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Mikolajczak et al.

[11] **3,873,229**

[45] **Mar. 25, 1975**

[54] **INLET GUIDE VANE CONFIGURATION FOR NOISE CONTROL OF SUPERSONIC FAN**

[75] Inventors: **Alojzy Antoni Mikolajczak,** Farmington; **Robert Alfred Arnoldi,** West Hartford, both of Conn.

[73] Assignee: **United Aircraft Corporation,** East Hartford, Conn.

[22] Filed: **Dec. 26, 1973**

[21] Appl. No.: **427,871**

[52] **U.S. Cl.**..... **415/119,** 415/181, 181/33 HA

[51] **Int. Cl.**..... **F01d 5/10,** F04d 21/00

[58] **Field of Search**..... 415/119, 181; 181/33 C, 181/33 D, 33 HA

[56] **References Cited**

UNITED STATES PATENTS

2,623,688	12/1952	Davidson	415/181
3,574,477	4/1971	Dolf	415/119
3,724,968	4/1973	Friberg et al.	415/181
3,820,918	6/1974	Goldstein	415/181
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Primary Examiner—Henry F. Raduazo

Attorney, Agent, or Firm—Robert C. Walker

[57] **ABSTRACT**

The inlet guide vanes positioned adjacent and upstream of a first stage supersonic fan are shaped to reflect virtually all the fan shock wave noise back toward the fan, thereby preventing this shock wave noise from leaving through the engine inlet.

6 Claims, 6 Drawing Figures

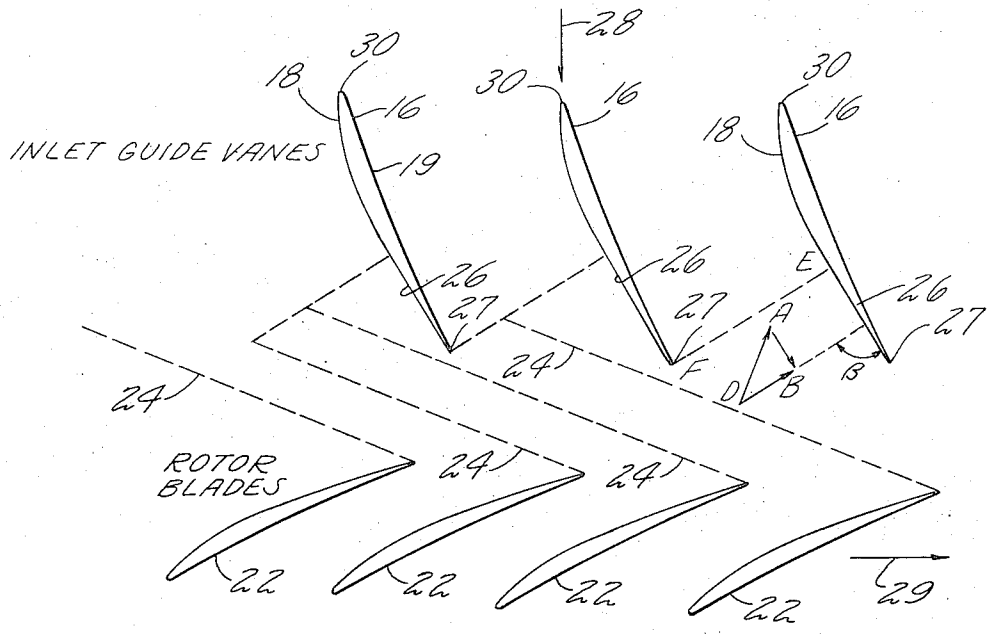


FIG. 1

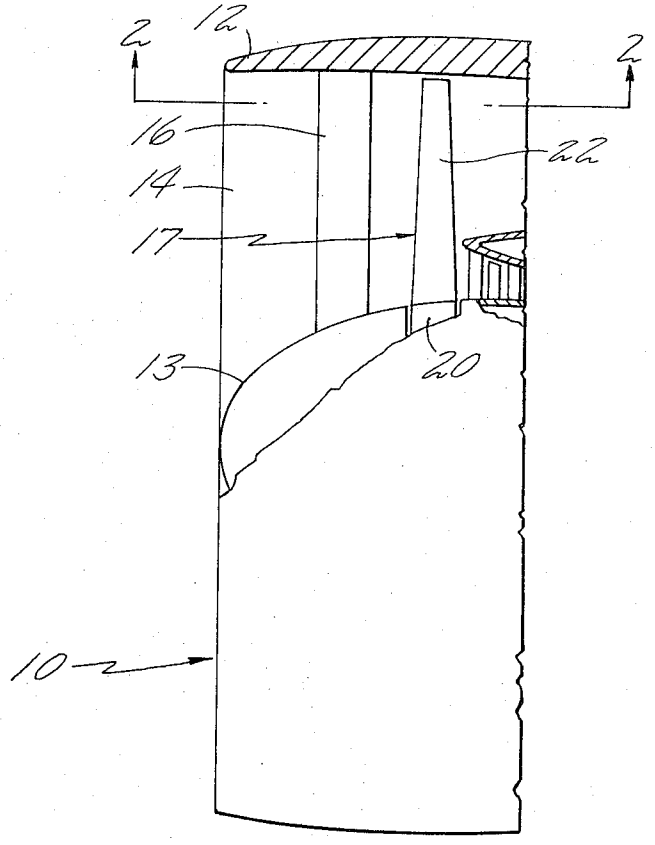

2
12
2
16
22
14
17
13
20
10

FIG. 2

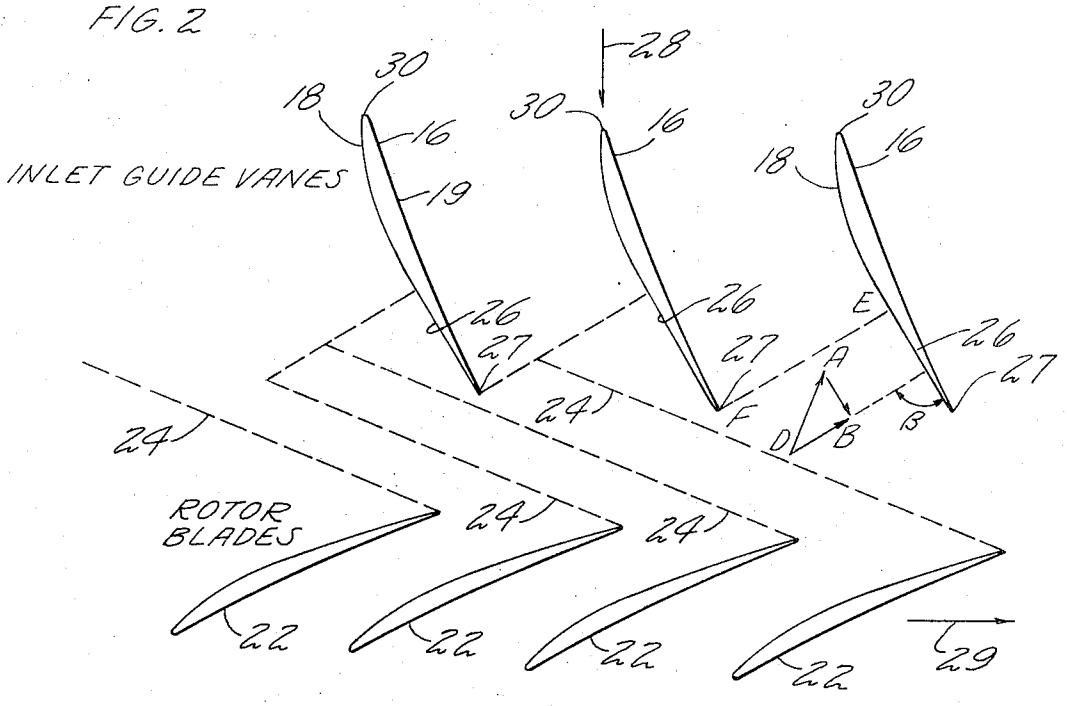

28
30
18
16
INLET GUIDE VANES
19
26
27
24
ROTOR BLADES
22
29
E
A
F
D
B

FIG. 3 (PRIOR ART)

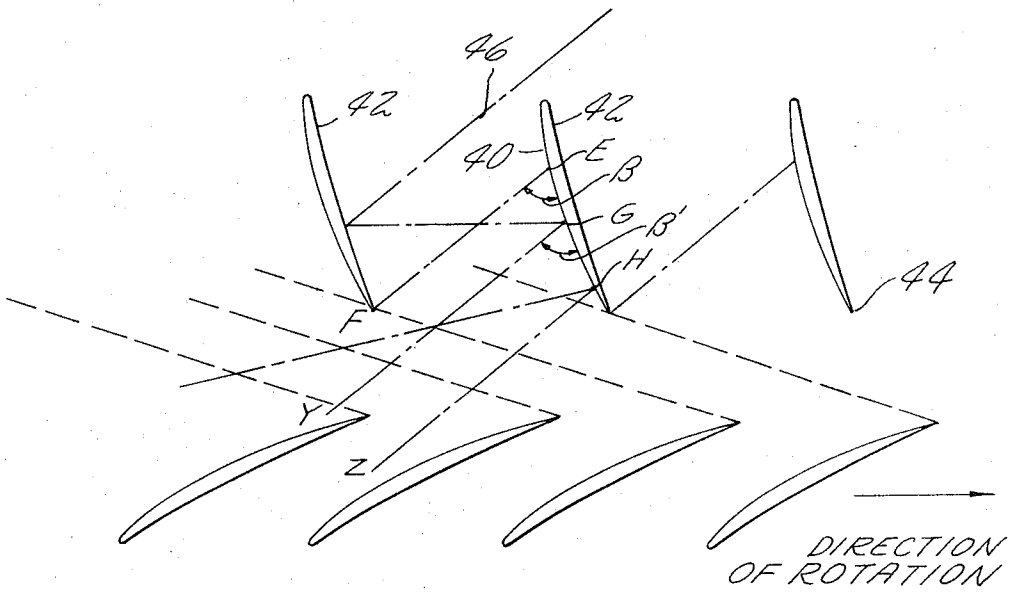


FIG. 4 (PRIOR ART)

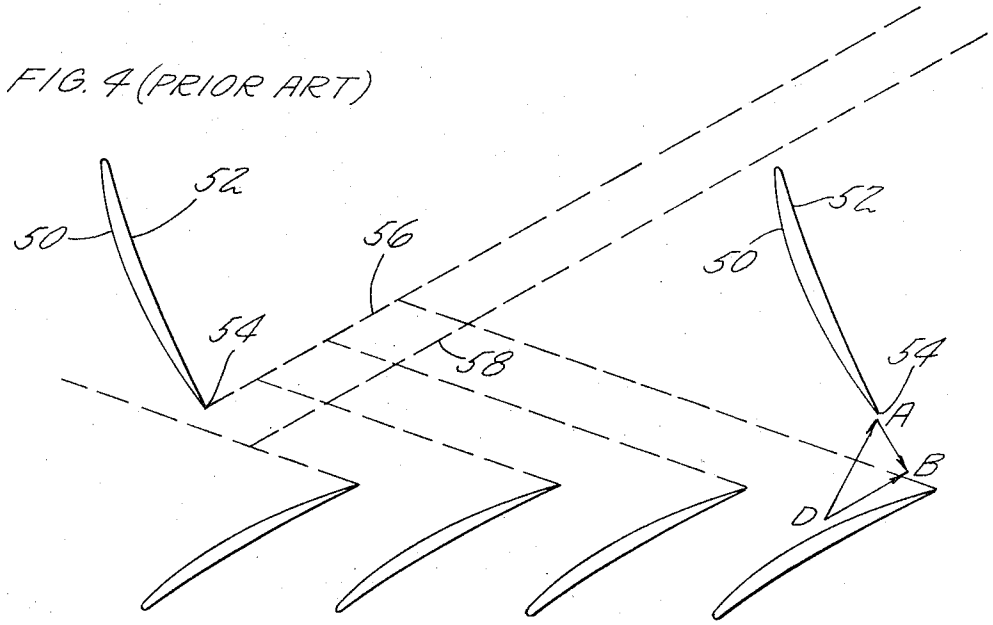


FIG. 5

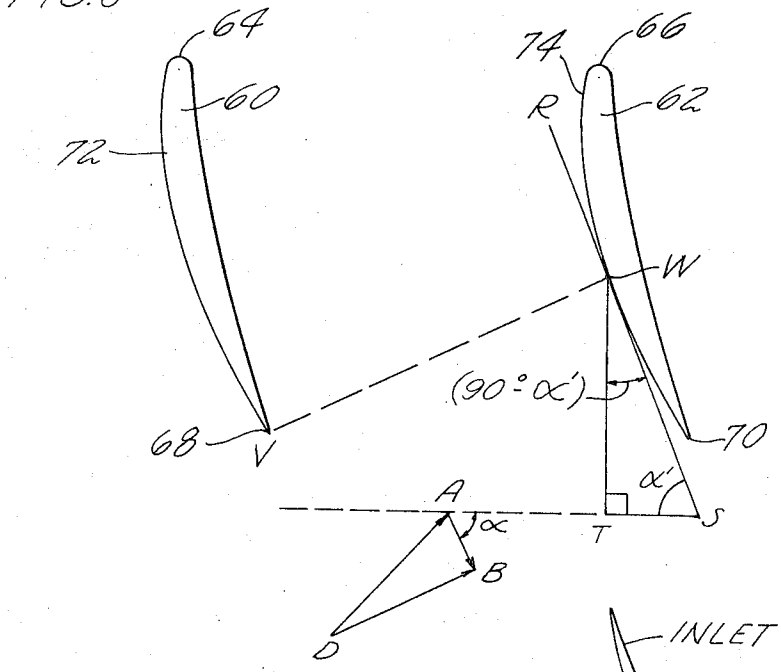
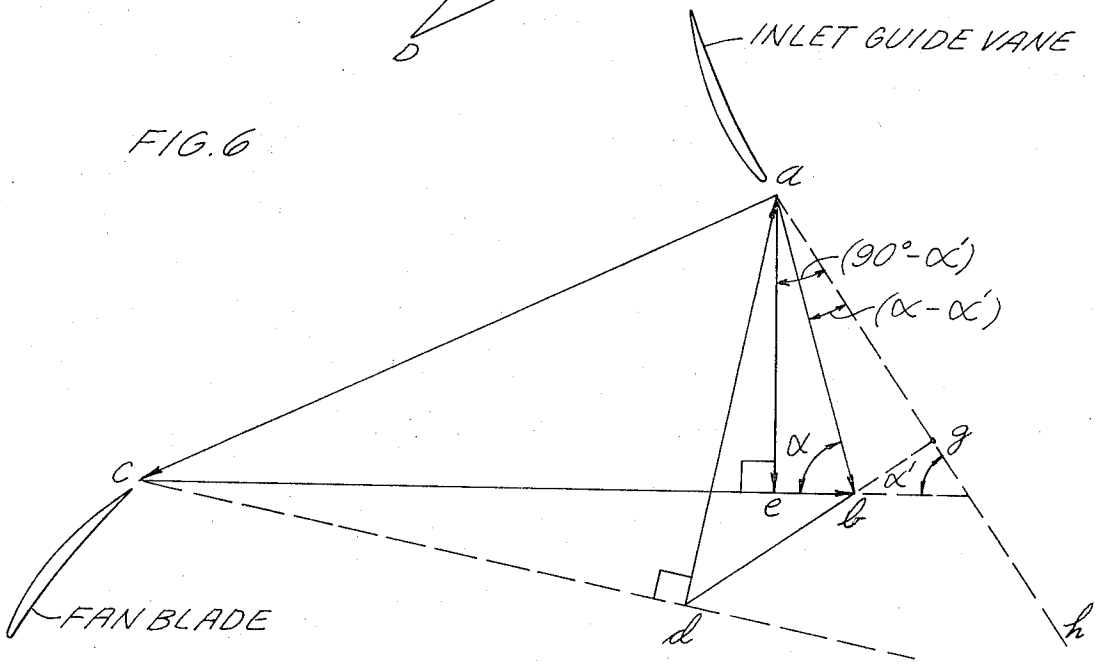

64
60
72
74
66
R
62
W
(90°-α')
68
V
70
α'
A
α
T
S
B
D

FIG. 6


INLET GUIDE VANE
a
(90°-α')
(α-α')
α
g
α'
c
e
b
FAN BLADE
d
h

INLET GUIDE VANE CONFIGURATION FOR NOISE CONTROL OF SUPERSONIC FAN

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to suppressing noise generated by a gas turbine engine.

2. Description of the Prior Art

Since the advent of the turbofan engine, fan noise has been recognized as a dominant noise source. Extensive theoretical and experimental programs have been conducted to develop methods of suppressing fan noise and the results of these programs have been incorporated in the basic design of modern high bypass ratio engines. Use of acoustic treatment in the engine or nacelle is an effective noise reduction measure, but both weight and performance penalties are associated with the use of such treatment. Inlet guide vanes have been used to improve aerodynamic performance, unintentionally offering partial blockage of noise from escaping upstream of the fan. Intentional blockage of the noise has been provided by rotating baffles, for example, in Dolf et al. U.S. Pat. No. 3,574,477, which discloses a fan mounted for free rotation in the fluid stream of a rotary engine, upstream of a first compressor stage. This freely rotating or "windmilling" fan is supposed to block sound waves or noise created by the first compressor stage thereby reducing the amount of noise which propagates out the front end of the engine. Dolf et al. indicates that the blocking effectiveness of the free-rotating fan is at a maximum when it is rotating faster than the speed of sound. Dolf et al. further suggests certain configurations for the airfoil portion of his free-rotating fan blades to regulate incoming air into a desired "air pressure column" for the first compressor stage. He claims that these configurations attenuate the noise and enhance engine performance to offset the losses caused by the presence of the free-rotating fan. Dolf et al. is discussed in detail in the following "Summary of the Invention."

Despite significant advances in noise reduction, still lower noise requirements are anticipated in future Federal regulations. Obtaining additional noise reductions through the extended use of current quieting techniques will only result in unacceptable aircraft system penalties in terms of weight and performance.

SUMMARY OF THE INVENTION

One object of the present invention is to further reduce the noise made by a gas turbine engine.

Another object of the present invention is to further reduce the noise emitted from the inlet of a gas turbine engine.

More particularly, an object of the present invention is to reduce the amount of noise associated with a supersonic fan stage in a conventional gas turbine engine while minimizing performance and weight penalties.

Accordingly, a row of stationary guide vanes is positioned upstream of a first stage compressor rotor, the guide vanes having airfoils configured to block the upstream propagation of the shock wave noise created by the first stage compressor. The airfoil surface of the vanes is set at such an angle with respect to the direction of noise propagation to reflect virtually all the shock wave noise back toward the compressor. The guide vane configuration of the present invention provides maximum shock wave noise reflection with virtually no performance penalty when compared to conventional guide vanes.

The present invention is based on the assumption that in a compressor rotor at a given radius where the relative air flow into the rotor blades is supersonic, the upstreamtraveling noise is consituted principally by the shock waves generated by the rotor blading; further, the noise energy travels in essentially one direction which can be determined. These assumptions are supported both analytically and empirically.

As hereinabove mentioned in the description of the prior art, it is known to use vanes to reflect noise back toward the compressor, such as described in Dolf et al.; however, Dolf et al. differs from the present invention in many significant respects. First and foremost is the fact that Dolf et al. uses a free rotating fan arrangement as the sound blocking means rather than the stationary vanes of the present invention. It is apparent that Dolf et al. relies in major part of the rotational speed of this free rotating fan to block noise rather than on the shape of the blades of the fan. For example, at column 2 lines 60–68 he suggests selecting the twist of the blades to obtain a rotational speed "as high as possible in order to obtain a high relative velocity of the incoming air relative to the [freely] rotating blades." He states that, "Relative velocities in excess of the velocity of sound will effectively block the direct propagation of sound through the channels formed by the blades." This is not necessarily true according to the reasoning used in the design of the inlet guide vanes of the present invention.

In column 5 at lines 32–36 Dolf et al. explains that it is desirable to have the blades of the free rotating fan "positioned at an angle which is perpendicular to the propagating noise traveling toward the exit area." How this is accomplished is unclear since Dolf et al. states in column 5 lines 23–30 that the sound waves or noise "propagates in various directions". Apparently Dolf only expects partial noise blockage by the foregoing technique, since he suggests in column 5 lines 36–40 that complete attenuation occurs only when the rotational speed of the free rotating fan blade is faster than the speed of the sound waves or the noise; evidently Dolf et al. is directing himself to noise created by a subsonic fan which would not have the highly directional nature of that created by the supersonic fan and shock wave system of the present invention. The present invention is quite different, not only because it relates to supersonic rotor noise, but because it teaches how to shape and size the guide vanes to assure that virtually all the noise produced in a shock wave system cannot pass upstream of the vanes. This is not taught in Dolf et al. Indeed, Dolf et al. teaches at column 2 lines 60–68 that the mere rotation of the free rotating fan at speeds faster than the speed of sound will result in effective noise blockage, irrespective of the direction of the sound escaping from the rotor. This is contrary to the teaching of the present invention which requires, first that the inlet guide vanes be stationary, and second, that optimum noise blockage results not from the rotation of the vanes but, rather, from the orientation of the vanes with respect to the direction of the sound escaping from the rotor.

Further distinguishing the teachings of Dolf et al. from the present invention is a discussion with reference to FIGS. **6–10.** Dolf et al. describes the free rotating fan blades as changing from a convex curvature (turbine type blade) near the tip to a concave curva-

ture (compressor type blade) at the root for purposes completely unrelated to the reflecting back of sound waves. With the statement in column 6 lines 14–16 that the principle of operation of the sound attenuating apparatus of FIG. 7 is basically the same as that of the apparatus described in FIGS. 1–5, it seems that Dolf et al. does not feel that the blade shape is of much significance in reflecting sound waves, but rather, it is the high rotational speed of the free rotating fan which does the job.

The foregoing and other objects, features and advantages of the present invention will become apparent in the light of the following detailed description of preferred embodiments thereof as illustrated in the accompanying drawing.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a cross sectional view of the forward portion of a tubofan engine.

FIG. 2 is a rotated diagrammatic cross sectional view taken along the line 2—2 of FIG. 1 for the purpose of illustrating the concepts of the present invention.

FIGS. 3 and 4 are rotated diagrammatic cross sectional views similar to the view of FIG. 2 by illustrating inlet prior art guide vanes which are not designed according to the present invention.

FIG. 5 is a rotated diagrammatic cross sectional view of two adjacent inlet guide vanes which further illustrate concepts of the present invention.

FIG. 6 is a vector diagram used to further explain the concepts of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Consider as an exemplary embodiment of the present invention the forward portion **10** of a turbofan engine. The forward portion **10** comprises an outer annular casing **12** and a hub **13** defining a annular inlet **14** of the forward portion **10.** Disposed within casing **12** is a row of stationary inlet guide vanes **16** and a first stage compressor rotor or fan **17.** The fan **17** comprises a disk **20** with a plurality of circumferentially spaced fan blades **22** extending radially outwardly therefrom. The fan **17** may be driven by a turbine (not shown) in a conventional manner which is well known to those skilled in the art.

Referring now to FIG. **2,** each of the guide vanes **16** comprises a forward surface **18** and a rearward surface **19,** the forward surface **18** being defined as the surface facing opposite to the direction of rotation of the fan **17.** The direction of rotation of the fan **17** in this embodiment is from left to right, as indicated by the arrow **29.** The forward surface **18** comprises a downstream portion **26;** the downstream portion **26** is hereinafter in the specification and in the claims referred to as the reflecting surface **26.** The reflecting surface **26** is hereinafter more fully defined. Each guide vane **16** also comprises a trailing edge **27** and a leading edge **30.**

The configuration of the vanes **16,** hereinafter to be described in detail, is a vane configuration best adapted for use with a supersonic fan. As used in the specification and in the claims the term "supersonic fan" or "supersonic rotor" is defined as a fan (or rotor) wherein the relative flow of air into the fan blades is supersonic at design speed over at least a portion of the span of the blades. Practically speaking this invention is most useful in engines where the fan is supersonic over a wide range of engine operating conditions. In all discussions relating to FIGS. **2–6** the relative flow of air into the fan blades is assumed to be supersonic at the particular radius which is depicted by the figure.

Since the relative flow of air into the fan blades **22** is supersonic at the particular radius of FIG. **2,** the blades **22** generate shock waves as indicated by the dashed lines **24.** The shock waves **24** travel at a speed and in a direction represented by the vector $\overline{DA}$ which is for the purposes of the present invention, perpendicular to the shock waves **24.** Air enters the inlet **14** in an axial direction represented by the arrow **28;** it passes between the vanes **16** and exits at the trailing edges **27** thereof at a speed and in a direction represented by the vector $\overline{AB}$. The direction of the vector $\overline{AB}$ is approximately parallel to the direction of the reflecting surface **26** near the trailing edge **27.** The vector sum of $\overline{DA}$ and $\overline{AB}$ is shown as the vector $\overline{DB}$ and is the sound energy velocity relative to the inlet guide vanes **16.** Hereinafter the direction of the vector $\overline{DB}$ is referred to as the "direction of noise propagation". It is contended that, relative to the inlet guide vanes **16,** essentially all the noise transmitted in the shock wave system travels in the direction of noise propagation.

By drawing a line FE parallel to the direction of noise propagation ($\overline{DB}$) from the trailing edge **27** of a vane **16** to the forward surface **18** of the next vane it becomes apparent that, theoretically, all the noise traveling with the shock waves **24** strikes the forward surface **18** of the vanes **16** downstream of the point E. Hereinafter in the specification the reflecting surface **26** is that portion of the forward surface **18** downstream of the point E. For ease of explanation this surface is shown as a straight line although that is not an absolute requirement of the present invention. Since the angle of reflectance of a sound wave from a surface is equal to the angle of incidence of the sound wave to the surface, the design requirements for maximizing the reflection of the sound energy back toward the fan **17** are as follows: (1) the angle β between the vector $\overline{DB}$ and the reflecting surface **26** must be greater than or equal to **90°** and, (2) the reflecting surface **26** should be of sufficient length so as to always completely intercept the propagation of the shock waves. The latter requirement is achieved so long as, along the span of the vane, the chord length of the inlet guide vane is at least as long as the length of the reflecting surface **26,** the chord length being the straight line distance between the leading edge **30** and the trailing edge **27** as measured perpendicular to the spanwise direction of the vane; in FIG. **2** the spanwise direction is a direction perpendicular to the plane of the paper.

FIG. **3** shows a prior art design and helps explain the former of the foregoing two requirements. In FIG. **3** the forward surface of the vanes is designated by the numeral **40;** the rearward surface is designated by the numeral **42;** and the trailing edge is designated by the numeral **44.** The line FE (and YG and ZH) is drawn parallel to the direction of noise propagation $\overline{DB}$ as it is in FIG. **2.** In this figure the vanes are improperly designed since the angle β between the line FE and the surface **40** (and also the angle β') is less than 90°. Thus a sound wave striking the surface **40** at a point E or G is reflected upstream out the inlet of the engine in the manner depicted by the dashed dot line **46.** Notice that a sound wave striking the surface **40** at a point H is reflected back toward the fan. Thus, when the angular re-

quirement of the downstream portion of the surface **40** is not satisfied, either all or some of the noise will be reflected upstream out the inlet of the engine. This is typical of the prior art designs wherein only partial blockage of the noise is achieved.

With reference to FIG. **4**, the forward surface is represented by the numeral **50**, the rearward surface is represented by the numeral **52** and the trailing edge is represented by the numeral **54**. The dashed line **56** is drawn from the trailing edge **54** toward the next adjacent vane in a direction parallel to the direction of noise propagation represented by the vector $\overline{DB}$. It it apparent that FIG. **4** represents a vane configuration which does not meet the second requirement that the inlet guide vanes be of sufficient length so as to always intercept the propagation of the shock waves. In other words the reflecting surface of the vanes is not long enough and some of the sound waves, such as represented by dot dash line **58**, can pass directly out of the inlet of the engine without striking the forward surface **50**; thus, all the noise traveling with the shock wave system cannot be blocked even if the entire surface **50** were at the proper angle for reflectance. The situation illustrated in FIG. **4** is also common to some prior art designs.

It is apparent that the foregoing design criteria for total shock wave noise blockage is valid only at a radius wherein the air velocity approaching the fan blades and relative thereto is greater than the speed of sound such that shock waves are produced. As hereinabove stated this is the case with respect to FIGS. **2–6**.

For the purposes of developing a more precise definition of the proper inlet guide vane shape according to the present invention reference is made to FIG. **5**. In FIG. **5** two adjacent inlet guide vanes **60, 62** are shown in cross section. Each guide vane has a leading edge **64, 66** respectively, a trailing edge **68, 70** respectively, and a forward surface **72, 74** respectively. A fan (not shown) would be positioned adjacent to the trailing edges of the vanes in a manner similar to that shown in FIG. **2**. Dash line VW represents a sound wave traveling in the shock wave system produced by the fan; it travels in the direction of noise propagation as hereinabove described passing through the trailing edge **68** of the vane **60** and striking the surface **74** at a point W. The line RS is drawn tangent to the surface **74** at the point W. The line WT is drawn through the point W parallel to the axial direction. The line TS is drawn perpendicular to the line WT. The velocity triangle ABD discussed previously in regard to FIG. **2** is also shown; $\overline{DA}$ is the velocity vector of the shock wave relative to the airstream, $\overline{DB}$ is the velocity vector of the shock wave relative to the vanes (parallel to VW) and $\overline{AB}$ is the air exit velocity vector, not parallel to WS but deviating from it slightly. $\overline{AB}$ forms an angle α with the direction TS while RS forms and angle α' with TS. In order to design an inlet guide vane to reflect the noise back downstream toward the fan in accordance with the present invention, it is necessary to have the angle VWS greater or equal 90°. If this criterion is met at the point W then it will be met at all other points between the point W and the trailing edge **70** as long as that portion of the surface **74** is straight or convex. The angle VWS is referred to as a "downstream angle" in the claims to differentiate from the angle VWR which would be the "upstream angle."

With the foregoing in mind reference is now made to FIG. **6** which is a vector diagram showing the relation of airflow and Mach line propagation. The inlet guide vane is labeled as such and the fan blade is spaced downstream thereof and is also labeled.

The vector $\overline{ac}$ represents the air velocity relative to the fan blade. It has a known magnitude and direction. The vector $\overline{ab}$ represents the velocity of the air leaving the inlet guide vanes; its magnitude, and direction can be known only after the shape of the inlet guide vane is chosen. The difference between these two vectors is the vector $\overline{cb}$ which represents the tangential blade velocity, also unknown until the inlet guide vane has been chosen. The construction line ah represents the metal tangent RS of FIG. **5**, forming an angle $\alpha-\alpha'$ (hab) with the vector $\overline{ab}$.

The vector $\overline{da}$ represents the velocity of sound relative to the moving air stream, known to be essentially perpendicular to the shock wave. *cd*. Point b is now chosen so that $\overline{db}$, when extended to meet *ah* at point *g* will form an angle *dgh* of at least 90°. (Note that the angle *dgh* corresponds to the angle VWS of FIG. **5**.)

When the angle dgh is 90° the following expression may be derived ($\overline{da}$ being of unit length) and used to calculate α', the angle which determines the proper orientation of the reflecting surface:

$$|\overline{cb}| = \frac{|\overline{ae}|^2 \csc^2\alpha\cos^2(\alpha-\alpha') - 1 + |\overline{ae}|\csc\alpha\sin(\alpha-\alpha')\sqrt{1-|\overline{ae}|^2\csc^2\alpha\cos^2(\alpha-\alpha')}}{|\overline{ae}|\cot\alpha - \sin\alpha'[\sqrt{1-|\overline{ae}|^2\csc^2\alpha\cos^2(\alpha-\alpha')} - |\overline{ae}|\csc\alpha\sin(\alpha-\alpha')]}$$

wherein the symbols ($\overline{cb}$) and ($\overline{ae}$) merely represent the magnitude of the respective vectors shown in FIG. **6**, and α is a function of α', the function being determinable from experimental data.

When, for example, the reflecting surface (such as the surface **26** of FIG. **2**) is a straight line and the vane spacing is close together then α approaches α' in magnitude and the above expression reduces to the following:

$$|\overline{cb}| = \frac{(|\overline{ae}|^2\csc^2\alpha) - 1}{|\overline{ae}|\cot\alpha - \sin\alpha\sqrt{1-|\overline{ae}|^2\csc^2\alpha}}$$

With the foregoing formulas the critical angle α' may be determined for any combination of fan speed ($\overline{cb}$) and air inlet velocity ($\overline{ae}$).

An important feature of the present invention that should now be apparent is that the critical angle α' decreases as rotor speed decreases. Thus, designing the inlet guide vane for total reflection at maximum rotor speed will assure total reflection at any slower speed. For example, if maximum rotor speed occurs at take off, then designing the vanes for total noise reflection at take off will assure a set of vanes that provides total shock wave noise reflection at all engine operating conditions where the fan is supersonic.

Referring once again to FIG. **2**, it should now be clear that the direction of noise propagation, which is a direction parallel to the line FE, varies with radial location since it is dependent upon the actual velocity of the fan blade at that particular radial location. The reflecting surface **26** may now be more precisely defined for use in the appended claims as that portion of the forward surface **18** downstream of an inmaginary surface which extends from the trailing edge **27** of an adja-

cent guide vane to the forward surface **18**, the imaginary surface being generated by lines parallel to the direction of noise propagation at each radial location along the span of the guide vanes where the relative flow of air into the fan blades is supersonic.

In FIG. **2** the reflecting surface **26** is a straight line from the point E to the trailing edge **27**. From a practical design standpoint it may often be desirable for the entire reflecting surface to be generated by straight lines, each line forming an angle of $(90-\alpha')°$ (as calculated from the foregoing formulas) with the axial direction so that all the sound waves strike the reflecting surface **26** at a 90° angle. However, as long as the tangent line to any point on the reflecting surface forms an angle of at least $(90-\alpha')°$ with the axial direction, then reflection of the sound waves back toward the fan is assured. As used in the claims, any reference to a line tangent to a vane surface means a line which is also perpendicular to the spanwise direction of the vane.

Although the invention has been shown and described with respect to a preferred embodiment thereof, it should be understood by those skilled in the art that various changes and omissions in the form and detail thereof may be made therein without departing fromthe spirit and the scope of the invention.

Having thus described typical embodiments of our invention, that which we claim as new and desire to secure by Letters Patent of the United States is:

1. In combination in a gas turbine engine, a casing, a row of stationary inlet guide vanes disposed therein, a supersonic rotor disposed downstream and adjacent said row of guide vanes, each of said guide vanes including a surface facing in a direction opposed to the direction of rotation of said rotor, said surface including a reflecting surface, the chord length of said vanes at each radial location along the span of said reflecting surface being longer than the length of said reflecting surface at said respective radial locations, and a tangent line to each point on said reflecting surface forming a downstream angle of at least 90° with a line parallel to the direction of noise propagation at each respective point on said reflecting surface.

2. The combination according to claim **1** wherein the direction of noise propagation is the direction of noise propagation calculated at maximum rotor speed.

3. The combination according to claim **1** wherein said downstream angle is 90° at each of said respective points.

4. In combination in a turbofan engine, a hub, an annular casing spaced therefrom and defining therebetween an annular inlet to the turbofan engine, a row of stationary inlet guide vanes circumferentially spaced about the circumference of said hub and extending radially across said annular inlet, a supersonic fan disposed within said casing downstream of said guide vanes, said supersonic fan comprising a disk including a plurality of circumferentially spaced radially extending fan blades attached thereto, said fan blades being spaced downstream and adjacent said guide vanes, each of said guide vanes including a surface facing in a direction opposed to the direction of rotation of said fan blades, said surface including a reflecting surface for reflecting sound waves traveling in the shock wave system created by said fan blades during engine operation, the chord length of said guide vanes at each radial location along the span of said reflecting surface being longer than the length of said reflecting surface at said respective radial locations, and a tangent line to each point on said reflecting surface forming a downstream angle of at least 90° with a line parallel to the direction of noise propagation at each respective point on said reflecting surface.

5. The combination according to claim **4** wherein said reflecting surface of each vane is defined by a plurality of straight lines, each line being both perpendicular to the spanwise direction of said vane and to the direction of noise propagation at its particular radial location.

6. The combination according to claim **5** wherein the direction of noise propagation is calculated at maximum rotor speed.

* * * * *

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 3,873,229

DATED : March 25, 1975

INVENTOR(S) : Alojzy Antoni Mikolajczak
Robert Alfred Arnoldi

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

Column 2, line 6: "upstreamtraveling" should read --upstream traveling--

Column 3, line 18: "tubofan" should read --turbofan--

Column 5, line 16: before the word "intercept" insert --completely--

Column 5, line 65: after the word "equal" insert --to--

Column 6, line 67: "inmaginary" should be --imaginary--.

Signed and Sealed this

fifth Day of *August 1975*

[SEAL]

Attest:

RUTH C. MASON
Attesting Officer

C. MARSHALL DANN
Commissioner of Patents and Trademarks