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United States Patent	12385400
Kind Code	B2
Date of Patent	August 12, 2025
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Method of manufacturing a mistuned rotor

Abstract

A method includes: obtaining a rotor having a hub and a plurality of blades protruding from the hub, the plurality of blades including first blades and second blades disposed in alternation around a central axis of the rotor, natural vibration frequencies of the first blades different from natural vibration frequencies of the second blades; determining that a difference between a first natural vibration frequency of a first blade of the first blades and a second natural vibration frequency of a second blade of the second blades is below a threshold; and modifying a shape of the first blade until the difference between the first natural vibration frequency and the second natural vibration frequency is at or above the threshold.

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Appl. No.: **17/661454**

Filed: **April 29, 2022**

Prior Publication Data

Document Identifier	Publication Date
US 20230349297 A1	Nov. 02, 2023

Publication Classification

Int. Cl.: **F01D5/16** (20060101); **B23H9/10** (20060101); **F01D5/14** (20060101)

U.S. Cl.:

CPC **F01D5/16** (20130101); **B23H9/10** (20130101); **F01D5/141** (20130101); F05D2240/303 (20130101); F05D2240/304 (20130101); F05D2240/305 (20130101); F05D2260/961 (20130101)

Field of Classification Search

CPC: F01D (5/16); F05D (2240/303); F05D (2240/304); F05D (2240/305); F05D (2260/961)

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Background/Summary

TECHNICAL FIELD
(1) The disclosure relates generally to turbine engines and, more particularly, to rotors, such as integrally bladed rotors.
BACKGROUND
(2) Compressor rotors of gas turbine engines, such as the fan of a turbofan, may experience two main types of aerodynamic instability: stall flutter and supersonic flutter. Stall flutter (sometimes simply called "flutter") is sub-sonic or transonic and may occur when two or more adjacent blades in a blade row vibrate at a frequency close to their natural vibration frequency and the vibration motion between the adjacent blades is substantially in phase. Stall flutter also typically occurs over a limited speed band. Supersonic flutter occurs in the high speed regime of the compressor or fan where tip speed is very high. Supersonic flutter may occur under certain flight conditions. Prolonged operation of a fan or compressor rotor undergoing supersonic flutter can produce a potentially undesirable result caused by airfoil stress load levels exceeding threshold values.
(3) Improvements are therefore sought.
SUMMARY
(4) In one aspect, there is provided a method comprising: obtaining a rotor having a hub and a plurality of blades protruding from the hub, the plurality of blades including first blades and second blades disposed in alternation around a central axis of the rotor, natural vibration frequencies of the first blades different from natural vibration frequencies of the second blades; determining that a difference between a first natural vibration frequency of a first blade of the first blades and a second natural vibration frequency of a second blade of the second blades is below a threshold; and modifying a shape of the first blade until the difference between the first natural vibration frequency and the second natural vibration frequency is at or above the threshold.
(5) The method may include any of the following features, in any combinations.
(6) In some embodiments, the method includes identifying a zone on the first blade, the modifying of the shape of the first blade including modifying the shape of the first blade by modifying the shape of the first blade within the zone.
(7) In some embodiments, the modifying of the shape of the first blade within the zone includes removing matter from the first blade within the zone.
(8) In some embodiments, the modifying of the shape of the first blade includes modifying a shape of a pressure side of the first blade.
(9) In some embodiments, the modifying of the shape of the first blade includes modifying the shape of the first blade within a zone on an aerodynamic surface of the first blade.
(10) In some embodiments, the modifying of the shape of the first blade within the zone includes modifying the shape of the first blade within the zone located radially outwardly of a mid-span line of the first blade.

(11) In some embodiments, the modifying of the shape of the first blade within the zone includes modifying the shape of the first blade within the zone being offset from a leading edge of the first blade.
(12) In some embodiments, the modifying of the shape of the first blade within the zone includes modifying the shape of the first blade within the zone being offset form a trailing edge of the first blade.
(13) In some embodiments, the modifying of the shape of the first blade within the zone includes modifying the shape of the first blade by creating a recessed area within the zone.
(14) In some embodiments, the creating of the recessed area includes increasing a depth of the recessed area from a perimeter of the zone toward a location within the zone, a depth of the recessed area being maximal at the location.
(15) In some embodiments, the location is offset from a center of the zone.
(16) In another aspect, there is provided a rotor comprising: a hub having a central axis; and a plurality of blades protruding from the hub and including: first blades circumferentially distributed around the central axis, and second blades disposed in alternation with the first blades around the central axis, a first natural frequency of a first blade of the first blades differing from a second natural frequency of a second blade of the second blades adjacent the first blade, at least one of the first blades having a modified shape different from a baseline shape of a remainder of the first blades, the modified shape differing from the baseline shape at a zone on the at least one of the first blades.
(17) The rotor may include any of the following features, in any combinations.
(18) In some embodiments, the modified shape is substantially identical to the baseline shape but for the zone.
(19) In some embodiments, the at least one of the first blades defines a recessed area within the zone.
(20) In some embodiments, a depth of the recessed area increases from a perimeter of the zone toward a location within the zone, a depth of the recessed area maximal at the location.
(21) In some embodiments, the location is offset from a center of the zone.
(22) In some embodiments, the zone is located radially outwardly of a mid-span line of the at least one of the first blades.
(23) In some embodiments, the zone is offset from a leading edge of the at least one of first blades and from a trailing edge of the at least one of the first blades.
(24) In some embodiments, the zone is located on a pressure side of the at least one of the first blades.
(25) In some embodiments, the hub and the plurality of blades are parts of a single monolithic body.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) Reference is now made to the accompanying figures in which:
(2) FIG. **1** is a schematic cross-sectional view of an aircraft engine depicted as a gas turbine engine;
(3) FIG. **2** is a three dimensional view of a frequency mistuned integrally bladed rotor of the gas turbine engine shown in FIG. **1**;
(4) FIG. **3** is a graph illustrating natural frequency difference between each two circumferentially adjacent blades of the rotor of FIG. **2**;
(5) FIG. **4** is a plan view of one of the blades of the rotor of FIG. **2**;
(6) FIG. **5** is a graph illustrating a variation of a depth of a zone of the blade of FIG. **4** as a function of a chordwise position;

(7) FIG. **6** is a graph illustrating a variation of the depth of the zone of the blade of FIG. **4** as a function of a spanwise position; and
(8) FIG. **7** is a flowchart illustrating steps of a method of manufacturing a rotor, such as a fan or compressor rotor, in accordance with one embodiment.

DETAILED DESCRIPTION

(9) FIG. **1** illustrates an aircraft engine depicted as a gas turbine engine **10** of a type preferably provided for use in subsonic flight, generally comprising in serial flow communication a fan **12** through which ambient air is propelled, a compressor section **14** for pressurizing the air, a combustor **16** in which the compressed air is mixed with fuel and ignited for generating an annular stream of hot combustion gases, and a turbine section **18** for extracting energy from the combustion gases. The fan **12**, the compressor section **14**, and the turbine section **18** are rotatable about a central axis **11** of the gas turbine engine **10**. In the embodiment shown, the gas turbine engine **10** comprises a high-pressure spool having a high-pressure shaft **20** drivingly engaging a high-pressure turbine **18**A of the turbine section **18** to a high-pressure compressor **14**A of the compressor section **14**, and a low-pressure spool having a low-pressure shaft **21** drivingly engaging a low-pressure turbine **18**B of the turbine section to a low-pressure compressor **14**B of the compressor section **14** and drivingly engaged to the fan **12**. It will be understood that the contents of the present disclosure may be applicable to any suitable engines, such as turboprops and turboshafts, and reciprocating engines, such as piston and rotary engines without departing from the scope of the present disclosure. Although illustrated as a turbofan engine, the gas turbine engine **10** may alternatively be another type of engine, for example a turboshaft engine, also generally comprising in serial flow communication a compressor section, a combustor, and a turbine section, and a fan through which ambient air is propelled. A turboprop engine may also apply. In addition, although the engine **10** is described herein for flight applications, it should be understood that other uses, such as industrial or the like, may apply.
(10) FIG. **2** illustrates a rotor R of the gas turbine engine **10**, which herein corresponds to the fan **12** of the gas turbine engine **10**, which is sometimes referred to as a first stage or low pressure compressor. It will be appreciated that the principle of the present disclosure may apply to any rotor of the gas turbine engine **10** such as, for instance, a compressor rotor, an impeller, to name a few. In some embodiments, the fan **12** is a mistuned integrally bladed rotor with slightly different alternating blade geometries. This difference in geometry is to achieve different natural frequencies between the blades which may prevent unstalled supersonic flutter of the fan blades.
(11) In the embodiment shown, the fan **12** includes a central hub **22**, which in use rotates about the central axis **11**, and a circumferential row of fan blades **24** that are circumferentially distributed and which project from the hub **22** in a span-wise direction (which may be substantially radially). The fan **12** may be either a bladed rotor, wherein the fan blades **24** are separately formed and fixed in place on the hub **22**, or the fan **12** may be an integrally bladed rotor (IBR), wherein the fan blades **24** are integrally formed with the hub **22**. In other words, the hub **22** and the blades **24** may be parts of a single monolithic body. Such an integrally bladed rotor is also referred to as a BLISK (Bladed Disk). Each circumferentially adjacent pair of the fan blades defines an inter-blade passage **26** therebetween for the working fluid.
(12) The circumferential row of fan blades **24** of the fan **12** includes two or more different types of fan blades **24**, in the sense that a plurality of sets of blades are provided, each set having airfoils with non-trivially different mechanical properties, including but not limited to natural vibrational frequencies. More particularly, these two or more different types of fan blades **24** are composed, in this example, of successively circumferentially alternating sets of fan blades, each set including at least first and second fan blades **28** and **30** (the blades **28** and **30** having airfoils that are different from one another). More than two sets of blades may be used. The different blades are distributed around the central axis **11** (e.g. A-B-A-B; A-B-C-A-B-C; etc.).
(13) In some embodiments, the first and second blades **28**, **30** may have identical geometries and

may be mistuned by being made of different materials. Any suitable ways of mistuning the first blades **28** from the second blades **30** are contemplated.

(14) The flutter may be effectively prevented only when the frequencies of alternating blades differ by a minimum value. Functional analysis is performed on each of the manufactured fan to assess their functional requirements. FIG. **3** presents results of this analysis. As illustrated, the rotor analysed, and for which FIG. **3** present the results of this analysis, does not meeting the frequency separation functional requirement. More specifically, two blades represented by points P**1** and P**2** on FIG. **3** may not be sufficiently mistuned from one another. Stated differently, the difference in natural vibration frequency between these blades is below a given threshold (represented by line L), which is undesired. This may occur because of manufacturing tolerances or other manufacturing parameters. The present disclosure presents a method of re-working such machined rotor which otherwise may have to be discarded due to non-compliance. In other words, because the blades are a monolithic part of the rotor with the hub, it may not be possible to simply substitute a new blade.

(15) Referring to FIG. **4**, a blade is shown at **40**. The blade **40** may be one of the first blades **28** or one of the second blades **30** of the rotor R (e.g., fan **12**). The blade **40** has an airfoil **41** that extends from a base **42** to a tip **43**. The blade **40** has a leading edge **44** and a trailing edge **45** downstream of the leading edge **44** relative to a direction of a flow through the fan **12**. The blade **40** has a pressure side **46** that extends from the base **42** to the tip **43** along a spanwise axis S and that extends from the leading edge **44** to the trailing edge **45** along a chordwise axis C. The blade **40** as a suction side **47** (FIG. **2**) opposite the pressure side **46** and that that extends from the base **42** to the tip **43** along the spanwise axis S and that extends from the leading edge **44** to the trailing edge **45** along the chordwise axis C.

(16) The blade **40** may correspond to one of either the first blades **28** or the second blades **30** that has been modified to meet mistuning requirements. In other words, the blade has a modified shape that substantially corresponds to a baseline shape of either the first blades **28** or the second blades **30**. In the present embodiment, the modified and baseline shapes differ from one another at a zone **50** on the blade **40**. Put differently, the modified shape is substantially identical to the baseline shape but for the zone **50**. Herein, the expression “substantially” implies that some minor differences may be present because of manufacturing tolerances. These differences in shapes may be invisible to the naked eye. Thus, a major portion of the blade **40** may be substantially identical to a corresponding major portion of either the first blades **28** or the second blades **30**. Herein, the expression “major” implies an entirety of a surface of the blade **40** but for the zone **50**. Herein, “substantially identical” implies that differences between the two blades outside the zone **50** would be less than from about 0.010 inch to about 0.02 inch at any point. Herein, “about” implies variations of plus or minus 10%.

(17) In the embodiment shown, the zone **50** has a substantially rectangular shape with rounded corners. However, any other suitable shapes (e.g., trapezoid, square, triangular, circular, ellipsoid, etc.) may be used. A rectangular or square shape may be simpler to design because it may have symmetry on two axes. The zone **50** may be substantially centered between the leading and trailing edges **44**, **45**.

(18) In the present embodiment, the blade **40** defines a recessed area **51** within the zone **50**. Therefore, a surface of the blade **40** may be offset from a baseline surface of the blade **40** within the recessed area **51**. A distance between the surface of the blade **40** within the zone **50** and the baseline surface of the blade **40** may define a depth of the recessed area **51**. Thus, for creating the modified shape of the blade **40**, material may be removed from the zone **50** of the blade **40**. In some other embodiments, material may be added (e.g., bonded, brazed, fastened, welded, etc.) to the zone **50** of the blade **40**.

(19) In the embodiment shown, the zone **50** is located radially outwardly of a mid-span line M. The zone **50** is herein offset from the leading edge **44** of the airfoil **41** and offset from the trailing edge

45 of the airfoil **41**. In some other embodiments, the zone **50** may extend up to the leading edge **44** and/or up to the trailing edge **45**. The zone **50** is herein located on the pressure side **46** of the airfoil **41**. Alternatively, the zone **50** may be located on the suction side **47** of the airfoil **41**. In some other embodiments, the zone **50** may include a plurality of zones separated from one another; these zones being located on the pressure side **46** and/or the suction side **47**. In some embodiments, it may be preferable to have the zone **50** on the pressure side rather than on the suction side for aerodynamics reasons. The zone **50** may occupy from 3% to 30%, preferably about 10%, of a surface area of the pressure side of the airfoil **41**.

(20) Referring now to FIGS. **5-6**, depth distributions are shown along the chordwise axis C (FIG. **5**) and along the spanwise axis S (FIG. **6**). As illustrated, a depth of the recessed area **51** at the zone **50** increases from a perimeter **52** of the zone **50** to a location **53** where the depth is maximal. This location **53** may correspond to a center of the zone **50**, or as shown in FIGS. **5-6**, is offset from said center. As shown, the maximal depth is about 0.02 inch. Herein, "about" implies variations of plus or minus 10%. In the embodiment shown, a ratio of a maximum depth of the zone **50** to a maximum thickness of a baseline shape the blade (i.e., without the zone **50**) ranges from 0.01 to 0.1. This maximum thickness is taken at a spanwise location registering with the location **53**.

(21) On FIG. **5**, the abscissa denotes the chordwise position from the leading edge **44** at **0** to the trailing edge **45** at **1**. As illustrated in FIG. **5**, a rate of variation of the depth is greater from the leading edge **44** to the location **53** of greatest depth than from the location **53** to the trailing edge **45**. The recessed area **51** may merge smoothly to the baseline surface of the airfoil **41** at the perimeter **52** of the zone **50**. In the disclosed embodiment, the location **53** of greatest depth is closer to the leading edge **44** than to the trailing edge **45**. The location **53** may be at about 40% of a chord of the airfoil **41** from the leading edge **44**. The chord is taken at a corresponding spanwise position of the location **53**. In some embodiments, a maximum depth and a location (chordwise position, spanwise position) of the location **53** of maximum depth is determined first. A remainder of the shape of the zone **50** is determined after such that the zone **50** merges smoothly into a remainder of the blade.

(22) On FIG. **6**, the abscissa denotes the spanwise position from the base **42** at **0** to the tip **43** at **1**. As illustrated in FIG. **6**, a rate of variation of the depth is greater from the base **42** to the location **53** of greatest depth than from the location **53** to the tip **43**. The recessed area **51** may merge smoothly to the baseline surface of the airfoil **41** at the perimeter **52** of the zone **50**. In the disclosed embodiment, the location **53** of greatest depth is closer to tip **43** than to the base **42**. The location **53** may be at about 60% of a span of the airfoil **41** from the base **42**. The span is taken at a corresponding chordwise position of the location **53**.

(23) The thickness distribution of the zone **50** in the chordwise and spanwise directions may be any suitable distribution such as, for instance, sinusoidal, quadratic, etc.

(24) Referring now to FIG. **7**, a method of manufacturing the rotor R is shown at **700**. The method **700** includes obtaining the rotor R having the hub and the plurality of blades protruding from the hub, the plurality of blades including first blades **28** and second blades **30** disposed in alternation around the central axis **11**, natural vibration frequencies of the first blades different from natural vibration frequencies of the second blades at **702**; determining that a difference between a first natural vibration frequency of a first blade of the first blades and a second natural vibration frequency of a second blade of the second blades is below a threshold at **704**; and modifying a shape of the first blade until the difference between the first natural vibration frequency and the second natural vibration frequency is at or above the threshold. The determining that the difference between the natural vibration frequencies is below the threshold at **704** may include identifying which pair of adjacent blades have their natural vibration frequencies differing by less than the threshold.

(25) The method **700** may include identifying the zone **50** on the first blade **40**, the modifying of the shape of the first blade **40** may include modifying the shape of the first blade by modifying the

shape of the first blade **40** within the zone **50**. This may be done by removing matter from the first blade within the zone **50**. In some embodiments, the modifying of the shape of the first blade **40** includes modifying a shape of the pressure side **46** of the first blade **40**. Any aerodynamic surface of the first blade **40** may be modified (e.g., suction side **47**, tip **43**, etc.). In some embodiments, both blades may be modified to achieve the desired difference in natural vibration frequencies.
(26) In the present embodiment, the modifying of the shape of the first blade within the zone **50** includes modifying the shape of the first blade **40** within the zone **50** located radially outwardly of the mid-span line M of the first blade **40**. The modifying of the shape of the first blade **40** within the zone **50** may include modifying the shape of the first blade **40** within the zone **50** being offset from the leading edge **44** of the first blade **40**. The modifying of the shape of the first blade **40** within the zone **50** may include modifying the shape of the first blade **40** within the zone **50** being offset form the trailing edge **45** of the first blade **40**. The modifying of the shape of the first blade **40** within the zone **50** may include modifying the shape of the blade by creating the recessed area **51** within the zone **50**. The creating of the recessed area **51** may include increasing the depth of the recessed area **51** from the perimeter **52** of the zone **50** toward the location **53** within the zone **50** where the depth of the recessed area **51** is maximal.
(27) In some embodiments, it may be required to compensate a rotational imbalance created by the removal of material from the zone **50**. This may be done using, for instance, counterweights. Alternatively, or in combination, a blade located at a diametrically opposed location of the blade that defines the zone **50** may also be modified to remove material to create a similar zone. This may alleviate the rotational imbalance. This may further help an overall mistuning of the rotor.
(28) The embodiments described in this document provide non-limiting examples of possible implementations of the present technology. Upon review of the present disclosure, a person of ordinary skill in the art will recognize that changes may be made to the embodiments described herein without departing from the scope of the present technology. Yet further modifications could be implemented by a person of ordinary skill in the art in view of the present disclosure, which modifications would be within the scope of the present technology.

Claims

1. A method comprising: manufacturing a rotor having a hub and a plurality of blades protruding from the hub, the plurality of blades including first blades and second blades disposed in alternation around a central axis of the rotor to form pairs, a pair of the pairs including a first blade of the first blades disposed adjacent to a second blade of the second blades, the first blades having a natural vibration frequency differing from a natural vibration frequency of the second blades by a frequency difference for mistuning the rotor, the rotor being an integrally bladed rotor such that the plurality of blades and the hub are parts of a monolithic body of the rotor; performing an analysis on the monolithic body of the rotor with the plurality of blades and the hub to obtain actual frequency differences for each of the pairs; determining that an actual frequency difference corresponding to the pair of the pairs is below a minimum threshold; and re-working the integrally bladed rotor by modifying a shape of one or more of the first blade and the second blade of the pair such that a modified frequency difference between natural vibration frequencies of the first blade and the second blade of the pair is at or above the threshold; wherein the modifying of the shape of the first blade of the pair includes modifying the shape of the first blade within a zone on an aerodynamic surface of the first blade by creating a recessed area within the zone; wherein the creating of the recessed area includes increasing a depth of the recessed area from a perimeter of the zone toward a location within the zone, a depth of the recessed area being maximal at the location; and wherein a chordwise rate of variation of the depth is greater from the leading edge to the location of greatest depth than from the location to the trailing edge.
2. The method of claim 1, comprising identifying a zone on the first blade of the pair, the

modifying of the shape of the first blade of the pair including modifying the shape of the first blade by modifying the shape of the first blade within the zone.
3. The method of claim 2, wherein the modifying of the shape of the first blade of the pair within the zone includes removing matter from the first blade within the zone.
4. The method of claim 1, wherein the modifying of the shape of the first blade of the pair includes modifying a shape of a pressure side of the first blade.
5. The method of claim 1, wherein the modifying of the shape of the first blade of the pair within the zone includes modifying the shape of the first blade within the zone located radially outwardly of a mid-span line of the first blade.
6. The method of claim 1, wherein the modifying of the shape of the first blade of the pair within the zone includes modifying the shape of the first blade within the zone being offset from a leading edge of the first blade.
7. The method of claim 6, wherein the modifying of the shape of the first blade of the pair within the zone includes modifying the shape of the first blade within the zone being offset form a trailing edge of the first blade.
8. The method of claim 1, wherein the location is offset from a center of the zone.
9. The method of claim 1, comprising compensating for a rotational imbalance created by the modifying of the shape of the first blade of the pair.
10. The method of claim 9, wherein the compensating for the rotational imbalance includes securing counterweights on the rotor.
11. A method comprising: manufacturing a rotor having a hub and a plurality of blades protruding from the hub, the plurality of blades including first blades and second blades disposed in alternation around a central axis of the rotor to form pairs, a pair of the pairs including a first blade of the first blades disposed adjacent to a second blade of the second blades, the first blades having a natural vibration frequency differing from a natural vibration frequency of the second blades by a frequency difference for mistuning the rotor, the rotor being an integrally bladed rotor such that the plurality of blades and the hub are parts of a monolithic body of the rotor; performing an analysis on the monolithic body of the rotor with the plurality of blades and the hub to obtain actual frequency differences for each of the pairs; determining that an actual frequency difference corresponding to the pair of the pairs is below a minimum threshold; and re-working the integrally bladed rotor by modifying a shape of one or more of the first blade and the second blade of the pair such that a modified frequency difference between natural vibration frequencies of the first blade and the second blade of the pair is at or above the threshold; wherein the modifying of the shape of the first blade of the pair includes modifying the shape of the first blade within a zone on an aerodynamic surface of the first blade by creating a recessed area within the zone; wherein the creating of the recessed area includes increasing a depth of the recessed area from a perimeter of the zone toward a location within the zone, a depth of the recessed area being maximal at the location; and wherein a spanwise rate of variation of the depth is greater from a base of the first blade to the location of greatest depth than from the location to a tip of the first blade.
12. The method of claim 11, comprising identifying a zone on the first blade of the pair, the modifying of the shape of the first blade of the pair including modifying the shape of the first blade by modifying the shape of the first blade within the zone.
13. The method of claim 12, wherein the modifying of the shape of the first blade of the pair within the zone includes removing matter from the first blade within the zone.
14. The method of claim 11, wherein the modifying of the shape of the first blade of the pair includes modifying a shape of a pressure side of the first blade.
15. The method of claim 11, wherein the modifying of the shape of the first blade of the pair within the zone includes modifying the shape of the first blade within the zone located radially outwardly of a mid-span line of the first blade.
16. The method of claim 11, wherein the modifying of the shape of the first blade of the pair within

the zone includes modifying the shape of the first blade within the zone being offset from a leading edge of the first blade.

17. The method of claim 16, wherein the modifying of the shape of the first blade of the pair within the zone includes modifying the shape of the first blade within the zone being offset form a trailing edge of the first blade.

18. The method of claim 11, wherein the location is offset from a center of the zone.

19. The method of claim 11, comprising compensating for a rotational imbalance created by the modifying of the shape of the first blade of the pair.

20. The method of claim 19, wherein the compensating for the rotational imbalance includes securing counterweights on the rotor.