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(54) **TURBINE BLADE DAMPING DEVICE WITH CONTROLLED LOADING**

(71) Applicant: **Siemens Energy, Inc.**, Orlando, FL (US)

(72) Inventor: **John J. Marra**, Winter Springs, FL (US)

(73) Assignee: **SIEMENS ENERGY, INC.**, Orlando, FL (US)

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Filed: **Dec. 14, 2009**

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F01D 5/26 (2006.01)
F01D 5/22 (2006.01)

(52) **U.S. Cl.**
CPC ... ***F01D 5/26*** (2013.01); ***F01D 5/22*** (2013.01)

(58) **Field of Classification Search**
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See application file for complete search history.

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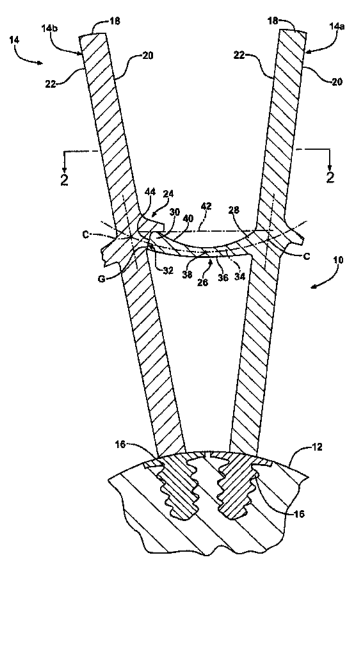
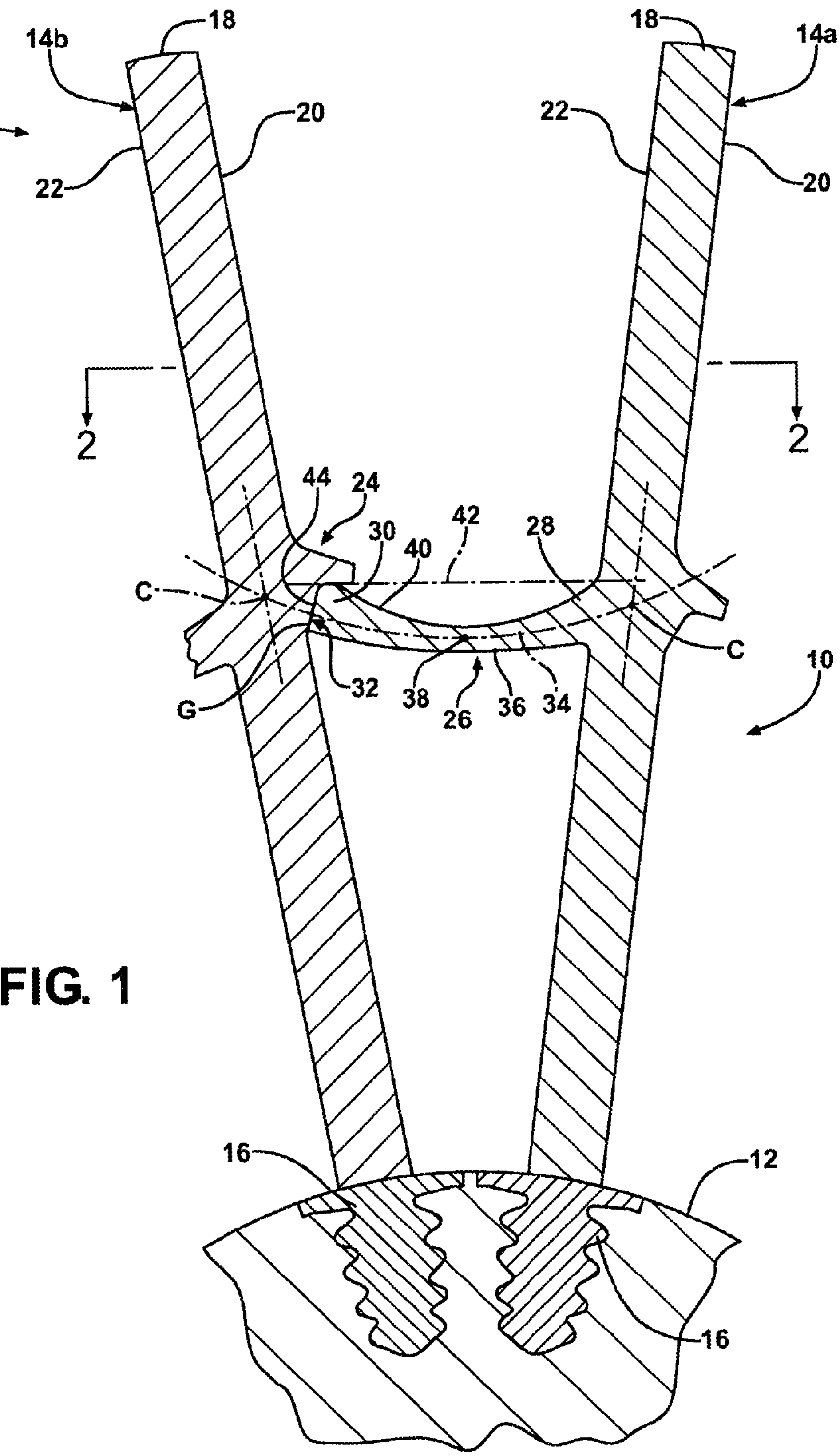
Primary Examiner — Russell Stormer

(57) **ABSTRACT**

A damping structure for a turbomachine rotor. The damping structure including an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface associated with the second blade. The snubber element has a centerline extending radially inwardly in a direction from the first blade toward the second blade along at least a portion of the snubber element between the first and second snubber ends. Rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

13 Claims, 4 Drawing Sheets

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22
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2
2
44
24
42
28
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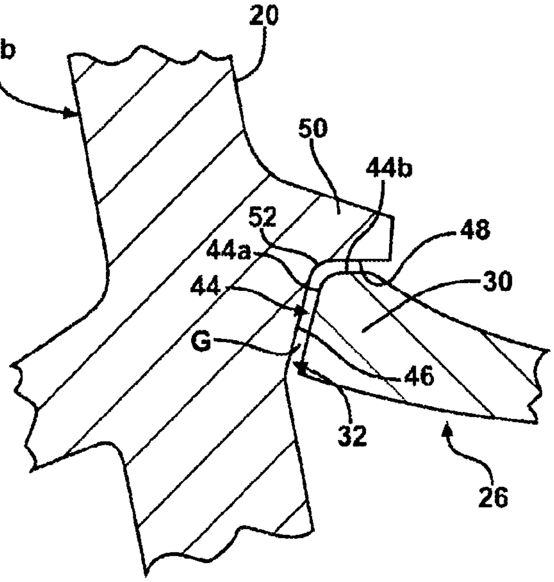
32
38
26
36
34
16
12
16

FIG. 1

FIG. 1A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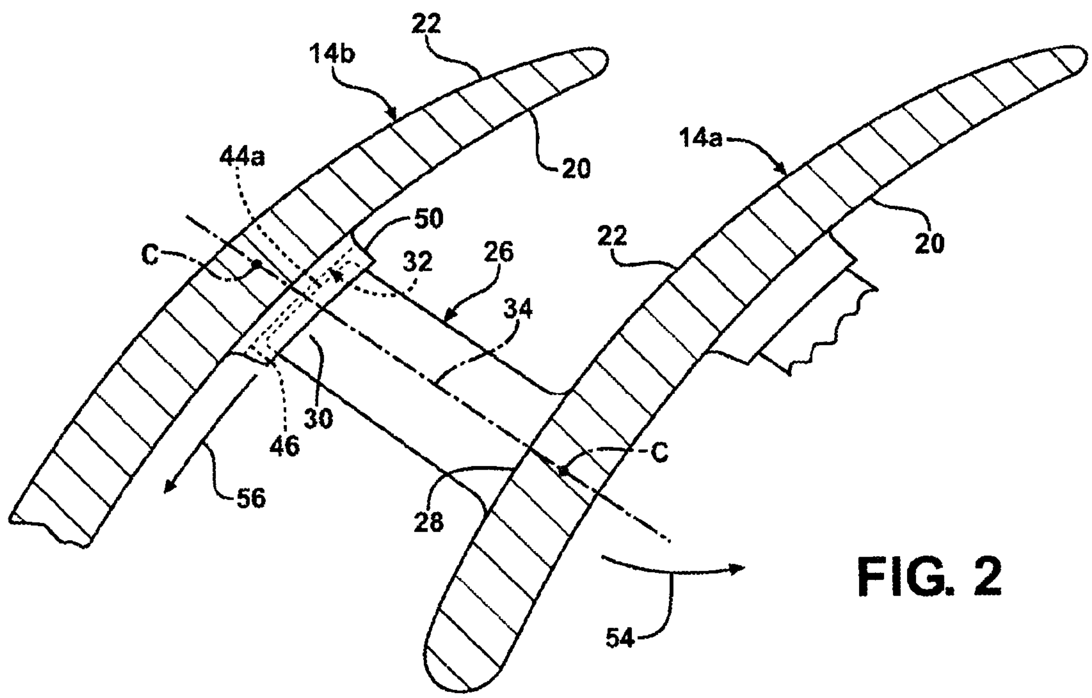
32
26


22
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46
56
C
28
54

FIG. 2

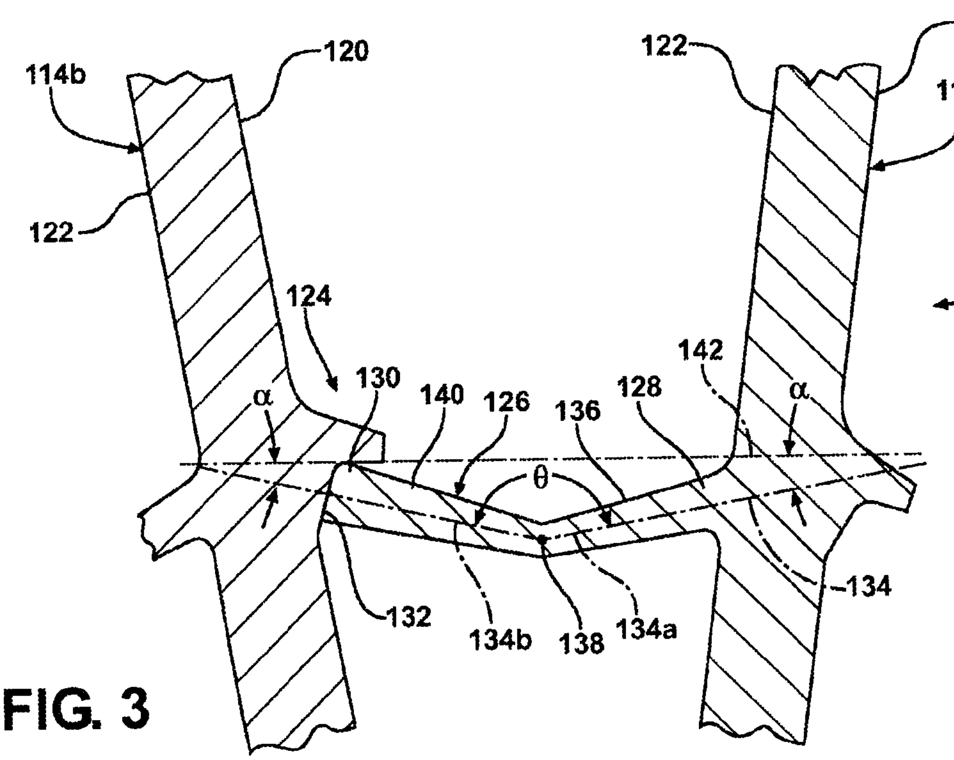
114b
120
122
122
120
114a
110
124
142
130
140
126
136
128
α
α
θ
134
132
134b
138
134a

FIG. 3

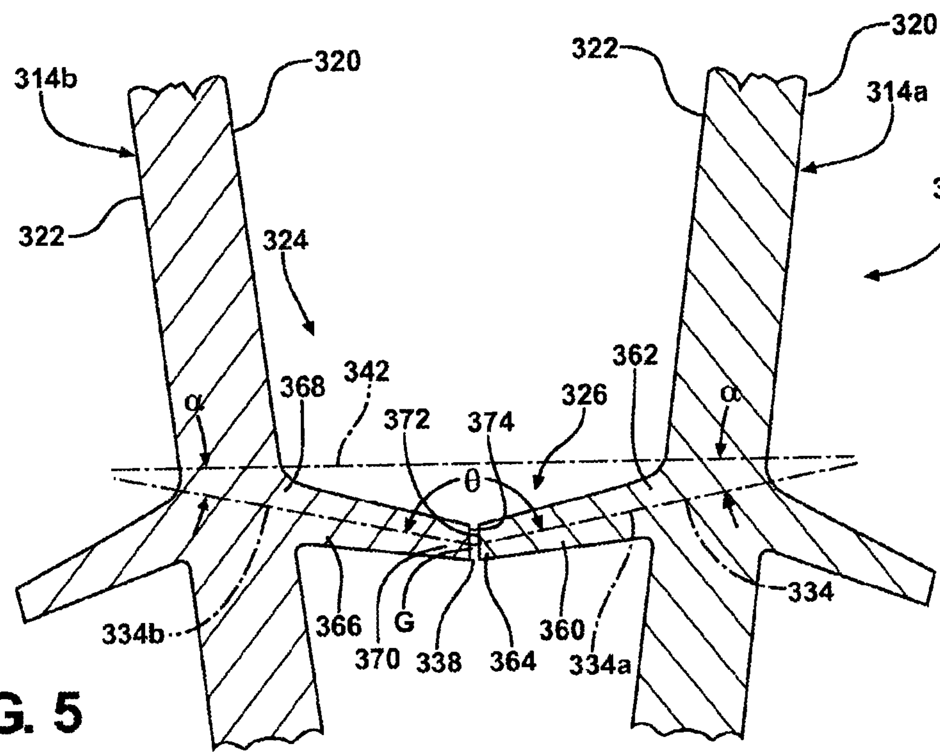
314b
320
322
320
314a
322
310
324
362
368
342
326
α
α
372
374
θ
334
334b
366
G
370
338
364
360
334a

FIG. 5

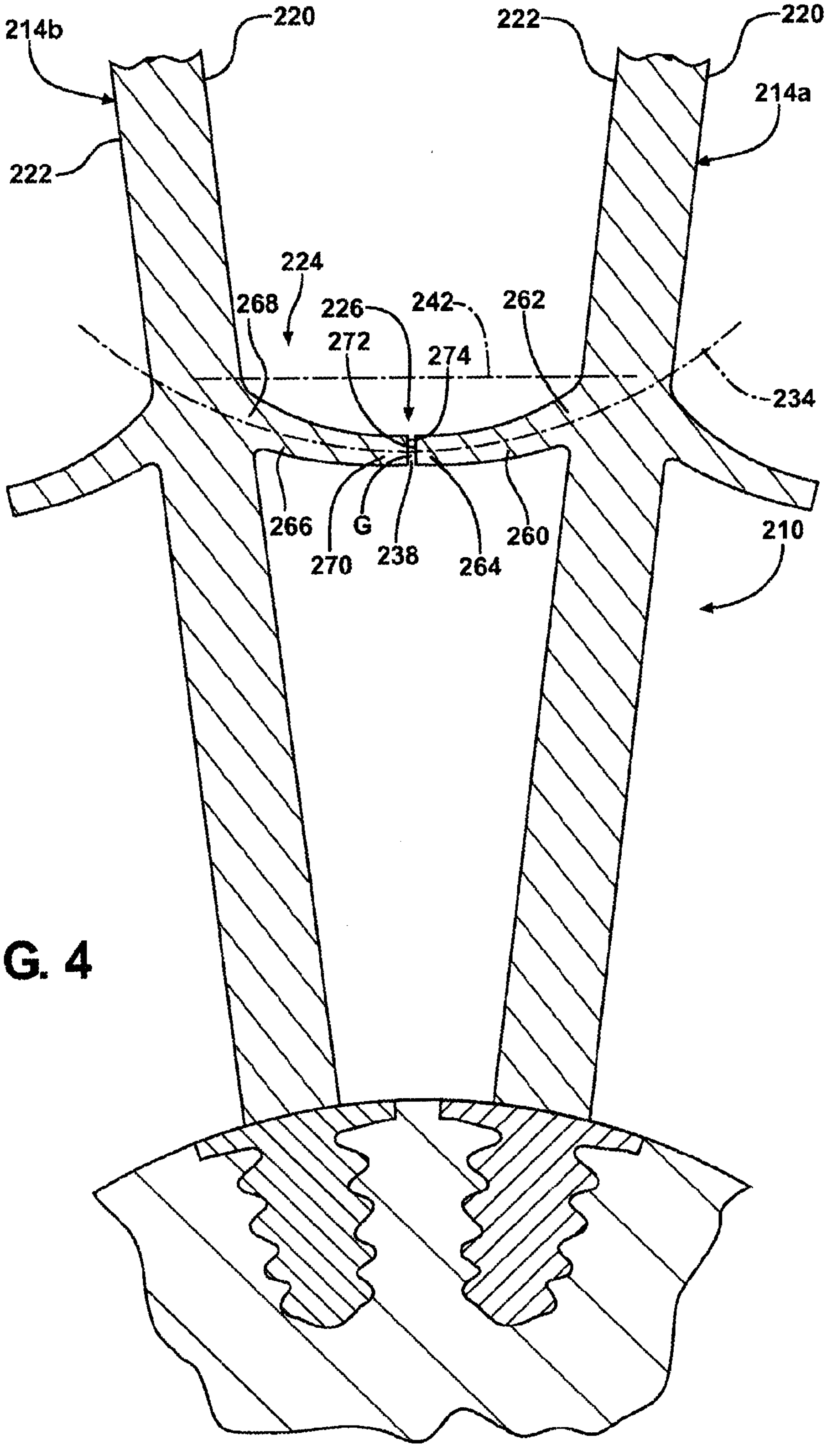
214b
220
222
220
222
214a
222
224
268
226
242
262
272
274
234
266
G
270
238
264
260
210

FIG. 4

TURBINE BLADE DAMPING DEVICE WITH CONTROLLED LOADING

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue; a claim printed with strikethrough indicates that the claim was canceled, disclaimed, or held invalid by a prior post-patent action or proceeding.

This invention was made with U.S. Government support under Contract Number DE-FC26-05NT42644 awarded by the U.S. Department of Energy. The U.S. Government has certain rights to this invention.

CROSS-REFERENCE TO RELATED APPLICATION

This application is related to and filed on even date with an application having Ser. No. 12/637,066 entitled, "TURBINE BLADE DAMPING DEVICE WITH CONTROLLED LOADING", which is incorporated herein by reference in its entirety.

FIELD OF THE INVENTION

The present invention relates generally to vibration damping of turbine blades in a turbomachine and, more particularly, to a damping structure comprising a snubber providing a controlled damping force.

BACKGROUND OF THE INVENTION

A turbomachine, such as a steam or gas turbine is driven by a hot working gas flowing between rotor blades arranged along the circumference of a rotor so as to form an annular blade arrangement, and energy is transmitted from the hot working gas to a rotor shaft through the rotor blades. As the capacity of electric power plants increases, the volume of flow through industrial turbine engines has increased more and more and the operating conditions (e.g., operating temperature and pressure) have become increasingly severe. Further, the rotor blades have increased in size to harness more of the energy in the working gas to improve efficiency. A result of all the above is an increased level of stresses (such as thermal, vibratory, bending, centrifugal, contact and torsional) to which the rotor blades are subjected.

In order to limit vibrational stresses in the blades, various structures may be provided to the blades to form a cooperating structure between blades that serves to dampen the vibrations generated during rotation of the rotor. For example, mid-span snubbers, such as cylindrical standoffs, may be provided extending from mid-span locations on the blades for engagement with each other. Two mid-span snubbers are located at the same height on either side of a blade with their respective contact surfaces pointing opposite directions. The snubber contact surfaces on adjacent blades are separated by a small gap when the blades are stationary. However, when the blades rotate at full load and untwist under the effect of the centrifugal forces, snubber surfaces on adjacent blades come in contact with each other. In addition, each turbine blade may be provided with an outer shroud located at an outer edge of the blade and having front and rear shroud contact surfaces that move into contact with each other as the rotor begins to rotate. The engagement between the blades at the front and rear shroud contact surfaces and at the snubber contact surfaces is designed to improve the strength of the blades under the tremendous centrifugal forces, and further operates to dampen vibrations by friction at the contacting snubber surfaces. A disadvantage of snubber damping is that on large diameter blades it is often difficult to achieve the desired contact forces produced between snubbers as a result of the centrifugal untwisting of the blades. In addition, the large mechanical load associated with large diameter blades typically necessitates larger snubber structures for mechanical stability to avoid outward bending of the snubber, resulting in increased aerodynamic losses and flow inefficiencies due to the flow restriction of larger snubbers positioned in the high velocity flow area through the part-span area.

SUMMARY OF THE INVENTION

In accordance with an aspect of the invention, a damping structure is provided in a turbomachine rotor comprising a rotor disk and a plurality of blades. The damping structure comprises an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface at least partly formed on the second blade. The snubber element has a centerline extending radially inwardly in a direction from the first blade toward the second blade along at least a portion of the snubber element between the first and second snubber ends. The cooperating surface defines an axially extending area for accommodating axial movement of the second snubber end along the cooperating surface as the first and second blades untwist during rotor spin-up. Rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

The damping structure may be located at a mid-span location between a blade root and a blade tip of the blade.

The centerline of the snubber element may comprise a substantially smooth curve with a concave side facing radially outwardly extending from the first snubber end to the second snubber end.

The centerline of the snubber element may comprise first and second linear centerline segments and an inflexion angle between the centerline segments at a midway point between the first and second blades, the first centerline segment angling radially inwardly from the first snubber end to the midway point and the second centerline segment angling radially outwardly from the midway point to the second snubber end.

The cooperating surface may comprise a circumferentially facing side at least partially formed on a side of the second blade and a radially inwardly facing side formed on a flange extending from the second blade. The circumferentially facing side and the radially inwardly facing side may define a recess for receiving the second snubber end.

A midway point is defined between the first and second blades and a radial thickness of the snubber element may decrease extending from each of the blades to the midway point.

In accordance with another aspect of the invention, a mid-span damping structure is provided in a turbomachine rotor comprising a rotor disk and a plurality of blades. The damping structure comprises an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface at least partly formed on a side surface of the second blade and defining an axially curved bearing surface. The snubber element having a centerline extending radially inwardly in a direction from the first blade toward the second blade along a portion of the snubber element between the first end and a midway point between the first and second blades, and extending radially outwardly from the midway point to the second snubber end. Rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

BRIEF DESCRIPTION OF THE DRAWINGS

While the specification concludes with claims particularly pointing out and distinctly claiming the present invention, it is believed that the present invention will be better understood from the following description in conjunction with the accompanying Drawing Figures, in which like reference numerals identify like elements, and wherein:

FIG. **1** is a partial end view of a rotor, as viewed in an axial flow direction, taken in a plane perpendicular to an axis of rotation and showing an embodiment of the invention;

FIG. **1**A is an enlarged view of a contact location between a snubber end and a cooperating surface of a blade;

FIG. **2** is view taken on the plane indicated by the line **2-2** in FIG. **1**;

FIG. **3** is a partial end view showing an alternative configuration of the embodiment of FIG. **1**;

FIG. **4** is a partial end view of a rotor taken in a plane perpendicular to an axis of rotation and showing an alternative embodiment of the invention; and

FIG. **5** is a partial end view showing an alternative configuration of the embodiment of FIG. **4**.

DETAILED DESCRIPTION OF THE INVENTION

In the following detailed description of the preferred embodiment, reference is made to the accompanying drawings that form a part hereof, and in which is shown by way of illustration, and not by way of limitation, a specific preferred embodiment in which the invention may be practiced. It is to be understood that other embodiments may be utilized and that changes may be made without departing from the spirit and scope of the present invention.

Referring to FIG. **1**, a section of a rotor **10** is illustrated for use in a turbomachine (not shown), such as for use in a gas or steam turbine. The rotor **10** comprises a rotor disk **12** and a plurality of blades **14**, illustrated herein as a first blade **14**a and an adjacent second blade **14**b. The blades **14** comprise radially elongated structures extending from a blade root **16**, engaged with the rotor disk **12**, to a blade tip **18**. Each of the blades **14**a, **14**b includes a pressure side surface **20** and a suction side surface **22**. The rotor **10** further includes a damping structure **24** extending between the first and second blades **14**a, **14**b, and located mid-span between the blade root **16** and the blade tip **18** of the blades **14**a, **14**b.

The damping structure **24** comprises an elongated snubber element **26** including a first snubber end **28** rigidly attached to the suction side surface **22** of the first blade **14**a and extending toward the adjacent pressure side surface **20** of the second blade **14**b. The snubber element **26** additionally includes an opposite second snubber end **30** positioned adjacent to a cooperating surface **32** associated with the second blade **14**b. The cooperating surface **32** is at least partially formed on the pressure side surface **20** of the second blade **14**b.

The snubber element **26** defines a centerline **34** extending radially inwardly in a direction from the first blade **14**a toward the second blade **14**b along a first portion **36** of the snubber element **26** between the first snubber end **28** and a midway point **38** between the first and second blades **14**a, **14**b. The centerline **34** extends radially outwardly along a second portion **40** of the snubber element **26** from the midway point **38** to the second snubber end **30**. The midway point **28** may be defined as any point that is generally at a central region of the snubber element **26** located spaced circumferentially from both the first and second blades **14**a, **14**b. In the embodiment illustrated in FIG. **1**, the centerline **34** comprises a substantially smooth curve that is bowed inwardly, e.g., in the manner of a classical Roman arch, from a circumferential line **42** extending between upper edges of the first and second snubber ends **28**, **30**, and having a concave side that faces radially outwardly extending from the first snubber end **28** to the second snubber end **30**. In addition, the centerline **34** passes through centroids C of the first and second blades **14**a, **14**b.

Referring further to FIG. **1**A, the second snubber end **30** is normally positioned with a small snubber gap G between a snubber end surface **44** and the cooperating surface **32** when the rotor **10** is stationary. The cooperating surface **32** comprises a circumferentially facing side **46** that may be angled circumferentially inwardly in a radial outward direction and faces a similarly angled circumferentially facing portion **44**a of the snubber end surface **44**. The cooperating surface **32** additionally includes a radially inwardly, facing side **48** formed on a flange **50** extending from the suction side **22** of the second blade **14**b. The circumferentially facing side **46** and the radially inwardly facing side **48** define a recess **52** for receiving the second snubber end **30**. The circumferentially facing side **46** is preferably angled such that it is substantially normal to the centerline **34** of the snubber element **26**, and is generally parallel to the circumferentially facing portion **44**a. A radially outer portion **44**b of the snubber end surface **44** is located adjacent to the radially inwardly facing side **48** of the flange **50**.

As seen in FIG. **2**, the circumferentially facing side **46** of the cooperating surface **32** extends in an axial direction for engaging the corresponding circumferentially facing portion **44**a on the snubber end surface **44**. Further, both the circumferentially facing side **46** of the cooperating surface and the circumferentially facing portion **44**a of the snubber end surface **44** may be formed with a curvature in the axial direction to accommodate relative movement between these members during blade untwist.

During spin-up of the rotor **10**, a centrifugal force exerted on the snubber member **26** causes the second snubber end **30** to move radially outwardly and into frictional engagement with the cooperating surface **32**. Specifically, the during rotation of the rotor **10**, the snubber element **26** pivots about the first snubber end **28** and radial outward movement of the second snubber end **30** causes the sloping or angled surfaces **44**a and **46** of the snubber end surface **44** and cooperating surface **32**, respectively, to engage each other with a predetermined force in a direction generally parallel or tangent to the centerline **34** and extending through the centroid C. Further, the radially outer portion **44**b of the snubber end surface **44** engages the radially inwardly facing side **48** of the flange **50**, defining a socket area, to limit outward movement of the second snubber end **30** and maintain the second snubber end **30** within the recess **52**.

In addition, since the first snubber end **28** is rigidly attached to the first blade **14**a, snubber element **26** will pivot with the first blade **14**a in a plane generally parallel to the axial and circumferential directions as the first blade untwists during spin-up of the rotor **10**. As illustrated in FIG. **2**, pivoting movement of the snubber element **26** during blade untwist, depicted by directional arrow **54**, will cause the second snubber end **30** to move axially in an arc, as depicted by arrow **56**. As noted above, the curvature in the axial direction of the circumferentially facing side **46** of the cooperating surface **32** and the circumferentially facing portion **44**a of the snubber end surface **44** accommodates or guides the movement of the second snubber end **30** as the blades **14** untwist. Also, the snubber gap G provided between the snubber end surface **44** and the cooperating surface **32** provides a reduced friction interface for relative movement between these components before centrifugal forces create an engagement force to lock the snubber end surface **44** to the cooperating surface **32**.

The second snubber end **30** engages the cooperating surface **32** with a predetermined minimum damping force, where the damping force may be controlled by the inward angle and mass of the snubber element **26**. It should be noted that it is desirable to configure the snubber element **26** to produce a damping force that is sufficient to produce damping at the interface between the second snubber end **30** and the cooperating surface **32** to control blade vibration without substantially exceeding this minimum damping force. An excess force at this location may lead to excessive wear and stress on the snubber element **26** and cooperating surface **32**.

The inward angle formed by the curvature of the snubber element **26**, as defined by the centerline **34**, substantially alters the damping force produced by centrifugal force on the snubber element **26**. The centrifugal force exerted on the snubber element **26** causes the snubber element **26** to bend outwardly and become less concave, producing the damping force between the blades **14**. A larger centerline curvature will produce a greater centrifugal load on the snubber element **26** and a greater damping force applied between the second snubber end **30** and the cooperating surface **32**. For example, it is believed that a snubber element **26** having a curvature that matches a catenary curve would cause the snubber element **26** to produce a substantially greater damping force between the blades **14** than would be required to dampen vibrations. Further, it is believed that a snubber element **26** configured with a centerline **34** having a relatively shallow curve may be sufficient to produce an adequate centrifugal force on the snubber element **26** and provide the necessary damping force to reduce blade vibration while effectively controlling the level of force applied.

In order to minimize or reduce inertial loads on the snubber element **26**, the snubber element **26** may be formed with a taper extending from either snubber end **28**, **30** toward the midway point **38**, as seen in FIG. **1**. That is the radial thickness of the snubber element **26** may progressively decrease from the snubber ends **28**, **30** toward the midway point **38**. In addition, the taper may reduce aerodynamic resistance by providing the snubber element **26** with a reduced cross-sectional area, facilitating flow through the turbine between the blades **14**.

It should be noted that although a particular configuration for accommodating axial movement of the second snubber end **30** is disclosed, other engagement structure may be provided to accommodate blade untwist. For example, a ball and socket configuration may be provided where the cooperating surface **32** may be formed as rounded socket surface for receiving a ball or partial spherical surface formed on the second snubber end **30**.

Referring to FIG. **3**, an alternative configuration is illustrated comprising a variation of the embodiment shown in

FIG. **1**. Elements in FIG. **3** corresponding to elements in FIG. **1** are labeled with the same reference number increased by 100.

In FIG. **3**, the snubber element **126** includes a first snubber end **128** rigidly affixed to a first blade **114**a and a second snubber end **130** supported adjacent to a cooperating surface **132** on a second blade **114**b. The snubber element **126** is formed with first and second linear portions **136**, **140** wherein the centerline **134** of the snubber element **126** comprises a first linear centerline segment **134**a and a second linear centerline segment **134**b. The centerline segments **134**a, **134**b meet at an inflexion angle θ at a midway point **138** between the first and second blades **114**a, **114**b. The first centerline segment **136** angles radially inwardly from the first snubber end **128** to the midway point **138**, and the second centerline segment **140** angles radially outwardly from the midway point **138** to the second snubber end **130**.

The configuration of FIG. **3** provides a damping structure **124** having a triangular configuration that includes a snubber element **126** extending radially inwardly from the circumferential line **142**. In a preferred embodiment, the first and second centerline segments **134**a and **134**b each angle inwardly from the circumferential line **142** at an angle α. The angle α may be in the range of from about 3° to about 20°, and preferably is about 6°, such that the inflexion angle θ is about 178°. The damping structure **124** operates in the manner described above for the damping structure **24** wherein centrifugal forces applied on the snubber element **126** cause the second snubber end **130** to engage the cooperating surface **132** with a predetermined force to provide a controlled damping force for damping blade vibrations. Further, a cooperating surface structure similar to the axially extending cooperating surface **32** of FIG. **2** may be provided to accommodate relative axial movement between the second snubber end **130** and the cooperating surface **132**.

Referring to FIG. **4**, an additional embodiment of the invention is described where elements in FIG. **4** corresponding to elements in FIG. **1** are labeled with the same reference number increased by 200. A rotor **210** including a damping structure **224** is illustrated. The damping structure **224** includes a snubber element **226** comprising an elongated first snubber element **260** extending from a first blade **214**a toward an adjacent second blade **214**b. The first snubber element **260** includes a first snubber end **262** rigidly attached to the first blade **214**a, and an opposite second snubber end **264** extending to a midway point **238**. An elongated second snubber element **266** extends from the second blade **214**b toward the first blade **214**a and includes a first snubber end **268** rigidly attached to the second blade **214**b, and an opposite second snubber end **270** extending to a midway point **238**.

The second snubber end **264** of the first snubber element **260** defines an engagement surface **272** located adjacent to a cooperating surface **274** on the second snubber end **270** of the second snubber element **266** at the midway point **238** between the first and second blades **214**a, **214**b. A snubber gap G is defined between the adjacent surfaces **272**, **274** when the rotor **210** is stationary, i.e., with no centrifugal forces acting on the first and second snubber elements **260**, **266**.

The first and second snubber elements **260**, **266** define a centerline **234** extending radially inwardly in a direction from the first blade **214**a toward the midway point **238** and extending radially inwardly in a direction from the second blade **214**b toward the midway point **238**. The centerline **234** defined by the first and second snubber elements **260**, **266** comprises a substantially smooth curve with a concave side facing radially outwardly toward a circumferential line **242** extending between radially outer edges of the first snubber end **262** of the first snubber element **260** and the first snubber end **268** of the second snubber element **266**.

Rotational movement of the rotor **210** effects relative movement between the second snubber ends **264**, **270** of the first and second snubber elements **260**, **266** to close the snubber gap G and position the engagement surface **272** in frictional engagement with the cooperating surface **274** with a predetermined damping force determined by a centrifugal force acting on the first and second snubber elements **260**, **266**. In particular, the centrifugal force acting on the first and second snubber elements **260**, **266** effect a movement of the snubber elements **260**, **266** radially outwardly, causing them to pivot toward each other and the snubber gap G to be closed. In addition, it should be noted that the second ends **264**, **270** of the snubber elements **260**, **266** are located to define the snubber gap G at a location between the blades **214**a, **214**b where the second ends **264**, **270** will remain at substantially the same position relative to each other during rotor spin-up and corresponding blade untwist. Hence, the engagement surface **272** will remain in facing relation to the cooperating surface **274** regardless of blade untwist during rotor spin-up and will be positioned in locking frictional engagement during operation of the turbine.

Referring to FIG. **5**, an alternative configuration is illustrated comprising a variation of the embodiment shown in FIG. **4**. Elements in FIG. **5** corresponding to elements in FIG. **4** are labeled with the same reference number increased by 100.

In FIG. **5**, a rotor **310** including a damping structure **324** is illustrated. The damping structure **324** includes a snubber element **326** comprising an elongated first snubber element **360** extending from a first blade **314**a toward an adjacent second blade **314**b. The first snubber element **360** includes a first snubber end **362** rigidly attached to the first blade **314**a, and an opposite second snubber end **364** extending to a midway point **338**. An elongated second snubber element **366** extends from the second blade **314**b toward the first blade **314**a and includes a first snubber end **368** rigidly attached to the second blade **314**b, and an opposite second snubber end **370** extending to the midway point **338**.

The second snubber end **364** of the first snubber element **360** defines an engagement surface **372** located adjacent to a cooperating surface **374** on the second snubber end **370** of the second snubber element **366** at the midway point **338** between the first and second blades **314**a, **314**b. A snubber gap G is defined between the adjacent surfaces **372**, **374** when the rotor **310** is stationary, i.e., with no centrifugal forces acting on the first and second snubber elements **360**, **366**. The first and second snubber elements **360**, **366** define a centerline **334** wherein the centerline **334** comprises a first linear centerline segment **334**a and a second linear centerline segment **334**b extending along the first and second snubber elements **360**, **366** respectively. The centerline segments **334**a, **334**b meet at an inflexion angle θ at the midway point **338** between the first and second blades **314**a, **314**b.

The configuration of FIG. **5** provides a damping structure **324** having a triangular configuration that includes the first and second snubber elements **360**, **366** extending radially inwardly from a circumferential line **342** connecting radially outer edges of the first snubber end **362** of the first snubber element **360** and the first snubber end **368** of the second snubber element **366**. In a preferred embodiment, the first and second centerline segments **334**a and **334**b each angle inwardly from the circumferential line **342** at an angle α. The angle α may be in the range of from about 3° to about 20°, and preferably is about 6°, such that the inflexion angle θ is about 178° when the rotor **310** is stationary. The damping structure **324** operates in the manner described above for the damping structure **224** of FIG. **4** wherein rotational movement of the rotor **310** produces a centrifugal force on the first and second snubber elements **360**, **366** to move the snubber elements **360**, **366** radially outwardly. As the snubber elements **360**, **366** move outwardly, they pivot toward each other and close the snubber gap G. As the snubber gap G is closed the engagement surface **372** is positioned in frictional engagement with the cooperating surface **374** with a predetermined damping force determined by the centrifugal force loading the first and second snubber elements **360**, **366**. It is believed that the damping structure **324**, including the first and second snubber elements **360**, **366** positioned at the described angle of 6°, may produce a force at the snubber gap G of approximately 500 N, above any forces that may occur as a result of movements of the blades **314**a, **314**b, such as may result from blade untwist.

In the embodiments of the invention described with reference to FIGS. **4** and **5**, in order to minimize or reduce the inertial loads on the first and second snubber elements **260**, **266** (**360**, **366**) these elements may be tapered extending from the respective first and second blades **214**a, **214**b (**314**a, **314**b) toward the snubber gap G at the midway point **238** (**338**). That is, the radial thickness may progressively decrease from the snubber ends **262**, **268** (**362**, **368**) toward the midway point **238** (**338**). In addition, the taper may reduce aerodynamic resistance by providing the snubber elements **260**, **266** (**360**, **366**) with a reduced cross-sectional area to flow through the turbine between the blades.

In each of the above-described embodiments, it should be noted that structure is provided for controlling the damping force at a snubber gap between a snubber element and a cooperating surface using a radially inwardly extending configuration to produce a predetermined outwardly directed centrifugal force and a corresponding circumferentially directed damping force at the engaging surfaces.

The present invention is particularly applicable to large diameter, cooled turbine blades designed for high temperature (i.e., 850° C.) applications, such as may be used in industrial gas turbines. The present invention enables application of a controlled damping force through a mid-span snubber structure such as may be required for vibration damping of large diameter blades subjected to increased aerodynamic vibrations wherein the damping structure may provide a greater or lesser force, as required, at the snubber gap by utilizing a predetermined centrifugal force acting on the inwardly angled snubber element or elements.

While particular embodiments of the present invention have been illustrated and described, it would be obvious to those skilled in the art that various other changes and modifications can be made without departing from the spirit and scope of the invention. It is therefore intended to cover in the appended claims all such changes and modifications that are within the scope of this invention.

What is claimed is:

1. A damping structure in a turbomachine rotor having a rotor disk and a plurality of blades, the damping structure comprising:

an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface at least partly formed on the second blade;

wherein the cooperating surface comprises a circumferentially facing side extending radially and circumferentially outwardly from a radially extending side surface of the second blade, forming an angle extending from the radially extending side surface, and the second snubber end has a surface extending radially outwardly at an angle similar to the angle of the cooperating surface;

the snubber element having a centerline extending radially inwardly in a direction from the first blade toward the second blade along [at least a portion of the snubber element between the first and second snubber ends] *a portion of the snubber element between the first snubber end and a midway point between the first and second blades, and extending radially outwardly from the midway point to the second snubber end*;

wherein the cooperating surface defines an axially extending area for accommodating axial movement of the second snubber end along the cooperating surface as the first and second blades untwist during rotor spin-up; and

wherein rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

2. The damping structure according to claim **1**, wherein the damping structure is located at a mid-span location between a blade root and a blade tip of the blade.

3. The damping structure according to claim **1**, wherein the centerline of the snubber element comprises a substantially smooth curve with a concave side facing radially outwardly extending from the first snubber end to the second snubber end.

4. The damping structure according to claim **1**, wherein the centerline of the snubber element comprises first and second linear centerline segments and an inflexion angle between the centerline segments at a midway point between the first and second blades, the first centerline segment angling radially inwardly from the first snubber end to the midway point and the second centerline segment angling radially outwardly from the midway point to the second snubber end.

5. The damping structure according to claim **1**, wherein the cooperating surface further comprises a radially inwardly facing side formed on a flange extending from the radially extending side surface of the second blade, the circumferentially facing side and the radially inwardly facing side define a recess for receiving the second snubber end.

6. The damping structure according to claim **1**, including a midway point between the first and second blades and a radial thickness of the snubber element decreases extending from each of the blades to the midway point.

7. A mid-span damping structure in a turbomachine rotor having a rotor disk and a plurality of blades, the mid-span damping structure comprising:

an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface at least partly formed on a side surface of the second blade and [defining an axially curved bearing surface] *formed with a curvature in the axial direction*;

the snubber element having a centerline extending radially inwardly in a direction from the first blade toward the second blade along a portion of the snubber element between the first end and a midway point between the first and second blades, and extending radially outwardly from the midway point to the second snubber end; and

wherein rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

8. The damping structure according to claim **7**, wherein the centerline of the snubber element comprises a substantially smooth curve with a concave side facing radially outwardly extending from the first snubber end to the second snubber end.

9. The damping structure according to claim **7**, wherein the centerline of the snubber element comprises first and second linear centerline segments and an inflexion angle between the centerline segments at the midway point between the first and second blades, the first centerline segment angling radially inwardly from the first snubber end to the midway point and the second centerline segment angling radially outwardly from the midway point to the second snubber end.

10. The damping structure according to claim **7**, wherein the cooperating surface defines [an axially curved] *a* socket area for accommodating axial movement of the second snubber end along the cooperating surface as the first and second blades untwist during rotor spin-up.

11. The damping structure according to claim **10**, wherein the cooperating surface comprises a circumferentially facing side at least partially formed on a side of the second blade and a radially inwardly facing side formed on a flange extending from the second blade, the circumferentially facing side and the radially inwardly facing side define a recess for receiving the second snubber end.

12. A damping structure in a turbomachine rotor having a rotor disk and a plurality of blades, the damping structure comprising:

an elongated snubber element including a first snubber end rigidly attached to a first blade and extending toward an adjacent second blade, and an opposite second snubber end positioned adjacent to a cooperating surface at least partly formed on the second blade, a gap being formed between the second snubber end and the cooperating surface when the rotor is stationary;

the snubber element having a centerline extending radially inwardly in a direction from the first blade toward the second blade along at least a portion of the snubber element between the first and second snubber ends;

wherein the centerline of the snubber element comprises first and second linear centerline segments and an inflexion angle between the centerline segments at a midway point on the snubber element between the first and second blades, the first centerline segment angling radially inwardly from the first snubber end to the midway point and the second centerline segment angling radially outwardly from the inflexion angle defined at the midway point to the second snubber end;

wherein the cooperating surface defines an axially extending area for accommodating axial movement of the second snubber end along the cooperating surface as the first and second blades untwist during rotor spin-up; and

wherein rotational movement of the rotor effects relative movement between the second snubber end and the cooperating surface to position the second snubber end in frictional engagement with the cooperating surface with a predetermined damping force determined by a centrifugal force on the snubber element.

13. The damping structure according to claim **12**, wherein a radial thickness of the snubber element decreases extending from each of the blades to the midway point.

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