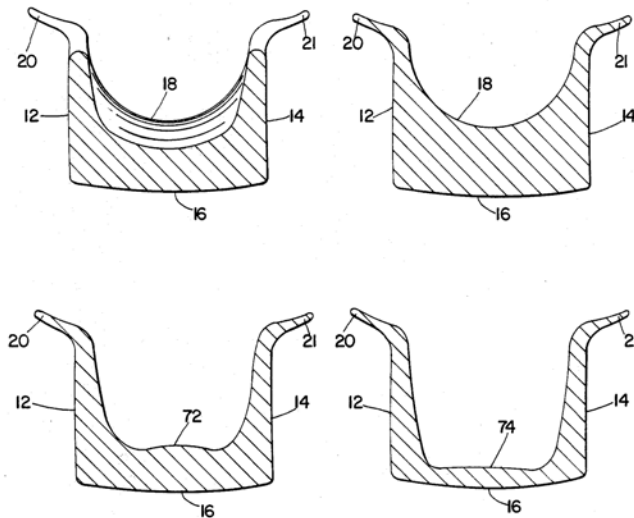


Fig. (36). Various cross sections of the semi-venturi channel [23].

Skoglun's 1997 patent describes an engine tilting system which would increase the lift production up to more than

100% by tilting the engine plus propeller combination downwards on a classical channel wing aircraft [24]. Figs. (37), (38) & (39) show views from the proposed design. The reason for tilting the propeller in such a way is to provide increased mass flow into the channel. The main point to pay attention is to never let the lowest point of the propeller disk exceed the trailing edge of the channel.

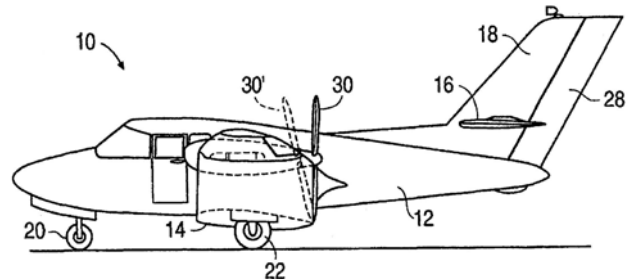


Fig. (37). The result of the tilting action [24].

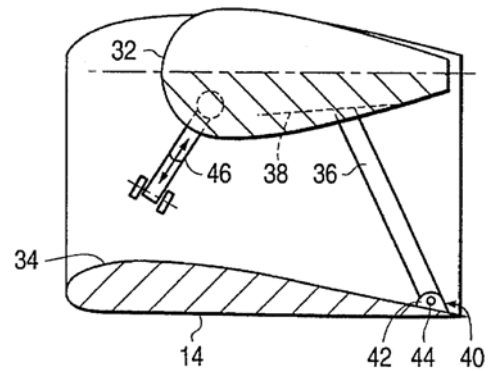


Fig. (38). Side view of the actuator plus strut system [24].

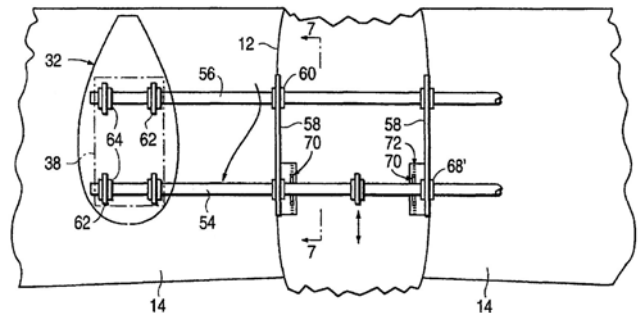


Fig. (39). Top view of the shafts used in the second design [24].

Skoglun describes three tilting device alternatives: The first one consists of a linear actuator and connecting strut working in combination. One end of the strut is connected to an engine mount bed; the other is connected to a pivot situated on the channel surface. The system is actuated by the linear actuators which are in contact with the engine and channel surfaces. A possible actuator type is the hydraulic cylinder. The wing structure is supported by spars that originate from the fuselage.

The second device uses an assembly of shafts that extend from the channel inner surface which is tangent to the fuselage, to the engine cowling. Nylon bushes which are situated at the contact points rotate with the shafts. Curved cam slots are placed on either end of the shafts. The shafts' end points trace these slots. The rear slot is shorter than the forward slot so as to make the engines' fore and aft ends tilt at an equal angle.

The third alternative is similar to the second one except for the fact that the shafts extend all the way through the engine to the other side-surface of the channel in this design. The rod-nylon bush-cam assembly is similar to the second design.

Englar and Bushnell's 2006 patent consists of a blown circulation control system that will increase the lift produced by the channel wing configuration, in addition to providing better control at low speeds and high angles of attack [25]. This design might help with solving a number of issues related to the channel wing. Figs. (40), (41) & (42) depict some of the crucial aspects of the design.

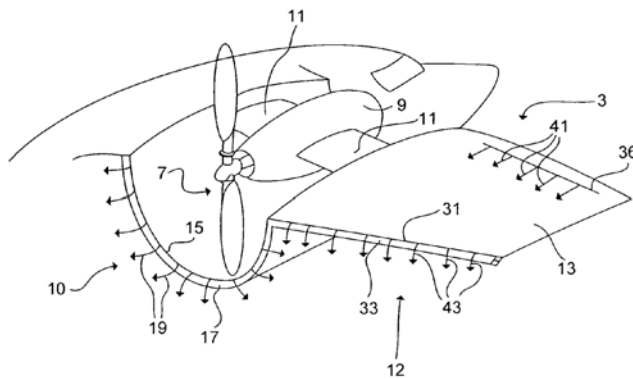


Fig. (40). The discharge mechanisms on the channel and wing [25].

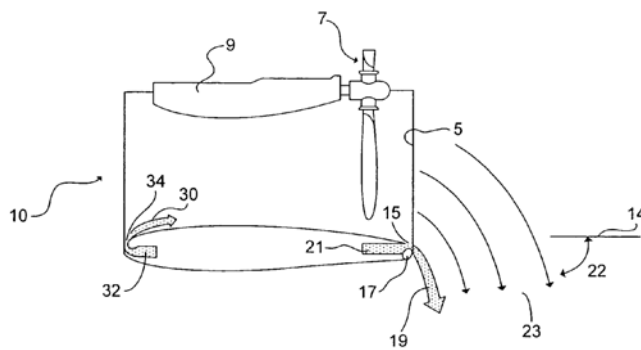


Fig. (41). Side view of the channel using the circulation control technology [25].

The blown circulation control system comprises of leading and trailing edge slots situated in the channel and on the wing. The trailing edges of the wing and the channel are rounded so as to make way for the Coanda effect, whereas the trailing edges of Custer's designs were sharp. The speed of the discharge air reduces the static pressure at the discharge location, and the fluid compensates for this change

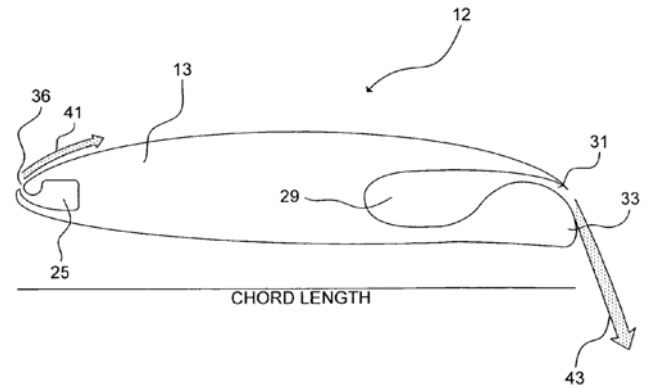


Fig. (42). Side view of an airfoil cross section and the slots [25].

by obeying centrifugal forces. In other words, the fluid traces the surface of the smooth, round trailing edge. This is the essence of the blown circulation control operation.

The trailing edge slots inside the channel draw pressurized air from a source within the aircraft's structure. The air discharged from these slots follow the rounded trailing edges, obeying the Coanda effect. The thrust stream is deflected downwards when it comes into contact with the discharge air from the slots. This is due to the thrust stream being at a higher pressure than the pressurized discharge from the slots. The blown circulation control system thus augments lift via thrust deflection as well as circulation control. Both phenomena are independent of angle of attack. As a result, the production of asymmetric moments, stall problems and the separation of channel flow of the classical channel wing design are eliminated, and the thrust vector is tilted upwards without giving a huge angle of attack to the aircraft.

The slots provide a thrust deflection of up to 85 degrees with respect to the horizontal at their normal operation rate. Via a control mechanism which changes the pressure of the discharge air (or blowing rate), the deflection angle can go up to 90 degrees. If it is further increased, it can even be around 165 degrees which means that the thrust can almost be reversed. This means that vertical thrust and slow approach speed goals can be achieved, without operating any moving parts.

The leading edge slots operate in a similar air discharging fashion, where their discharge provides attached flow over the channel upper surface, all the way to the trailing edge. Furthermore, it nullifies the nose-down pitching moment generated by the trailing edge discharge by providing a nose-up pitching moment.

The slots on the wings work in a similar fashion. They provide additional lift and control moments which ease the operational conditions of the aircraft.

An alternative version of the trailing edge slots contains a flap attached to the exit of the slot to provide more thrust deflection. It also increases drag in order to give the aircraft a slower approach speed (Super STOL approach).

The slots of the channel and wing can be continuous; that is to say, they can extend from the root to the tip of the entire

wing. Or, they can be in the form of multiple slots, separate from each other. The slots are designed to be controlled independently of each other and operated at the same time to provide a number of control alternatives.

The patent places the propeller to about 60 -70% of the chord length, unlike Custer's designs. Such a configuration silences the sound of the propeller more, and is safer for people who come close to the aircraft.

3.3. Channel Wing Articles

The literature review carried out for articles on the channel wing system has revealed that there are very few academic studies conducted on this subject. Thus, it is very difficult to find analytical information on how effective the concept is in actual practice.

The first and most comprehensive of the published articles is the National Advisory Committee for Aeronautics (NACA) report of 1953 [26]. This study was conducted on models constructed using Custer's first patents. Static tests showed that the resultant vector of the propeller thrust and channel lift was inclined 23 degrees upwards from the propeller axis. This means the aircraft would have to have an angle of attack of about 67 degrees and its weight would have to be lower than the resultant vector, in order for it to hover. Furthermore, the aircraft had inadequate control characteristics because the propeller slipstream fell below the conventional tail. Leading edge stall occurred, and this issue could not be resolved unless there was a cross wind. Wind tunnel tests conducted with low forward velocities did generate better results, and the aircraft had better aerodynamic properties. Forward flight led to better results in terms of control effectiveness as well; however, one engine out situations resulted in a poor control performance.

Englar and Campbell conducted research on a design which applied circulation control to Custer's channel wing design [27], using the circulation control system that was patented by Englar and Bushnell [25]. A 0.075-scale, powered semi-span model of a Channel wing aircraft employing the pneumatic circulation control technology was tested in a subsonic wind tunnel. When blowing was applied (circulation control was on), huge C_L values were obtained for various angles of attack. For example, a C_L value of 9 was measured at 10 degrees angle of attack. Thus, it was proved that the design achieved the expected super-STOL capability. It was also seen that an increase in blowing (the amount of air discharged through the circulation control mechanism) was more effective in improving the lift coefficient than an increase in the thrust coefficient. The authors noted that the controllability issues at low speed and trimming options still need to be evaluated, and the lift characteristics have to be analyzed for other conditions.

4. CURRENT & FUTURE DEVELOPMENTS

The review conducted for this paper showed that despite the considerable number of interesting patents on the channel wing concept and its possible potential to provide the basis for a low-cost, high efficiency, multi-purpose and compact aircraft capable of V/STOL flight, the design of such a vehicle requires further study. The small number of technical

publications on the same topic indicates that this system has long awaited its due interest. This paper, which is, to the authors' knowledge the first review of all significant patents and publications relevant to the improvement of the channel wing system, is an attempt to renew interest in this neglected area of flight research.

Custer carried out a large number of experiments and came up with intriguing designs. The inventor's designs were indeed promising but a number of issues, especially those related to aircraft control and flow separation, could not be resolved. Recently, other inventors have showed renewed interest in the topic. Skoglun's engine tilting design [24] might be effective in modifying the direction of the thrust vector without employing huge angles of attack. Englar's research group has published papers on [27] and obtained patents [25] using the circulation control technology. Circulation control might be a solution to both the flow separation problem and the large angle of attack requirement.

When combined with the efforts of contemporary inventors, Custer's designs might lead to the development of a very efficient and well performing channel aircraft which could satisfy the aviation world's V/STOL requirements. The use of jet propulsion in combination with the channel wing might lead to design complications. The properties of the engine exhaust air that flows over the channel might adversely affect the aircraft structure. This is a field which requires further analysis. It is also observed that the control characteristics of the aircraft have been investigated to a very small extent. Thorough analysis is required in this field in order to solidify the channel aircraft's status as an effective V/STOL vehicle. Our group is continuing research on the channel wing concept.

This review revealed that a prototype aircraft which combines Custer's ideas with newer concepts like circulation control has to be designed and tested in order to fully understand how effective the aircraft can be when it is produced in that configuration. Adding Custer's [6] or Fletcher's [18] boundary layer removal system could improve the aerodynamic efficiency of the channel wing. Applying circulation control as proposed by Englar [25] could solve a number of issues and increase the lift produced. Finally, a thrust vectoring method, as proposed by Fletcher [18], Taylor [17] or Skoglun [24] could help the channel wing aircraft achieve V/STOL requirements easier. The resulting aircraft might be very effective, safe and suitable for a wide range of civil and military operations.

ACKNOWLEDGEMENTS

There are no acknowledgments to mention.

CONFLICT OF INTEREST

There are no conflicts of interest to our knowledge.

REFERENCES

- [1] Custer, W.R.: US2424556 (1947).
- [2] Custer, W.R.: US2437684 (1948).
- [3] Custer, W.R.: US2476482 (1949).
- [4] Custer, W.R.: US2510959 (1950).
- [5] Custer, W.R.: US2514478 (1950).
- [6] Custer, W.R.: US2532482 (1950).

- [7] Custer, W.R.: US2532481 **(1950)**.
- [8] Custer, W.R.: US2589994 **(1952)**.
- [9] Custer, W.R.: US2611555 **(1952)**.
- [10] Custer, W.R.: US2611556 **(1952)**.
- [11] Custer, W.R.: US2665083 **(1954)**.
- [12] Custer, W.R.: US2687262 **(1954)**.
- [13] Custer, W.R.: US2691494 **(1954)**.
- [14] Custer, W.R.: US3123321 **(1964)**.
- [15] Custer, W.R.: US3704842 **(1972)**.
- [16] Custer, W.R.: US3705700 **(1972)**.
- [17] Taylor, C.G.: US2693920 **(1954)**.
- [18] Fletcher, C.J.: US2937823 **(1960)**.
- [19] Shew, G.B.: US2957647 **(1960)**.
- [20] Taylor, C.G.: US2961188 **(1960)**.
- [21] Shew, G.B.: US3081965 **(1963)**.
- [22] Spence, W.G.: US3504873 **(1970)**.
- [23] De Angelis, L.J.: US4726546 **(1988)**.
- [24] Skoglun, W.: US5597137 **(1997)**.
- [25] Englar, R.J., Bushnell, D.M.: US7104498 **(2006)**.
- [26] Pasamanick J., Langley Full-Scale-Tunnel Tests of the Custer Channel Wing Airplane. NACA RM L53A09, National Advisory Committee for Aeronautics 1953.
- [27] Englar, R.J., Campbell, B.A., Experimental Development and Evaluation of Pneumatic Powered-Lift Super-STOL Aircraft, Progress in Astronautics and Aeronautics, 2006, Vol. 214, pp. 315-336. (AIAA paper 2002-2375)