March 14, 1961 E. G. JOHNSON 2,974,927

SUPERSONIC FLUID MACHINE

Filed Sept. 27, 1955 3 Sheets-Sheet 1

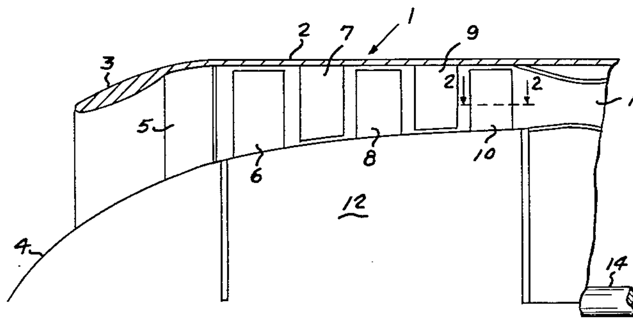

Fig-1

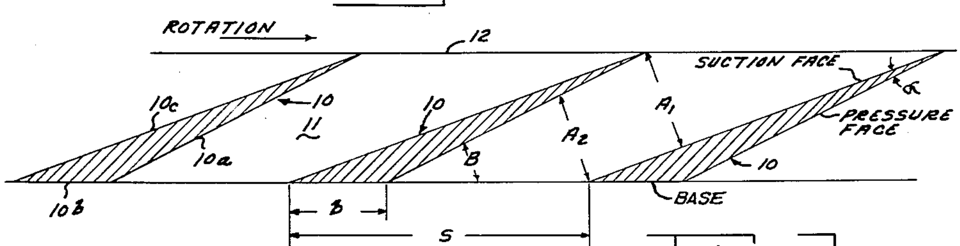

Fig-2

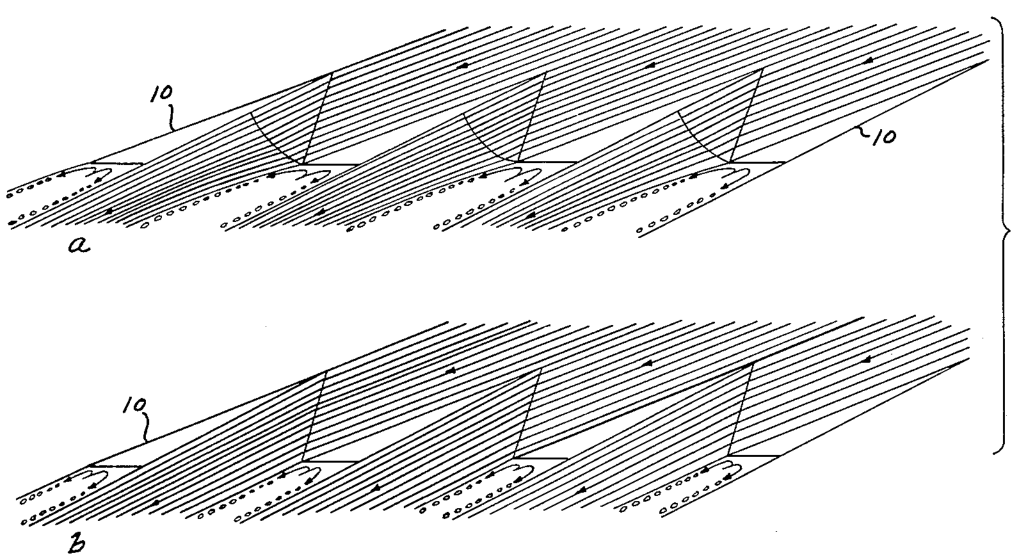

Fig-4

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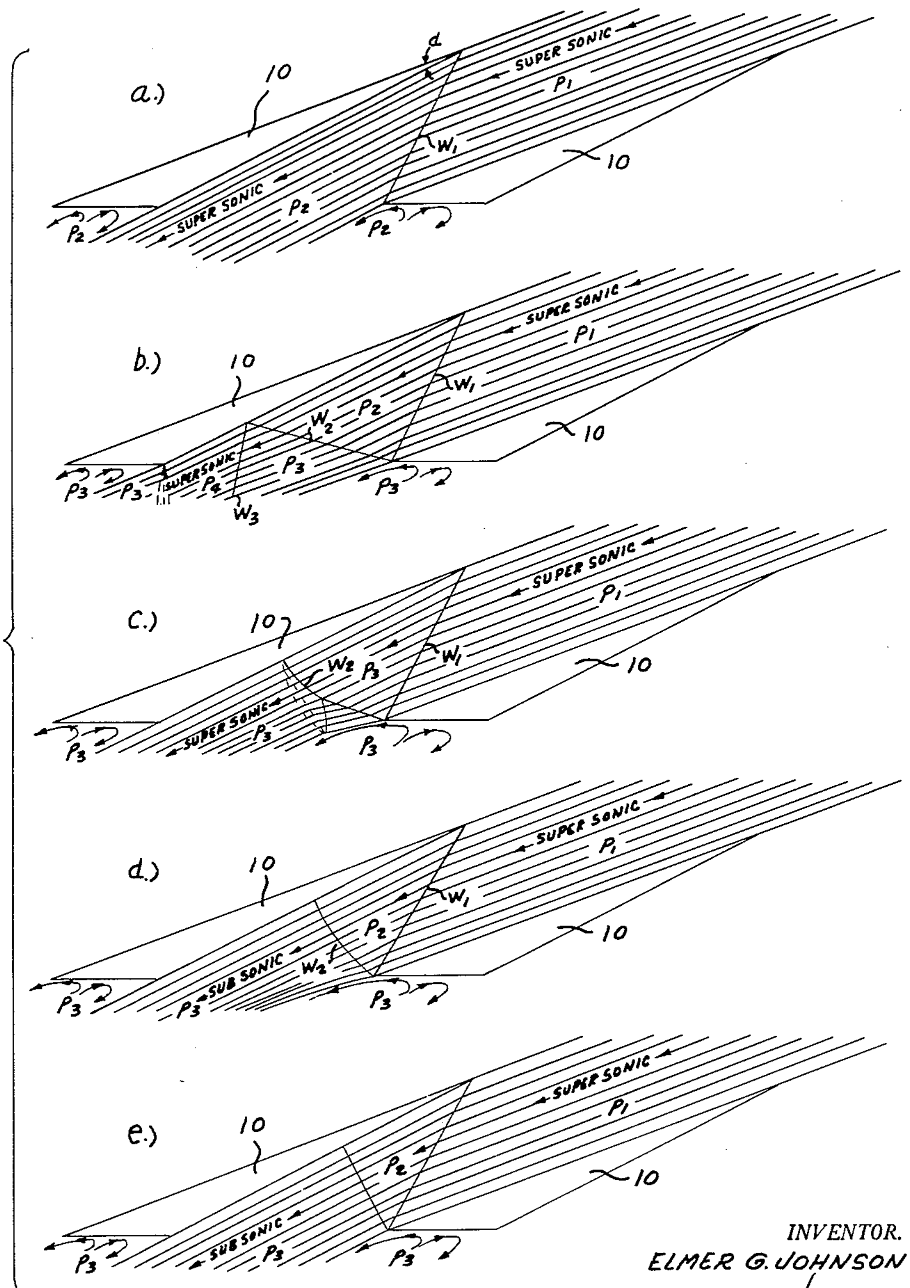

Fig-3

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SUPERSONIC FLUID MACHINE

Filed Sept. 27, 1955 3 Sheets-Sheet 3

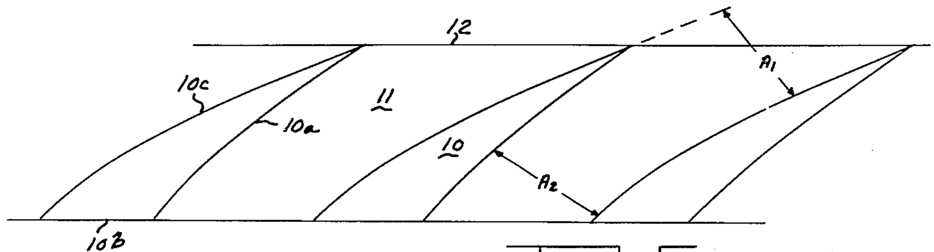

Fig-5

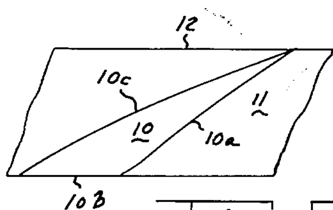

Fig-6

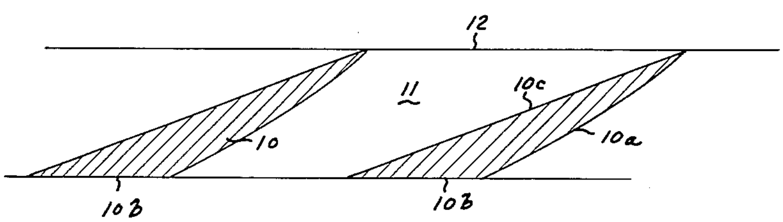

Fig-7

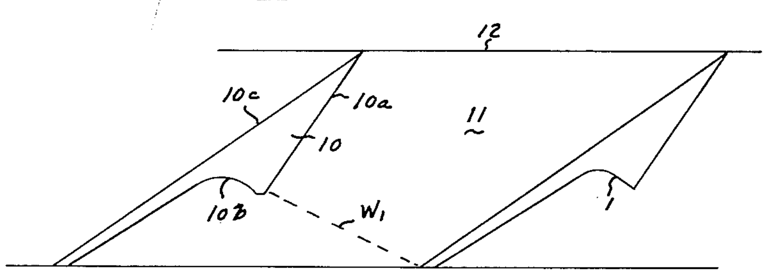

Fig-8

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SUPERSONIC FLUID MACHINE

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7 Claims. (Cl. 253—69)

(Granted under Title 35, U.S. Code (1952), sec. 266)

The invention described herein may be manufactured and used by or for the United States Government for governmental purposes without payment to me of any royalty thereon.

This invention relates to improvements in turbo machinery and more particularly with supersonic compressors, that is, in which one or more stages of the machine receive fluid flow at supersonic velocity and convert the velocity head into pressure energy primarily through the medium of shock wave phenomena. A good resume of the technical aspects of supersonic compressors is given in the unclassified publication entitled "Supersonic Axial Flow Compressor," NACA Report No. 974 by Arthur Kantrowitz, published in the NACA Annual Report for 1950. The advantage of the supersonic compressor as clearly pointed out in the aforementioned publication lies in the fact that pressure ratios as high as four-to-one are possible in a single stage as compared to a maximum pressure ratio of about 1.25 to 1 for a subsonic axial flow compressor stage.

One of the greatest difficulties encountered, however, with supersonic compressors is that of flow separation in the blade passages due to shock boundary layer interaction. This difficulty was experienced with converging-diverging supersonic blade passages where flow separation occurred during the transition from supersonic to subsonic velocity thereby causing large energy losses and dangerous blade vibration. The blades presently employed for supersonic compressors are generally thin and mostly formed in such a manner as to provide converging-diverging flow passages between adjacent blades. While such a compressor may possibly be designed to give an acceptable efficiency at a single design point, the performance under conditions above the design point lead to surging and in general the efficiency for conditions below the design point is so poor that bringing such a machine up to speed by conventional methods is practically impossible. In those designs in which converging flow passages without subsequent diverging channel passages have been employed with thin trailing edges on the blades the passage convergence must be obtained by radial variation in the direction of the flow passages or by curving the blades away from the axial direction which have given rise to very poor efficiency in the sonic and trans-sonic regions.

It is the aim of this invention to provide an improved supersonic compressor having superior characteristics with respect to operational range, stability, efficiency, pressure ratio, simplicity of fabrication and overall blade ruggedness by a more suitable type of blading. The term blade cascade as hereinafter employed in the specification refers to a number of radially extending blades symmetrically arranged in spaced relation about the hub with the spaces between adjacent blades forming flow passages being less than the chord of the blades. In contrast to the known types of supersonic axial flow compressor cascades the supersonic cascade according to the invention is composed of so-called "aerodynamic half

body" blades. Such a cascade can be originated by cutting any known cascade blading by a plane near maximum blade thickness in such a manner as to form a cascade blading with a distinctly blunt trailing edge. Application of aerodynamic half body type blades in a supersonic cascade results in essential improvements with respect to operational stability and range. In accordance with the invention an individual rotor blade has essentially the appearance of an oblique wedge with its base being located at the exist side of the cascade. The blade profile can be described essentially as having three sides; a pressure side, a suction side and a base side, the intersection of the pressure and suction sides forming a sharp leading edge with the base side lying primarily in a plane of rotation. The junction of the base side with the pressure and suction sides need not necessarily be sharp corners but may be rounded off. The blading further may be constructed so that the pressure and suction sides need not necessarily be flat planes but either or both may be curved. When arranged with constant pitch spacing on a rotor the space between adjacent blades form flow passages having substantially constant radial dimensions but converging from inlet to outlet.

For more detailed description of the invention reference should be made to the detailed description hereinafter given and to the appended drawings in which:

Figure 1 is a schematic longitudinal view partly in section of a three-stage compressor constructed in accordance with the invention;

Figure 2 is a developed top plan view of the rotor and compressor blades such as seen on line 2—2 of Figure 1;

Figure 3 is a view in five parts illustrating the flow pattern in the rotor blading at design speed with various back pressures for the special case that the shock waves strike the end of the suction side of the adjacent blades;

Figure 4 is a view similar to Fig. 3 in two parts illustrating the wake formations behind the blades at two different back pressures;

Figure 5 is a top plan view of a rotor and blading in which the pressure and suction faces are curved;

Figure 6 is illustrative of a modified form of supersonic blades in accrodance with the invention in which the juncture of the pressure face and base portion of the blade is rounded off;

Figure 7 is representative for a blading with a curved pressure side portion;

Figure 8 is illustrative for a blading where the wakes are originated by the base of the profile being arranged within the blade channel.

Referring now to Figure 1, the reference numeral **1** generally indicates an air compressor constructed in accordance with the invention and primarily useful when used as the compressor section of a jet engine. The compressor **1** is made with a cylindrical casing **2** having a streamlined entrance portion **3** and stationary entrance cone **4**, providing for the entrance of air into the compressor generally at a subsonic velocity. The compressor is provided with a first stage stationary set of stator blades **5** and first stage rotor blades **6** cooperating therewith to form a subsonic compressor stage. The stator blades **7** and rotor blades **8** form a second stage and are designed to operate in, for example, a transonic range which delivers compressed air into stator blades **9** which cooperate with the supersonic rotor blades **10** to form the third or supersonic stage such that the flow through the passages between the blades **10** is supersonic from entrance to exit. The rotor blades **6**, **8** and **10**, inclusive, are adapted to be secured to and rotatable with a rotor **12** which is adapted to be turned by means of an axial shaft **14** either by a turbine in the case of an aircraft power plant or by a separate power source where the compressor is employed as a separate unit for compressing air or gas. The outlet from the supersonic rotor blades 10 delivers air into a converging diffuser section 15 which may in the case of a jet engine form the entrance to an annular or other type combustion chamber which forms no parts of the present invention.

The blade geometry of the supersonic blades 10 on rotor 12 of Figure 1 can be seen in Figure 2 and modified forms in Figures 5, 6, 7 and 8 which the rotor blades generally indicated by the reference numeral 10 are seen to be constructed in the form of inclined wedges having a pressure face 10*a* and a suction face 10*c* which intersect to form a sharp leading edge and the blades being formed with a base section 10*b*. The space between the suction face of one blade and the pressure face of an adjacent blade forms a flow passage generally indicated by reference numeral 11 which is essentially constant in radial dimensions from inlet to outlet but which is more or less converging laterally from its entrance to its exit. In other words the cross-sectional area taken at the plane of dimension A_1 is greater than the cross-sectional area in the plane of the dimension A_2 for a blading according to Fig. 2, while for a curved blading according to Fig. 5 the decrease in area from A_1 to A_2 may be insignificant. The length of the base portion indicated as b of a blade is approximately of the order of one-third of the pitch between adjacent blades indicated by the dimension S. The wedge angle indicated by angled α will vary with design conditions but generally will be in the order of 5 to 10 degrees and is primarily determined by the desired angular turning of the flow through the blade row. The angle of inclination of the pressure face of a blade to the plane of rotation of the rotor, indicated as angle β, in general will lie between 25 and 45 degrees.

The mechanism of the development of pressure through supersonic compressor blading according to this invention is as follows: Air entering the rotor 12 at supersonic velocity into the entrance of the flow passages 11 creates a compression wave or family of such waves from the leading edge of the pressure side of one blade and which go out into the direction of the trailing edge of the suction side of the adjacent blade. There is thus developed a pressure increase across these wave fronts which depends on the inlet Mach number and blade geometry. A second family of compression waves is going out from the base of the profile and their strength is dependent on the static pressure existing behind the blade row.

By referring to Figure 3 the flow path of the rotor blading for the designed rotational speed at various back pressures will be made clear. In Figure 3*a* air is assumed to be entering relative to the blade row in a direction parallel to the suction face of the blades and sets up a shock wave W_1 which is directed to intersect the trailing edge of the suction face of the adjacent blade. The air entering at supersonic velocity with a pressure P_1 is turned across the wave front through an angle substantially equivalent to the wedge angle α and emerges with a lower supersonic velocity and a higher pressure P_2. Conditions as illustrated in Figure 3*a* are for the condition where the back pressure existing behind the blade row is relatively low.

For conditions where the static pressure behind the blade row or cascade is higher the flow will begin to assume a condition similar to that shown in Figure 3*b* in which again the entering air at supersonic velocity and pressure P_1 set up an oblique wave front W_1 which develops the pressure P_2. The wave front W_1, however, is reflected from the trailing edge of the suction face of the adjacent blade to form an oblique reflected wave W_2 which is transmitted across the blade channel to again be reflected from the pressure face of the first mentioned blade as an oblique wave front W_3. The wave fronts W_2 and W_3 give rise to the increased pressures P_3 and P_4 but the discharge from the blade cascade is still supersonic but at a lower velocity than at entrance.

In the conditions as seen in Figure 3*c* the back pressure behind the blade row is higher still and the wave front W_2 begins to be curved toward the normal and the static pressure P_3 will be considerably higher than in the case of Figure 3*b* but the exit velocity will still be at lower supersonic velocity.

In the conditions as illustrated in Figure 3*d* the back pressure behind the blade row will be of the order which will be reached at the normal design operating conditions of the supersonic compressor rotor. In this condition it will be seen that the wave front W_2 is closely approaching a normal shock and the velocity of exit is now subsonic and the pressure P_3 will be approaching a maximum. From a standpoint of boundary layer shock interaction it would be preferable that the oblique shock hits the suction side of the adjacent blade somewhat before the trailing edge. However, for simplicity such a wave pattern is not shown in the figure.

In the flow conditions as illustrated in Figure 3 the wave front W_2 has become normal to the pressure face and now exists as a strong normal shock wave in which the maximum pressure rise will occur across this shock wave and the exit velocity from the blade row will be subsonic and lower than for the condition Figure 3*b*. The flow conditions as illustrated in Figure 3*e* are for the maximum back pressure condition under which the supersonic rotor can operate satisfactorily and if the back pressure corresponding to the pressure P_3 were to be further increased the normal shock wave would move forward through the rotor blade channel. This condition corresponds to non-started flow having an external shock pattern which is associated with reduced flow and increased losses.

It will be noted that the pressure increase of the flow through the blade passage 11, as illustrated in Figure 2, is accomplished partly by the decreasing cross-sectional area from entrance to exit, and partly by the rear shock system. It will be further noted that the flow through the blade row will be turned through an angle approximately equal to the wedge angle of the blades and accordingly the change in momentum caused by the flow deflection will give rise to an increase in total pressure.

It will be noted from the various examples illustrated in Figure 3 that the flow discharge from any flow passage between a pair of adjacent blades is similar to flow from a nozzle and will give rise to large wakes behind each respective blade. At first sight the formation of such wakes would be indicative of very large losses and would tend to indicate that a blade construction in accordance with the invention would not be an improvement. Actually, however, a computation of the mixing losses incurred at some distance down stream from the supersonic blade row where the subsonic velocity wakes merge with the air discharge from the blade channels indicates that the total energy loss is only of the order of 1 to 2 percent of the energy input to the rotor.

As best seen in Figure 4 the flow in Figure 4*a*, which is the same as that illustrated in Figure 3*d*, shows the shape of the wake formation behind each blade at a back pressure corresponding to approach to the design rotational speed or at the design point. From this figure it will be seen that as the back pressure was at optimum conditions the thickness of the wake is relatively small and the boundaries of the wakes in effect form continuations of the airfoil contours. As the back pressure increases to the maximum point as illustrated in Figure 4*b*, the thickness of the wakes varies accordingly and it is this variation in the wake thickness and boundary contours with changing back pressure which give rise to the wide range of operation with high efficiency and stability of the new blade configuration. Since the wake can adapt itself in its dimensions and contours to the existing back pressure, flow separation that occurred in the prior supersonic compressors is avoided and accordingly it is possible to obtain good efficiencies in the subsonic and transonic regions of operation as well as in the desired supersonic condition. This makes it possible to bring the supersonic rotor up to operating speeds and pressures through normal procedures as with any other axial flow compressor operating in the subsonic region. The fact that the bases of the wedge-shaped blades lie substantially in the plane of rotation and create large wakes actually is a benefit rather than an apparent detriment and by the use of two such supersonic rotors arranged for contrarotation it is possible to achieve a pressure ratio of as much as 10 to 1 with a machine having only two stages.

In order to further enhance the starting characteristics of a supersonic rotor in accordance with the invention the rotor blades may be made in the form as illustrated in Figure 5 in which the pressure face **10***a* and suction face **10***c* are curved from the sharp entrance end to the base portion **10***b*. This type of construction will considerably enhance the operation of the machine in the subsonic range and will not have an adverse effect in the supersonic region. The blade channel **11** between a pair of adjacent blades in this form of the invention also converges from entrance to exit in the same manner as the blade configuration previously described with respect to Figure 2.

It should be noted in conjunction with Figure 6 that the curved blade formation can be used on both pressure and suction faces as shown or on either face singly.

Figure 6 illustrates a form of blade similar to that shown in Figure 5 with the exception that the sharp edges at the intersection of the pressure face and the base is rounded off to form a smooth curve. This change will also improve the operation of the blades of the subsonic region without adversely affecting performance of the supersonic range. While under most operating conditions it will not be desired to employ a fixed row of stator blades behind the supersonic rotor, a stator may be employed providing that the flow space downstream of the supersonic rotor and the entrance to the stator blades is made converging so as to decelerate the flow under normal operating conditions to subsonic before entering into the stator section.

Figure 7 illustrates a form of blading in which the pressure face **10***a* only of the blade is curved from the sharp entrance edge to the base portion **10***b*. Blades of this character will have improved subsonic and transonic characteristics and aid in easy starting.

Figure 8 illustrates a form of blade having the same aerodynamic characteristics as the wedge blades of Figure 2, but in which the base portion **10***b* is curved so as to lie substantially wholly within the blade channel **11**, with the wakes originated by the base of the profile extending into the blade channel.

It is obvious that the supersonic blading in a cascade in accordance with the invention need not be limited to wedge with straight pressure, suction and base sides but in general may encompass a blade shape coming within the term "aerodynamic half body," i.e., an aerodynamic section in which the point of maximum thickness is positioned at or adjacent the trailing edge of the section or wherein the airflow streamlines leave the body adjacent to the point of maximum thickness with the formation of wakes whose boundaries form in effect a continuation of the airfoil section which is variable dependent on the external pressures existing in the vicinity of the wakes.

It should be understood that in a compressor designed in accordance with the principles of the invention the primary means for developing supersonic flow is by means of blading of a configuration as disclosed which produces flow passages converging from entrance to exit and of substantially constant radial dimensions. The term substantially as herein employed contemplates a reasonable variation in radial passage dimensions. For example it is contemplated that the annular flow area at entrance may be reduced at the exit by as much as twenty percent due to variation in hub radius or housing contour.

Having now described my invention, what I wish to secure by Letters Patent is:

1. An axial flow turbo machine of the character described having a casing forming a flow boundary for radially confining the flow of a gaseous medium therethrough, a bladed rotor rotatable in said casing with the blades thereof having a running clearance with the interior wall of the casing, said casing having an inlet opening at one end thereof and a discharge opening at the other end thereof, the blading on said rotor comprising at least one supersonic stage with the space between adjacent blades forming flow passages with the width of the passages less than the chord length of the blades and the flow passages communicating with said casing inlet and outlet, said flow passages having substantially constant radial dimensions from the passage inlet to the passage outlet, and the supersonic blades having pressure and suction faces on opposite sides thereof and the blades being of the aerodynamic half-body type in cross section, that is the pressure and suction faces intersect only at the entering end and the blades increasing in thickness in the axial direction from the leading edge thereof to a maximum thickness at the trailing edge thereof, to thereby cause a flow separation with a corresponding large wake in the flow aft of each of the blades.

2. A supersonic axial flow compressor having a casing forming a flow boundary for radially confining the flow of a gaseous medium therethrough, a bladed rotor rotatable in said casing with the blades thereof having a running clearance with the interior wall of the casing, said casing having an inlet opening at one end thereof and a discharge opening at the other end thereof, the blading on said rotor comprising at least one supersonic stage with the space between the blades defining fluid flow passages with the width of the passages being less than the chord length of the blades and communicating with said casing inlet and outlet, the radial dimensions of the flow passages being of substantially constant radial dimensions from the passage entrance to the passage exit, the supersonic blades being inclined to the plane of rotation and having sharp entrance edges with pressure and suction faces on opposite sides thereof intersecting only at the entrance edges and the blade thickness increasing in the axial direction from the entrance edges to a maximum thickness at the trailing edge so as to produce continuous convergence of the flow passages from entrance to the exit thereof with flow separation and corresponding large wakes in the flow aft of the blades.

3. An axial flow turbo machine of the character described having a casing forming a flow boundary for radially confining the flow of a gaseous medium therethrough, a bladed rotor rotatable in said casing with the blades thereof having a running clearance with the interior wall of the casing, said casing having an inlet opening at one end thereof and a discharge opening at the other end thereof, the blading on said rotor comprising at least one supersonic stage with the space between adjacent blades forming flow passages with the width of the passages less than the chord length of the blades and the flow passages communicating with said casing inlet and outlet, said flow passages having substantially constant radial dimensions from the passage inlet to the passage outlet, and the supersonic blades having pressure and suction faces on opposite sides thereof and the supersonic blades being essentially wedge shaped in cross section and inclined to the plane of rotation with sharp leading edges and having pressure and suction faces on opposite sides thereof intersecting only at the leading edge with the maximum blade thickness substantially at the blade trailing edge to thereby cause a flow separation with a corresponding large wake in the flow aft of each blade.

4. The structure as claimed in claim 3, in which the pressure and suction faces of the wedge shaped blades are

shaped such that at least one of said faces is curved so that the flow passages are slightly turned at their exits toward the axial direction.

5. The structure as claimed in claim 3, in which the pressure and suction faces of the wedge shaped blades are curved to provide flow passages between adjacent blades which are slightly turned at their exits toward the axial direction.

6. The structure as claimed in claim 3, in which the wedge shaped blades are in the form of triangular wedges with the base portion of the wedges being substantially the point of maximum blade thickness.

7. An axial flow turbo machine of the character described having a plural stage bladed rotor, at least one supersonic stage of blading on said rotor comprising a blade cascade with the spaces between adjacent blades forming flow passages with substantially constant radial dimensions and with the width of the flow passages less than the blade chord, a casing in which said rotor is rotatably mounted with the blades on the rotor having a running clearance with the interior wall of the casing which serves to radially confine the flow within the said flow passages, said casing having an inlet and an outlet with the blade flow passages communicating therewith for axial flow of a gaseous medium therethrough, the blades of the supersonic stage having pressure and suction faces on opposite sides thereof which intersect only at the entering edge and progressively increasing in thickness in the axial direction from the leading edge to a maximum thickness at the trailing edge, the surface connecting the terminal portions of the pressure and suction faces being aerodynamically inactive to affect the fluid flow in the flow passages, the fluid flow through the flow passages of the supersonic blade cascade separating from the blades substantially at the point of maximum thickness thereof to leave wakes downstream in the flow behind the blades.

References Cited in the file of this patent

UNITED STATES PATENTS

1,063,294	Seaver	June 3, 1913
2,408,788	Ludington et al.	Oct. 8, 1946
2,721,693	Fabri et al.	Oct. 25, 1955

FOREIGN PATENTS

306,642	Germany	July 4, 1918
1,012,058	France	Apr. 9, 1952