United States Patent

[11] 3,580,692

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[21] Appl. No. **843,114**
[22] Filed **July 18, 1969**
[45] Patented **May 25, 1971**
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[54] **SEAL CONSTRUCTION**
1 Claim, 4 Drawing Figs.

[52] **U.S. Cl.** **415/174,** 415/BL
[51] **Int. Cl.** **F01d 11/08**
[50] **Field of Search** 415/174, 119; 181/33.1

[56] **References Cited**

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ABSTRACT: A seal construction of the honeycomb type for turbomachinery, the cell geometry of the honeycomb being selected and arranged to provide an increase in boundary layer stability and an improvement in overall compressor or turbine performance.

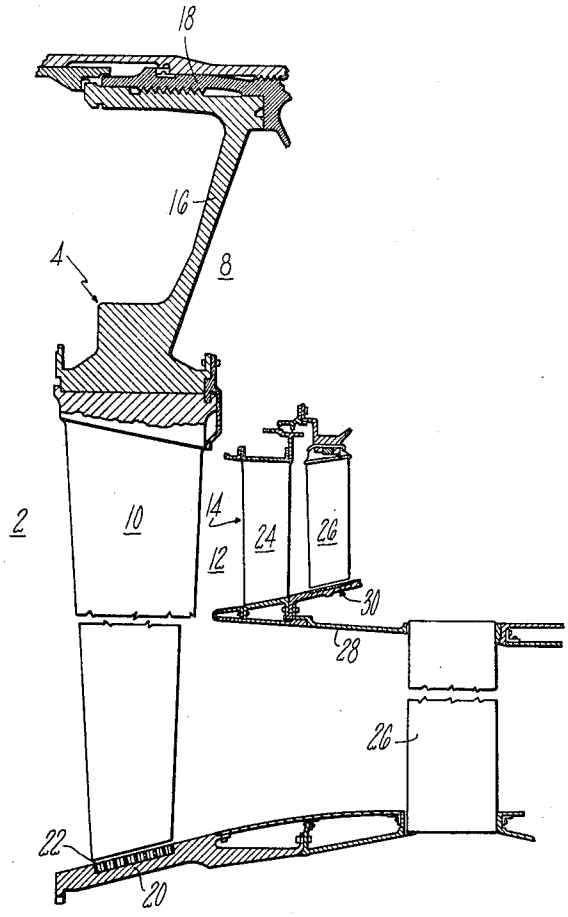
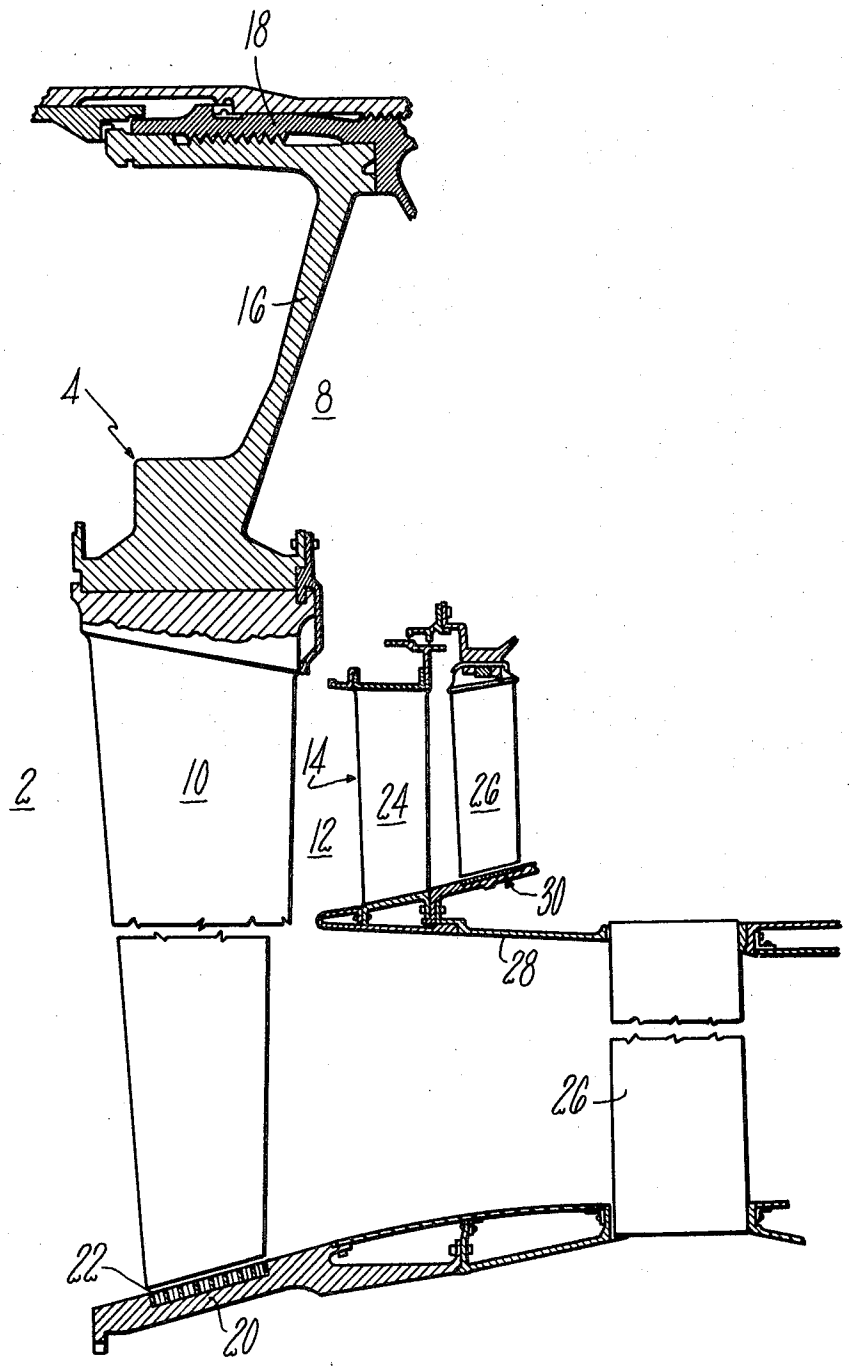


FIG. 1



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FIG. 2

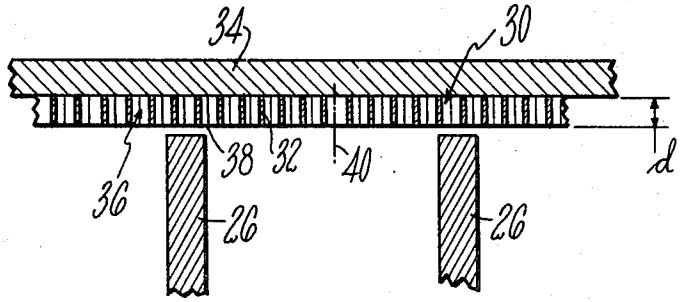


FIG. 3

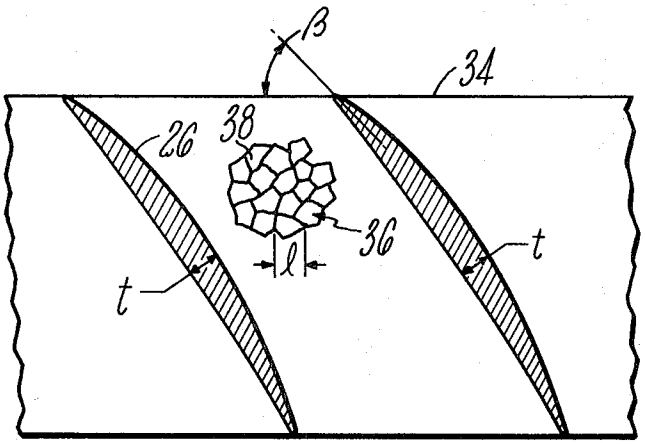
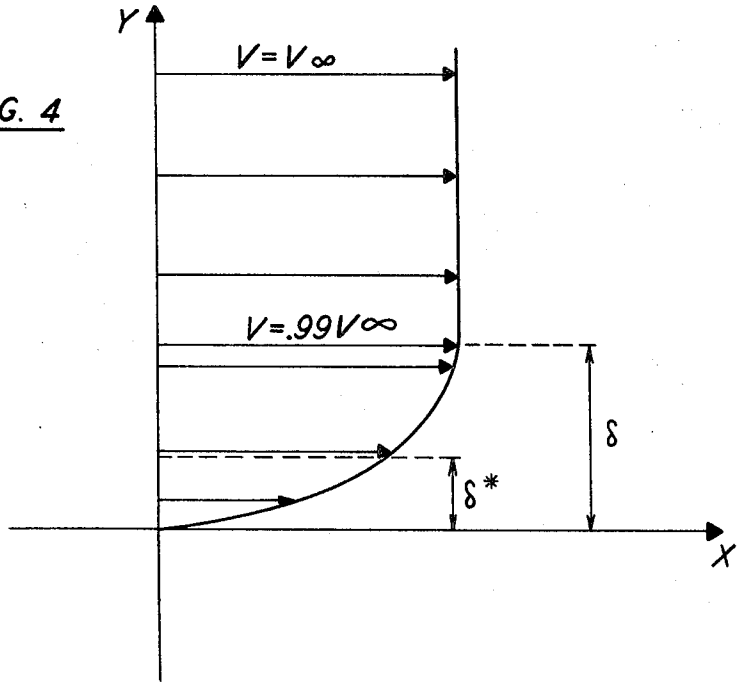


FIG. 4



SEAL CONSTRUCTION

BACKGROUND OF THE INVENTION

This invention relates to a honeycomb sealing means for turbomachinery and more particularly to a construction for improving the performance of a compressor or a turbine.

In turbomachines such as axial flow compressors and turbines, the overall operating efficiency may be adversely affected by leakage of the working fluid around the tips of the rotating airfoils. Specifically, in a compressor, leakage of the compressed fluid around the tips of the blades from high to low pressure side of the airfoils results in a loss of lift and introduces viscous losses. This in turn reduces the pressure rise capability of the compressor and causes wasteful conversion of input mechanical energy into gas energy. Similarly, leakage of fluid around the tips of the turbine blades also results in reduced work output from the turbine due to reduced pressure drop capability and wasteful conversion of gas energy into mechanical energy.

Additionally, inside the blade row there exists an adverse axial pressure gradient which the air being compressed has to negotiate. There exists a limiting value of this pressure gradient beyond which the flow at the wall will reverse locally and lead to unstable compressor operation. The shroud treatment discussed here extends the adverse pressure gradient limit thereby increasing the compressor stability margin.

The amount of working fluid leakage depends primarily upon the clearance between the tips of the rotor blades and the surrounding casing. This clearance in turn depends on the rigidity and dimensional stability of the compressor. In addition to the warpage and elastic deformation encountered in operation, the differential expansion of the compressor or turbine parts over the wide range of temperatures encountered in use makes it highly impractical to manufacture a compressor or turbine having a minimum clearance for optimum efficiency.

To minimize the clearance problems, various shroud and sealing arrangements have been used in the past. The primary objective of the prior art construction has been to surround the blade tips during operation as closely as possible. However, as hereinbefore noted, because of the different thermal transient growths and design or assembly tolerances, it has been necessary to install shrouds with relatively large tip clearances to avoid interference under all possible operating conditions. One type of shroud which the prior art has utilized to reduce tip clearance somewhat is the abradable honeycomb type seal; however, the abradable type shrouds presently available have tended to display performance losses due to surface roughness generating high turbulence on the shroud surface. In addition, after a bedding-in operation, the effective clearance is generally equal to the physical clearance. Efforts have been made to provide abradable honeycomb seals having improved aerodynamic characteristics; however, in general, the prior art constructions have not satisfactorily met this requirement. More specifically, while the abradable honeycomb seal construction may allow the compressor or turbine to operate with tighter tip clearances, it does not provide added compressor stability.

SUMMARY OF THE INVENTION

It is a primary object of this invention to provide an abradable seal of a honeycomb type capable of maintaining relatively small seal tip clearances while maintaining or improving the aerodynamic characteristics and efficiency of a compressor or turbine of a turbomachine.

For the sake of brevity and convenience, the present invention will be described in the environment of a compressor; however, it should be noted that the concept and construction hereinafter described has equal application in other areas of a turbomachine, such as the turbine or compressor fan. In a typical compressor, static pressure rises across a blade row, and to insure good compressor performance, it is necessary that the end wall support this pressure rise without boundary layer separation. The present invention utilizes a cellular shroud or honeycomb-type abradable seal construction over the blade tips and in so doing stabilizes the flow near the compressor casing or wall allowing a higher pressure rise before separation and/or desensitizing the performance of the compressor to inlet radial velocity profile changes near the cellular shroud or honeycomb seal. The present invention has determined that for optimum performance of the compressor over its entire operating range a particular relationship exists in the cell geometry of the honeycomb structure. More specifically, it has been discovered that the stability of the flow near the end wall is improved by providing a ratio between the cell depth to cell aerodynamic opening that is in the range of 0.5 to 10. It has also been determined that the absolute value of the cell aerodynamic opening depends on the thickness of the wall boundary layer entering the blade row when this boundary layer is on the verge of separation and is on the order of the boundary layer displacement thickness at separation.

A second feature of the present invention is that of improving the performance of a compressor while maintaining boundary layer stability, that is, either maintain or increase compressor efficiency while improving blade tip loading capability or tolerance to radial distortion. To accomplish this feature it is necessary that for a given tip clearance, that the leakage across the blade tip be kept low. The present invention does this by utilizing a cell structure wherein the cell aerodynamic opening is smaller than the maximum thickness of the compressor blade at its tip, and preferably limits the aerodynamic opening of each cell to a dimension that is less than one-half the blade tip thickness.

Another feature of the present invention is to reduce the effective tip clearance between the compressor blade and honeycomb seal structure and hence reduce the leakage across the blade tip. More specifically, the honeycomb seal structure is arranged, with respect to the compressor blade, on its support member, so that each of the cells of the honeycomb structure periodically discharges a fluid or air therefrom perpendicular to the blade tip and this discharge of air is to occur approximately in the time it takes the blade tip to pass the cell aerodynamic opening. The mechanism of the foregoing is that as the tips of the blade cross or pass the cell aerodynamic opening, the pressure drops rapidly over the cell aerodynamic opening causing air to be discharged from the cell perpendicular to the blade tips, the discharge being complete essentially in the time it takes the blade tip to pass the aerodynamic opening. By so doing, the effective leakage past the blade tip is reduced. To accomplish this it has been discovered that a preferred cell aerodynamic depth, determined as a function of blade tip thickness, blade tip speed, blade stagger angle and blade pressure distribution on the honeycomb seal is desired, and this cell aerodynamic depth is to be determined from the following formula:

$$d/t = k \frac{1}{U_T} \frac{1}{\sin \beta} \frac{1}{\cos^{-1} \sqrt{\frac{P \text{ suction side}}{P \text{ pressure side}}}}$$

where d = aerodynamic depth defined as volume inside the cell divided by area of aerodynamic opening

t = blade tip maximum thickness

U_T = relative velocity between airfoil and casing

β = stagger angle measured to the plane of the rotor

P = pressure on the blade surface

k = a constant depending on the motive fluid

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of a compressor and a compressor fan showing a honeycomb-type seal positioned over the blade tips.

FIG. 2 is an illustration of the cellular honeycomb shroud construction.

FIG. 3 is a fragmentary view showing several compressor blades and the cellular structure of the honeycomb seal construction.

FIG. 4 is a pictorial graph depicting boundary layer and boundary layer displacement thickness thereof.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In order to provide maximum efficient operation of an aircraft gas turbine engine, it is necessary that the blades of the compressor and turbine be positioned as close as possible to the compressor and turbine casings respectively so as to avoid large tip losses. However, during certain operating conditions the operating temperatures are such as to cause different rates of thermal expansion between these members, and also different rates of rotational growth and contraction so as to cause an interference or rubbing the casings and the blades. The present invention hereinafter described provides a cellular-type honeycomb seal which permits interference to occur between the rotating and stationary members of the engine without injury to the engine.

For the sake of brevity, the cellular-type honeycomb cell structure will be described in conjunction with the compressor fan and compressor of an engine. This is illustrative only as the present invention has utility throughout any turbomachine and in any location where it is desired to control leakage between a rotating and stationary member.

Referring first to FIG. 1, an engine inlet is indicated generally by reference character 2. As shown, the illustrated embodiment includes a fan 4 mounted downstream of inlet 2. Fan 4 is mounted forwardly of a conventional turbojet engine 8 of the type described in greater particularity in U.S. Pat. No. 2,747,367 which is assigned to the present assignee. As herein described, only a portion of engine 8 is illustrated, the remainder of the engine not being shown.

As illustrated, fan 4 includes a row of fan rotor blades 10 which are positioned forwardly of engine compressor inlet 12 and engine compressor 14. Fan rotor blades 10 are mounted in fan rotor disc 16 which is in turn rotatably mounted on shaft 18 by any appropriate means. The outer end of blades 10 rotate inside fan case wall 20, on which a cellular honeycomb shroud 22 is positioned, the honeycomb structure hereinafter being described in greater detail.

Engine compressor 14 is a conventional compressor construction and as shown includes a row of stator vanes 24, a row of rotatable blades 26 and a compressor case 28. Additionally mounted on compressor case 28 and positioned over the tips of blades 26 is a cellular honeycomb seal 30 hereinafter described.

Referring to FIGS. 2 and 3, the device of the invention is more particularly illustrated. As shown therein, a cellular honeycomb shroud or seal 30 is positioned over the tips of blades 26. The honeycomb shroud 30 is formed by a plurality of strips 32 disposed at substantially right angles, this being illustrative and not mandatory, and connected to a backing strip or casing wall 34 so that a seal construction is formed that includes a plurality of individual cells 36, sealed at one end by backing strip 34 and having an open face 38 at its other end. As herein illustrated, the alternate strips 32 may be secured to adjacent strips so as to form a complete cellular structure as shown; however, this is illustrative only inasmuch as the construction contemplated would also include a cellular honeycomb seal where the individual cells 36 are not adjacent to one another.

As hereinbefore stated, the purpose of the present invention is to improve the performance of a compressor or turbine particularly with respect to radial inlet distortion and increased wall loading. Again limiting the description to a compressor, to insure good compressor performance, the end wall or casing 34 has to support a static pressure rise across the blade row 26. The use of a cellular shroud stabilizes the flow near the casing wall 34 allowing a higher pressure rise before separation and desensitizes the performance of the compressor to inlet radial velocity profile changes near shroud 30. Additionally, it has been discovered that the stability of endwall boundary layer can be improved by maintaining the relationship of each individual cell depth "d" to cell aerodynamic opening as represented by length "1" relative to the circumferentially moving direction of the blade tip within a preferred range. More specifically, it has been determined that if the ratio is within the range of 0.5 to 10 while it has been discovered that the absolute value of "d" is dependent upon the thickness of the wall boundary layer before separation and is of the order of boundary layer displacement thickness at separation, it has been determined that within this range the modification has produced significant results in boundary layer stability. This particular feature is illustrated on FIG. 4 wherein δ represents boundary layer, V represents velocity and δ^* represents boundary layer displacement thickness. Using the relationships between these parameters, boundary layer displacement thickness can be determined from the following formula:

$$\delta^* = \int_{y=0}^{\infty} \left(1 - \frac{V}{V_\infty}\right) dy$$

The construction of the present invention also improves compressor performance while maintaining boundary layer stability. More specifically, for a given tip clearance the leakage across the blade tip has to be kept low, and, this reduction leads to an improvement in aerodynamic performance. It was discovered that to accomplish this, that a preferred relationship existed between the aerodynamic opening "1" and the blade tip thickness "t." More particularly, it was determined that the aerodynamic opening had to be less than twice the maximum thickness of the blade "t," and more preferably less than one-half "t," the tip blade thickness.

Finally, the honeycomb seal structure herein described provides a way for reducing the effective tip clearance between the blade tip and the seal, thereby further reducing the leakage across the blade tip. To accomplish this feature the individual cells 36 are arranged on the support member or backing strip 34 so that a periodic discharge of air from each cell occurs onto the blade tip approximately in the time it takes the blade tip to pass over the aerodynamic cell opening "1." To satisfy this requirement it was determined that the axis 40 of each cell 36 should be substantially perpendicular to the flow path through the compressor and that the cell aerodynamic depth "d" be determined as a function of blade tip thickness, blade tip speed, blade stagger angle and blade pressure distribution as determined with the following relationship:

$$d/t = k \frac{1}{U_T} \frac{1}{\sin \beta} \frac{1}{\cos^{-1} \sqrt{\frac{P \text{ suction side}}{P \text{ pressure side}}}}$$

where d = aerodynamic depth defined as volume inside the cell divided by area of aerodynamic opening

t = blade tip maximum thickness

U_T = relative velocity between airfoil and casing

β = stagger angle measured to the plane of the rotor

P = pressure on the blade surface

k = a constant depending on the motive fluid

I claim:

1. In a turbofan engine, a fan rotor with at least one row of fan rotor blades extending therefrom, a fan casing surrounding the rotor blades, a honeycomb-type seal supported from the fan casing, the honeycomb seal being positioned over the fan rotor blades and providing a tip clearance therebetween, the honeycomb seal including a plurality of open-faced cells, each of the cells being formed by at least one wall extending from a backing strip, the backing strip also sealing one end of the cells, said opened-faced cells face the axis of the fan rotor, the open face of each of the cells being substantially parallel to the motive flow path through the fan,

each of the cells has a cell depth "*d*" to effective face opening as represented by length "**l**" ratio substantially in the range of 0.5 to 10;

the effective face opening as represented by length "**l**" being less than one-half "t;" and

the cell aerodynamic depth of each cell is determined by the formula:

$$d/t = k \frac{1}{U_T} \frac{1}{\sin \beta} \frac{1}{\cos^{-1} \sqrt{\frac{P \text{ suction side}}{P \text{ pressure side}}}}$$

where *d* is the aerodynamic depth
t is the blade tip thickness
U_T is the tip speed
β is the blade stagger measured to the plane of the rotor
k is a constant depending on the motive fluid
P is the pressure on the blade.