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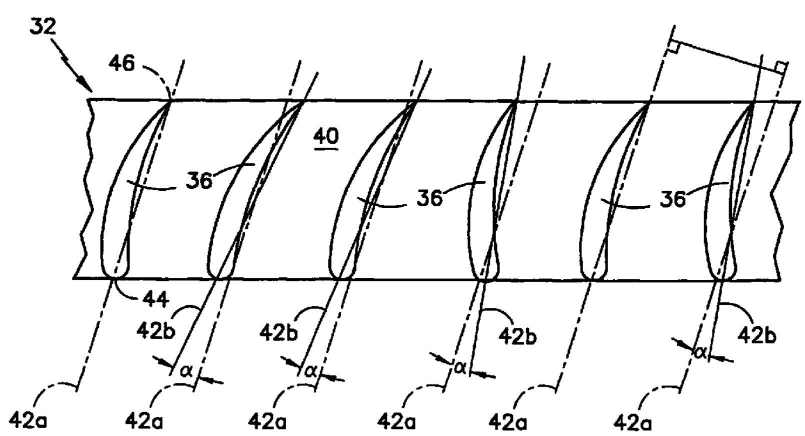
(54) Aerodynamically damping vibrations in a rotor stage of a turbomachine

(57) A rotor stage for a gas turbine engine is provided which includes a rotor disk (34) and a plurality of rotor blades (36). The rotor disk includes a bore (38) centered on the axis of rotation and an outer radial surface. The rotor blades extend radially outward from, and are distributed around, the outer radial surface. At least one of the rotor blades is selectively skewed from an adjacent rotor blade. The skewed rotor blade(s) increases the aerodynamic damping of the rotor stage.

FIG.4



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Description

[0001] This invention relates to gas turbine engine rotor assemblies in general, and to apparatus for controlling vibrations in rotor stages in particular.

[0002] Most conventional rotor stages within a gas turbine engine include a plurality of rotor blades mechanically attached to a disk for rotation around an axis. The rotor blades typically have a "fir-tree" or "dovetail" style blade root which fits into a mating slot disposed in the outer radial surface of the disk. A disadvantage of mechanically attached rotor blades is that considerable stress develops within the disk under load, adjacent the attachment slots. Increasing the disk outer diameter, and therefore the distance between adjacent slots, helps to minimize the stress. Unfortunately, increasing the disk diameter also increases the overall size and weight of the rotor stage. Recently, relatively lightweight "integrally bladed rotors" (IBR's) have become more widely used. The blades in an IBR are integrally formed (which includes blades metallurgically attached) with the disk, rather than mechanically attached to the disk. The integral blade is much more efficient at carrying the load of the blade compared to conventional mechanical attachment schemes. As a result, the size and weight of the rotor disk is advantageously minimized.

[0003] Conventional rotor stages are often tuned to avoid vibrational response and damped to minimize any vibrational response that does occur. Tuning generally refers to measures directed at changing the natural frequency(ies) of the rotor stage to avoid the frequency(ies) of periodic forcing functions present in the operating environment of the rotor stage. Damping generally refers to measures taken to minimize vibrational response caused by periodic or non-periodic (which may also be described as random) forcing functions. Periodic forcing functions operate at discrete frequencies and can cause a resonant response in the rotor blade as the frequency of the forcing function reaches unity with a natural frequency of the rotor blade. Non-periodic forcing functions, on the other hand, do not operate at a particular frequency, but rather cause the rotor blade to respond (deflect) in a non-periodic fashion. In the absence of sufficient damping, both periodic and non-periodic excitation forces can produce high blade vibratory responses for all modes of vibration present in the operating speed range.

[0004] Mechanical, aerodynamic, and material damping represent the three principal types of damping potentially of use in a rotor stage. Material damping, although occurring in conventional rotor stages and IBR's alike, is the least efficient of the three and generally will not, by itself, provide adequate damping for a rotor blade. Mechanical damping, on the other hand, is the most efficient of the three types and can be accomplished by several different methods. In one method, vibrational motion is damped by friction between a blade root and disk slot; i.e., "blade root" damping. In another method, frictional devices are externally or internally attached to a rotor blade to damp motion. In a further example, blade-to-blade shrouds are used to dissipate energy along the blade tips. These examples of mechanical damping are not, however, practical with most IBR's because of the integral nature of the IBR blades. Separate damper devices between IBR rotor blades and the disk or devices between adjacent IBR rotor blades are not practical either.

[0005] Aerodynamic damping generally refers to the exchange of work between the rotor stage and the air passing through the rotor stage. If the net work done by the air on a rotor blade, for example, exceeds the work done by the rotor blade on the air, then the air adds energy to the blade. This reflects an unstable condition, where blade oscillations can begin and/or increase in magnitude and ultimately result in fatigue. On the other hand, if the net work done by a rotor blade on the air exceeds the work done by the air on the rotor blade, then the rotor blade dissipates energy into the air flow. This transfer of energy away from the rotor blade reflects the desirable condition of aerodynamic damping.

[0006] Hence, what is needed is apparatus and/or a method for damping vibrational responses in a rotor stage, one that may be used in an IBR, one that damps periodic forcing functions and non-periodic (random) perturbations, and one that effectively damps vibrations in moderate and low aspect rotor blades.

[0007] According to a first aspect of the present invention, a rotor stage for a gas turbine engine is provided which includes a rotor disk and a plurality of rotor blades. The rotor blades extend radially outward from, and are distributed around, the outer radial surface of the rotor disk. At least one of the rotor blades is selectively skewed from an adjacent rotor blade. In one preferred embodiment, the chordline of at least one rotor blade is selectively skewed relative to the chordline of an adjacent rotor blade. The skewed rotor blade(s) increases the aerodynamic damping of the rotor stage.

[0008] From an aerodynamic damping point of view, energy transmitted to the rotor blades may be described as unsteady work done by the blade on the air passing by the blade during a cycle of oscillation, using the following mathematical expression:

$$\oint\int \tilde{P}(x,y,z,t) \cdot W(x,y,z,t)dAdt$$

where $\tilde{P}(x,y,z,t)$ represents the difference in unsteady air pressure acting on the suction and pressure side surfaces of the rotor blade at any point as a function of time as a result of the blade undergoing a vibratory motion, and W(x,y,z,t) represents the deflection of the rotor blade in any direction as a function of time. The work expression is integrated over time period "T", where "T" equals the time duration of one blade oscillation. Positive work per cycle (indicated by a positive value of the work expression) describes work being done on the blade by the passing air; i.e., an unstable condition. Negative work per cycle (indicated by a negative value of the work expression) indicates that work is being done by the blade on the passing air; i.e., the desirable condition of aerodynamic damping. A zero value of the work expression is referred to as a neutral condition; i.e., the blade is neither receiving nor doing work.

[0009] Because the goal of aerodynamic damping is to damp a given mode of vibration, one can assume that the deflection term W(x,y,z,t) in the above equation can be considered a non-variant. Aerodynamic damping can be achieved, therefore, by manipulating the unsteady pressure variable ($\tilde{P}(x,y,z,t)$) to ensure work is being done by the blade as opposed to being done on the blade. The difference in unsteady pressure acting on the rotor blade is a function of : 1) the air passing the rotor blade; 2) the volume of air between adjacent rotor blades; and 3) the relative motion of the adjacent blades. In the present invention, the unsteady aerodynamic characteristics of the air between adjacent rotor blades are being manipulated by selectively skewing the chordline of at least one rotor blade relative to an adjacent rotor blade(s) to increase the resultant aerodynamic damping.

[0010] Viewed from a second aspect, the present invention provides a method of damping vibrations in a rotor stage for a gas turbine engine which comprises a rotor disk having a plurality of rotor blades extending radially outward from, and distributed around, the outer radial surface of the disk, wherein at least one of the rotor blades is skewed from a parallel orientation to increase aerodynamic damping of the rotor stage.

[0011] An advantage of the present invention is that a means for aerodynamic damping is provided. In some applications, aerodynamic damping can be used to augment mechanical and/or material damping. In other applications where mechanical and/or material damping is limited (e.g., an IBR), aerodynamic damping can be provided as a principle means of damping.

[0012] Another advantage of the present invention is that rotor stage damping apparatus is provided that is effective against vibrations caused by periodic forcing functions and non-periodic perturbations. The selective rotor blade skewing of the present invention enables the rotor blades to do work on the air passing the rotor blade, regardless of whether the blade is subject to a periodic forcing function or a non-periodic perturbation.

[0013] Another advantage of the present invention is that vibrations in moderate and low aspect ratio rotor blades can be effectively damped. Moderate and low aspect ratio rotor blades, conventionally attached or integrally formed, are particularly susceptible to chordal modes of vibration. The selective rotor blade skewing of the present invention enables the rotor blades to damp deflections caused by periodic and nonperiodic perturbations of fundamental as well as complex chordal modes of vibration.

[0014] Another advantage of the present invention is that it does not require additional hardware, internal blade machining, or the like. Rather, the present invention provides damping by selectively skewing at least one rotor blade. A person of skill in the art will recognize that simplicity generally equates to reliability.

[0015] Certain preferred embodiments of the present invention will now be described by way of example and with reference to the accompanying drawings, in which:

FIG. 1 is a diagrammatic sectioned view of a gas turbine engine;

FIG. 2 is a diagrammatic perspective partial view of a prior art gas turbine rotor stage;

FIG. 3 shows a linear representation of rotor blades extending out from a rotor disk to illustrate a prior art parallel rotor blade orientation, as evidenced by the parallel chordlines of the rotor blades; and

FIG. 4 shows a linear representation of rotor blades extending out from a rotor disk to illustrate a rotor blade(s) skewed from a parallel orientation, as evidenced by the skewed chordline(s) of the rotor blade(s).

[0016] Referring to FIG. 1, a gas turbine engine 10 includes a fan 12, a low pressure compressor 14, a high pressure compressor 16, a combustor 18, a low pressure turbine 20, a high pressure turbine 22, an augmentor 24, and a nozzle 26 symmetrically disposed relative to an axis of rotation 28. The fan 12 is forward of the nozzle 26 and the nozzle 26 is aft of the fan 12. The fan 12 and the low pressure compressor 14 are connected to one another and are driven by the low pressure turbine 20. The high pressure compressor 16 is driven by the high pressure turbine 22. Air worked by the fan 12 will either enter the low pressure compressor 14 as or will enter a passage 30 outside the engine core as "bypass air".

[0017] Referring to FIGS. 2-4, a rotor stage 32 includes a disk 34 and a plurality of rotor blades 36. The disk 34 includes a bore 38 centered on the axis of rotation 28 and an outer radial surface 40. The rotor blades 36 extend radially outward from the outer radial surface 40 and may be attached to the disk 34 via conventional attachment methods (e.g., fir tree or dovetail root - not shown) or may be integrally attached as a part of an integrally bladed rotor (IBR). Each rotor blade 36 has a chordline 42 that extends between the leading edge 44 and the trailing edge 46 of the rotor blade 36.

[0018] A conventional rotor stage 32, shown in FIGS. 2 and 3, has rotor blades 36 equally spaced apart from one another, distributed around the circumference of the rotor disk 34. Each rotor blade 36 is in parallel orientation with the other rotor blades 36 in the stage 32, as is evidenced by the parallel chordlines 42 of the rotor blades 36. In the present invention, one or more rotor blades 36 may be selectively skewed from the conventional parallel orientation to achieve an increase in aerodynamic damping. The amount a rotor blade 36 is skewed, if at all, depends upon the application at hand. In most applications, a rotor blade 36 may be skewed up to five degrees (5°) from the conventional parallel orientation, in either direction (if adjacent rotor blades 36 are oppositely skewed, the difference may be 10° total). In the preferred embodiment, a rotor blade 36 is skewed no more than three degrees (3°) from the conventional parallel orientation, in either direction. FIG. 4 shows several rotor blades 36 skewed from conventional parallel orientation, in both directions, to illustrate an embodiment of the present invention. The skew angle is shown as "α" extending between the position of the chordline 42a associated with the parallel orientation, and the chordline 42b associated with the skewed rotor blade 36. The optimum skew of each rotor blade 36 in a rotor stage 32 (and therefore the optimum damping) is a function of the circumstances of the application, and can be determined analytically or empirically.

[0019] In some applications, a majority of the rotor blades 36 are maintained in a parallel orientation, and only a few rotor blades 36 are skewed from the parallel orientation. In other applications, a majority or all of the rotor blades 36 will be skewed from the parallel orientation.

[0020] Thus, it will be seen that at least in the illustrated embodiments, the present invention provides a rotor stage for a gas turbine engine that includes apparatus for damping vibrations; which may be used for damping vibrations in an IBR; which is effective against vibrations caused by periodic forcing functions and non-periodic perturbations; and which effectively damps vibrations in moderate and low aspect ratio rotor blades.

[0021] Although this invention has been shown and described with respect to the detailed embodiments thereof, it will be understood by those skilled in the art that various changes in form and detail thereof may be made without departing from the scope of the invention as defined by the following claims.

Claims

1. A rotor stage for a gas turbine engine, for rotating around an axis of rotation (28), comprising a rotor disk (34) having a plurality of rotor blades (36) extending radially outward from, and distributed around, the outer radial surface (40) of the disk, wherein at least one of said rotor blades is skewed relative to an adjacent said rotor blade.

2. A rotor stage for a gas turbine engine, for rotating around an axis of rotation (28), comprising a rotor disk (34) having a plurality of rotor blades (36) extending radially outward from, and distributed around, the outer radial surface (40) of the disk, each rotor blade having a chordline (42), wherein said chordline (42b) of at least one of said rotor blades is selectively skewed relative to said chordline (42a) of an adjacent said rotor blade.

3. A rotor stage according to claim 2, wherein said chordline (42b) of said at least one said rotor blade (36) is skewed not more than 10° from said chordline (42a) of said adjacent said rotor blade.

4. A rotor stage according to claim 3, wherein said chordline (42b) of said at least one said rotor blade (36) is skewed not more than 5° from said chordline (42a) of said adjacent said rotor blade.

5. A rotor stage according to claim 4, wherein said chordline (42b) of said at least one said rotor blade (36) is skewed not more than 3° from said chordline (42a) of said adjacent said rotor blade.

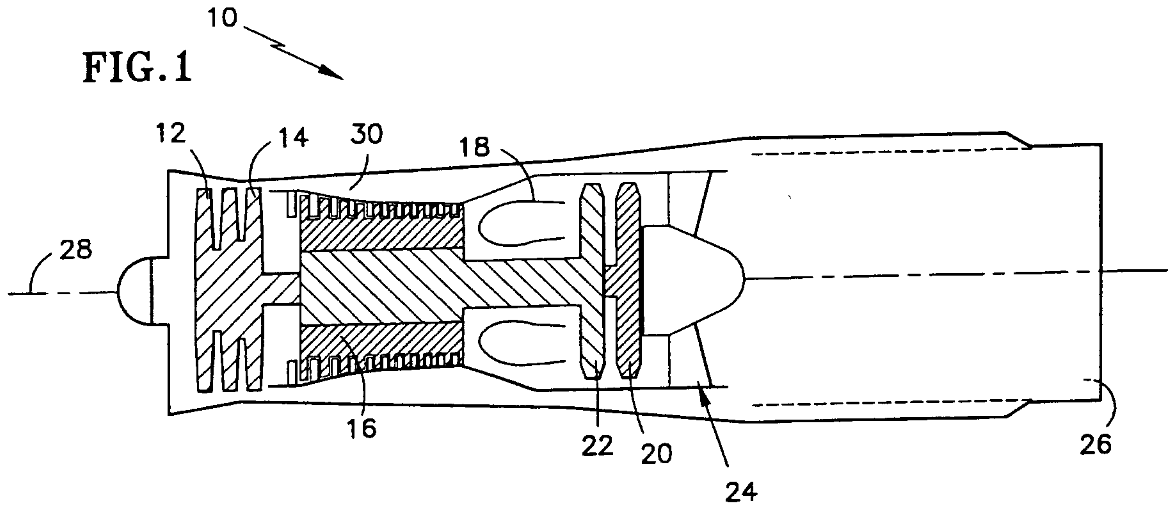
6. A rotor stage according to claim 2, wherein said chordline (42b) of said at least one said rotor blade (36) is skewed not more than 5° from a parallel orientation of said rotor blades.

7. A rotor stage according to claim 6, wherein said chordline (42b) of said at least one said rotor blade (36) is skewed not more than 3° from said parallel orientation of said rotor blades.

8. A rotor stage according to any preceding claim, wherein said rotor stage is an integrally bladed rotor.

9. A method of damping vibrations in a rotor stage for a gas turbine engine which comprises a rotor disk (34) having a plurality of rotor blades (36) extending radially outward from, and distributed around, the outer radial surface (40) of the disk, wherein at least one of the rotor blades is skewed from a parallel orientation to increase aerodynamic damping of the rotor stage.

FIG. 1



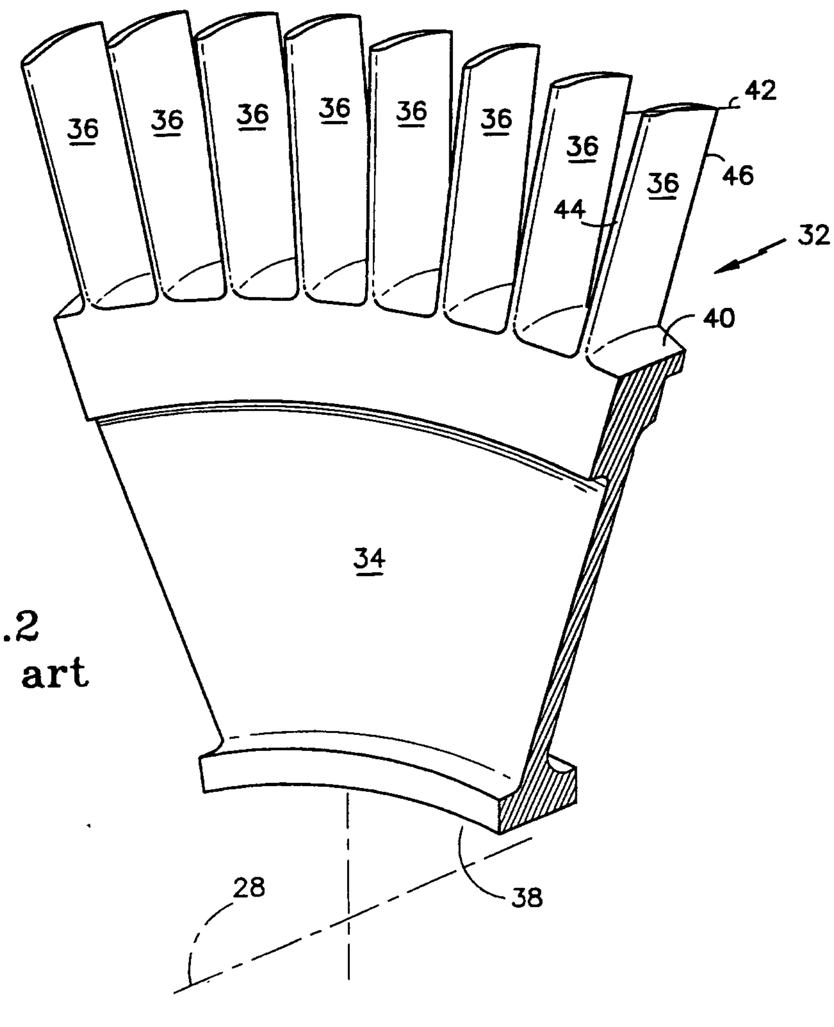


FIG.2
prior art

FIG.3
prior art

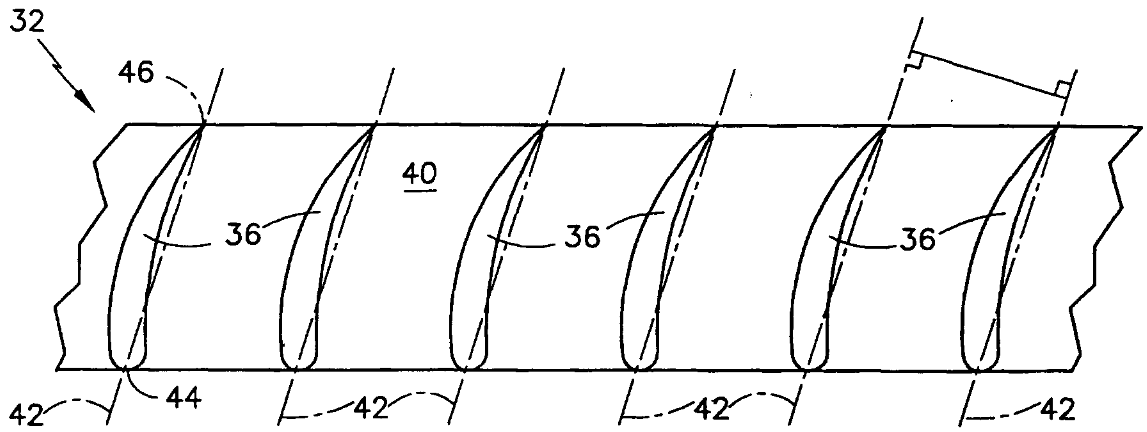


FIG.4