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(54) Title: TECHNIQUE FOR PROVIDING A SIGNAL FOR CONTROLLING BLADE VORTEX INTERACTION NOISE OF A ROTORCRAFT

(57) Abstract

A technique for providing a signal representative of blade vortex interaction (BVI) noise for a multi–blade rotorcraft. The fluid (air) pressure at one, two, or more predetermined locations on a rotor blade is measured during at least one predetermined azimuthal segment of blade rotation during operation to provide respective pressure measurements. The pressure measurements are processed to provide a signal for use as a control variable in a control system for the active control of BVI noise. The pressure measurements are made within 10 % blade chord length of the blade leading edge and preferably two or more are made between 65 % and 95 % of blade radial–length. The pressure measurements are filtered and the band of retained frequencies is between 20 and 48 times the rotor rotation frequency. An algorithm operative over a determined blade frequency range optimizes the signal for control use.

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Description

Technique for Providing a Signal for Controlling Blade Vortex Interaction Noise of a Rotorcraft

The invention described herein was made in the performance of work under U.S. Navy Contract No. N00014-96-C-2079.

Technical Field

This invention relates to the control of blade vortex interaction (BVI) noise in rotorcraft, and more particularly to signals useful in the control of such BVI.

Background Art

In the realm of rotorcraft (e.g., helicopter and tilt rotor) design and operation, the phenomenon of blade-vortex interaction (BVI) noise has long been recognized as an undesirable characteristic. This phenomenon results from the vortices, shed by the rotor blades and blade tips as they advance, impacting a following rotor blade. The noise occasioned by BVI is most pronounced during descent of the rotorcraft, at low speed, typically upon approach to a landing site or field. Such noise may be particularly annoying to persons on the ground near the landing site and/or in the flight path. Moreover, the BVI noise may pose a security hazard to the rotorcraft under military conditions, because it is rendered more detectable to the human ear and/or to other acoustical sensing devices. For these reasons, considerable analysis has been conducted and a variety of techniques have previously been suggested or used in an effort to reduce the occurrence and/or intensity of BVI noise during rotorcraft operation.

Examples of analyses conducted and data obtained regarding BVI are contained in papers by the present inventor, Peter F. Lorber, entitled "Aerodynamic Results of a Pressure-Instrumented Model Rotor Test at the DNW", presented in the Journal of the American Helicopter Society, 1990, and "Blade-Vortex Interaction Data Obtained from a Pressure-Instrumented Model Rotor at DNW", presented in 1991. These materials disclose the instrumenting of rotor blades with numerous pressure sensors and obtaining blade pressure measurements occasioned by BVI under a variety of simulated operating conditions and at various azimuthal positions of the instrumented blades. This data revealed significant information about the physics and aerodynamics of BVI noise generation.

Efforts to diminish BVI noise have broadly involved passive means and active means. The passive means have typically involved structural modifications of or additions to the rotor blades, generally in the tip region which generates the vortices. An example of such a passive device is described in US Patent 5,788,199 to Wake et al. for "Half-Plow Vortex Generators for Rotor Blades for Reducing Blade-Vortex Interaction Noise," assigned to the assignee of the present application. There, a supplemental structure is mounted on each main rotor bade to generate a vortex rotating in opposition to that naturally generated by the blade tip to thereby attenuate any resulting vortex.

Examples of active devices for reducing BVI noise also include the aforementioned US Patent 5,788,199 in that it also discloses selectively deploying and retracting the vortex generator **10** either as a function of general flight conditions, i.e., descent, or as a more rapid function of azimuthal position of the rotor blade during rotation of the rotor (column 6, line 65 to column 7, line 29). A further example of an active means for attenuating BVI noise is described in a paper entitled "Effects of a Trailing Edge Flap on the Aerodynamics and Acoustics of Rotor Blade-Vortex Interactions" by B. D. Charles, et al. at pages 153-161 of Vol. 1 of the Proceeding of DGLR/AIAA 14th Aeroacoustics Conference of May 11-14, 1992. That paper describes the active control of flaps on rotor blades as a technique for BVI noise attenuation. Deployment of the flaps to various angles during various angular or azimuthal segments of blade rotation were analyzed for optimum results. The principles of the aforementioned paper appear also in US Patent No. 5,711,651 for "Blade Vortex Interaction Noise Reduction Techniques for a Rotorcraft" by Charles et al., which describes an active device (flaps) selectively deployable during rotation of the rotor blades through predetermined regions of the rotor azimuth.

While the passive devices provide the advantage of reduced complexity and perhaps less cost and weight, they do not afford the flexibility of active devices to adapt to changing BVI conditions throughout the flight regime, as with changes in speed and descent rate. Both of the aforementioned Patents 5,788,199 and 5,711,651 mention the advantages of deploying or actuating the active device only during the period in which the rotorcraft is operating in a flight condition wherein significant BVI noise is likely to be generated. As disclosed in the US Patent 5,711,651, a predetermining schedule may be used to deploy the active device during the relevant region, or regions, of the blade rotation azimuth.

Relative to a fixed passive system or device, the actuation of active devices in response to a predetermined schedule affords a greater degree of flexibility in attaining BVI noise abatement and reducing the penalties associated with the drag caused by continuous deployment of a device. However, inefficiencies remain because of the need to predetermine a schedule of actuation based solely on previously determined BVI conditions as a function of descent rate, flight speed, device geometry and characteristics, etc.

What is needed is a technique for increasing or optimizing the efficiency and effectiveness of an active system for the reduction of BVI noise associated with the rotor of a rotorcraft.

Disclosure of Invention

A principal object of the present invention is to provide a technique for improving the efficiency and/or effectiveness of controlling active devices for the reduction of BVI noise associated with rotorcraft.

According to the present invention, there is provided a technique for improving the efficiency and/or effectiveness of controlling active devices for reducing BVI noise associated with rotorcraft. More specifically, according to the present invention there is provided a method for providing a control signal representative of blade vortex interaction noise for a rotorcraft having a multiblade rotor, which signal is provided for use as a control variable in a rotorcraft control system for the active control of BVI noise. The signal is provided by measuring the fluid (air) pressure at one or more predetermined locations on a rotor blade during at least one predetermined azimuthal segment of blade rotation to provide respective pressure measurements, and processing the respective pressure measurements to provide a signal for use as a control variable.

The air pressure is measured at two or more locations on the blade between 65% and 95% of the radial length of the blade and within 10% blade chord length of the leading edge of the rotating blade. The pressure is measured preferably at least during an azimuthal segment in which the blade is advancing relative to forward flight of the rotorcraft, particularly within the quadrant measured angularly forward 90° from the tail of the rotorcraft. It may additionally be separately measured during an azimuthal segment in which the blade is retreating relative to forward flight of the rotorcraft.

The pressure measurements are processed by filtering to retain substantially only a frequency band commensurate with BVI sources, typically between 20 and 48 times the rotation frequency of the rotor. The filtered pressure measurements are further processed in accordance with:

$$F_{n_1,n_2} = \sqrt{\frac{1}{n_2 - n_1 + 1} \sum_{n1}^{n2} f_n^{2}}\text{, where}$$

F_{n_1,n_2} is the signal for use as the control variable, f_n is the Fourier amplitude over a specified azimuthal segment of blade rotation, and n_1 and n_2 are frequency limits based on n per full revolution.

The value of n_1 and n_2 are initially determined by wind tunnel measurements for a particular set of test conditions simulating descent and are subsequently correlated with BVI far field acoustic sound pressure levels for the same set of test conditions. Values of n_1 and n_2 being substantially **24** and **32** respectively have been determined for one rotorcraft system.

The resulting signal is then available for use as the control variable in a rotorcraft control system for the active control of BVI noise, typically as a feedback type of signal to be nulled or minimized by the active control.

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

Brief Description of Drawings

Fig. 1 is a simplified top plan view of a rotorcraft depicting blade vortices and the BVI noise suppression technique of the invention;

Fig. 2 is a top plan view of a portion of an instrumented rotor blade in accordance with the invention;

Fig. 3 is a schematic functional block diagram of the BVI noise suppression control in accordance with the invention;

Fig. 4A is a typical graphical plot of pressure at a rotor blade as a function of blade azimuth;

Fig. 4B is a graphical plot of pressure depicted in Fig. 4A following filtering to remove lower harmonics of the blade rotation frequency;

Fig. 5A is a graphical plot of blade pressure coefficients versus BVI far field acoustic sound pressure levels for different values of frequency ranges; and

Fig. 5B is a graphical plot of blade section thrust values for a selected frequency range from Fig. 5A over multiple sweeps of the rotor.

Best Mode for Carrying out the Invention

Referring to Fig. 1, there is depicted a helicopter or rotorcraft **10** viewed from above during flight. In the illustrated example, the rotorcraft **10** has a rotor assembly **12**, comprised of four rotor blades **14A, 14B, 14C** and **14D** respectively, each having a radial length R. The rotor blades **14A-D** are disposed at 90° to each adjacent blade and rotate counterclockwise as indicated by direction arrow **16**. In Fig. 1, the rotorcraft **10** is shown in forward flight, as represented by the flight vector arrow **18**.

As the rotor **12** rotates about an axis **20**, the tips of rotor blades **14A-D** generate vortices **14A′**, **14B′**, **14C′** and **14D′** respectively. The paths of the vortices **14A′-D′** leaving the blades as the blades advance will vary as a function of forward flight speed, rotor thrust, and descent angle amongst other things. It can be seen from the paths of vortices **14A′-D′** in Fig. 1 that they appear to move in a helical pattern when viewed from above radially inward relative to succeeding blades **14A-D**, at least in the two advancing-blade quadrants depicted as extending from 0° (over the rotorcraft tail) through 90° (to right of rotorcraft) to 180° (forward of the rotorcraft). The azimuthal position of a blade **14A-D** is conveniently referenced in an angular reference system which places 0° over the tail of the rotorcraft **10**.

At certain regimes within the operation of rotorcraft **10** the impact of vortices on advancing blades, particularly in the first quadrant from 0° to 90°, such as the near parallel interaction of vortex **14B′** and blade **14A**, may be very significant and create significant undesirable audible BVI noise in the far field where persons or listening devices may be located. As noted, such operating regimes typically involve descent and/or maneuver of the rotorcraft **10**.

The physics and aerodynamic research results disclosed in the aforementioned publications of the present inventor are incorporated herein by reference. More specifically, some of the information developed therein may be utilized and refined to provide a control signal in accordance with the invention. That control signal is then available to be used for refined control of various active devices to secure improved attenuation or suppression of BVI noise acoustically detected in the far field.

Referring further to Fig. 1 and additionally to Fig. 2, the rotor assembly **12** is depicted as having at least two pressure sensors, $\mathbf{S_1}$ and $\mathbf{S_2}$, mounted on the surface of a blade, e.g., blade **14A**, relatively toward the leading edge and the radially outer region. Moreover, each blade **14A-D** includes a respective active device (AD) **22A-D** capable of actuation between various states for attenuating the creation of blade tip vortices **14A'-D'** and/or for moving blades **14A-D** relatively out of plane so as to lessen the blade-vortex interaction. This latter type of control may be afforded by active devices of the type disclosed in the aforementioned US Patent 5,711,651, i.e., independently controlled flaps.

Further depicted in Fig. 1, a control system **24** receives, at least, pressure measurements from sensors $\mathbf{S_1}$ and $\mathbf{S_2}$ and provides a signal which is reflective of pressure-dependent BVI noise characteristics, which signal is then used as a control variable in the control and actuation of the active devices **22A-D**.

Referring further to Fig. 2, the radially outer portion of the instrumented blade **14A** of Fig. 1 is shown enlarged and depicting the placement of at least the two pressure sensors $\mathbf{S_1}$ and $\mathbf{S_2}$ within a region which has been determined to be a strong BVI source. Specifically, at least those two pressure sensors, and preferably also any additional pressure sensors $\mathbf{S_n}$, are positioned on the surface of blade **14A** in a region between about 65% and 95% of the blade radius **R** and within 10% blade chord length of the leading edge of the blade. The scale appearing adjacent the leading edge of the blade **14A** in Fig. 2 reveals the station r of sensor $\mathbf{S_1}$ to be about 0.75, or 75%, of blade radius **R** and the station r of sensor $\mathbf{S_2}$ to be about 0.85, or 85%, of blade radius **R**. The optional further pressure sensors $\mathbf{S_n}$ are also within the same range between 65% and 95° **R**. Moreover, the sensors S_1 and S_2 (and S_n) are depicted as being at respective stations c which are each within 10% blade chord length **C** of the leading edge of blade **14A** or built into the blade with a measurement port on the surface. The pressure sensors S_1 and S_2 are preferably of a known type having good sensitivity and a very small size and low profile. The sensors S_1 and S_2 are affixed, as by bonding, to a surface of blade **14A**. Although shown here as being affixed to the upper surface of blade **14A**, which reduces abrasion by debris from below, the sensors S_1 and S_2 may alternatively be mounted to the lower surface of blade **14A**.

Referring to Fig. 3, the pressure sensors S_1, S_2 . . .S_n extend their respective signals to the control system **24**, and more particularly to a pressure signal processor **30** forming a portion thereof. The pressure signal processor **30** analyzes the pressure signals from the sensors S_1, S_2 in a manner to be hereinafter described, and provides a resulting value or signal, **Pcv** on line **32**, shown as extending to controller **34**. The controller **34** also forms part of control system **24**. The pressure signal processor **30** and the controller **34** may be separate, dedicated elements or they may be structurally integrated in form. Moreover, it is preferable that most or all of the electronic processing be performed by a digital processor suitably programmed to accomplish the requisite functions. The controller **34** is also shown as receiving an Operating Regime input on line **36** and a Rotor Azimuth input on line **38**. These inputs may alternatively, or additionally, be extended to the pressure signal processor **30**. The output, or outputs, from controller **34** and thus from control system **24**, extend to the respective active devices **22A-D** to effect the commanded action. The pressure signals from sensors

S_1, S_2 . . . S_n to control system **24**, and the signals from control system **24** to the active devices **22A-D** pass between the rotor blades **14A-D** and the fuselage of rotorcraft **10** via an appropriate slip ring arrangement (not shown).

It will be appreciated that the controller **34** may execute suitable control algorithms for the particular active devices **22A-D**; however, the particular algorithms are not within the scope of the present invention. Rather, the controller **34** and the active devices **22A-D** are programmed or scheduled to respond to the control variable signal **Pcv** in a way that seeks to lessen or null that signal by reducing BVI noise. For example, the Operating Regime input on line **36** and the Rotor Azimuth input on line **38** may serve to command and control a basic, or primary, schedule of control signals to reduce BVI; however, the control variable signal **Pcv** serves to refine that schedule.

Attention is now turned to the development of signal **Pcv** in accordance with the invention. Referring to Fig. 4A, there is depicted a plot of pressure versus blade azimuth, as measured by a pressure sensor such as S_1 or S_2 positioned on blade **14A** as previously described. In Fig. 4A, the pressure sensor was positioned at about 77% of the radial length **R** of blade **14A** and about 5% blade chord length from the leading edge of the blade. The resulting pressure signal has been normalized to account for the effects of free stream pressure and rotational dynamic pressure.

Referring to Fig. 4B, the pressure signal of Fig. 4A has been filtered to retain the frequency band important as a BVI source for the particular rotorcraft system. The BVI noise source is typically comprised of a narrow band of frequencies, typically between 20 and 48 times the rotor rotation frequency. For example, if the rotor

12 rotates at 5 Hz, the BVI source band would include 100 to 240 Hz. Thus the signal depicted in Fig. 4B shows the results of digitally filtering the pressure signal of Fig. 4A and clearly reveals the significant activity in the first quadrant for the advancing blade at about 70°azimuth and in the fourth quadrant for the retreating blade at about 275° azimuth. It is preferable to separate the advancing side signal from the retreating side signal so that each may provide the requisite control at the appropriate time or position during rotation of rotor **12**. Moreover, because there are at least two pressure signals from the sensors $\mathbf{S_1}$ and $\mathbf{S_2}$ respectively, it is desirable to average those values to provide the pressure signal for signal processing.

After filtering the raw pressure signal, the pressure signal processor **30** defines as the metric **Pcv**, the sum of Fourier amplitudes of the blade pressure measured at blade **14A** over the relevant frequency limits $\mathbf{n_1}$ and $\mathbf{n_2}$. This summation may be expressed as:

$$F_{n_1,n_2} = \sqrt{\frac{1}{n_2 - n_1 + 1}} \sum_{n1}^{n2} f_n^2 ,$$ where

F_{n_1,n_2} is the signal for use as the control variable,

fn is the Fourier amplitude over a specified azimuthal segment of blade rotation, and

n_1 and n_2 are frequency limits based on n per full revolution.

It is preferable also to apply a window function before computing the finite Fourier Transform (FFT), since the signals are not periodic over a partial azimuth range. In the present instance, a Welch window was used as follows: The pressure data $P(t_n)$ was multiplied by the window function $W(t_n) = \left(P(t_n) - \bar{p} \right) \left(1 - \frac{n - \frac{N}{2}}{\frac{N}{2}} \right)^2$ prior to computation of the Fourier transform, where $\bar{p}$ is the average value of the pressure data used.

To identify effective values of $\mathbf{n}_1$ and $\mathbf{n}_2$ for use in the summation of the Fourier transform, tests may be conduced on models during wind tunnel tests or on actual rotorcraft under conditions simulating descent to identify probable values offering the most effective results. Further, that test data is correlated with the measurement of actual BVI far field acoustic sound pressure levels (BVISPL) under the same conditions. The results of such wind tunnel tests for a single forward flight speed and five different simulated descent angles for several ranges of $\mathbf{n}_1$ and $\mathbf{n}_2$ values are depicted in Fig. 5A, where **Pcv** is computed using pressure measurements averaged from two sensors at 77% and 92% **R** and Adv Side BVISPL represents the BVI noise from the advancing side blade as actually measured in the far field. The preferred ranges of $\mathbf{n}_1$, $\mathbf{n}_2$ values are those only having positive slopes, and the more linear with respect to the far field measurements, the better. In the embodiment tested and described herein for a 1/6 scale UH-60A Black Hawk helicopter, the range wherein $\mathbf{n}_1$ is 24 and $\mathbf{n}_2$ is 32 appears to provide the best results. This is further confirmed in Fig. 5B which depicts a plot of **Pcv** versus the measured far field noise for several other forward flight speeds and descent angles. The linearity appears to be preserved.

Having thus determined the appropriate arrangement of sensors $\mathbf{S}_1$, $\mathbf{S}_2$ . . . $\mathbf{S}_n$ and the appropriate frequency limits for summing the Fourier amplitudes, the pressure signal processor **30** determines the metric control variable designated **Pcv**. That signal, typically in conjunction with the scheduling provided by the Operating Regime and the Rotor Azimuth inputs, serves to control the respective active devices **22A-D** as a function of their azimuthal positions and in a manner to reduce BVI noise. The provision and use of the signal **Pcv** as a control variable in a mode which feeds back an accurate measure of BVI noise as it appears in the far field, assures the optimal minimization of that noise.

Claims

We claim:

1. A method of providing a signal representative of blade vortex interaction (BVI) noise for a rotorcraft having a multi-blade rotor, said method comprising:

a) measuring the fluid (air) pressure at one or more predetermined locations on a blade of the rotor during at least one predetermined azimuthal segment of the rotation of the blade during operation to provide respective pressure measurements;

b) processing the respective pressure measurements to provide a signal; and

c) providing the signal for use as a control variable in a control system for the active control of BVI noise.

2. A method as in claim 1 wherein the air pressure is measured at two or more locations on the blade between 65 and 95% of the radial length of the blade.

3. A method as in claim 1 wherein the air pressure is measured within 10% blade chord length of the leading edge of the rotating blade.

4. A method as in claim 1 wherein one of said at least one azimuthal segments of blade rotation comprises a blade advancing region relative to forward flight of the rotorcraft.

5. A method as in claim 4 wherein said one of said at least one azimuthal segment is within the quadrant measured angularly forward 90° from the tail of the rotorcraft.

6. A method as in claim 4 wherein an other of said at least one azimuthal segments of blade rotation comprises a separate blade retreating region relative to forward flight of the rotorcraft.

7. A method as in claim 1 wherein the pressure measurements are processed by filtering the pressure measurements to retain substantially only a frequency band commensurate with BVI sources.

8. A method as in claim 7 wherein the band of retained frequencies is between about 20 and 48 times the rotation frequency of the rotor.

9. A method as in claim 7 wherein the filtered pressure measurements are further processed to provide the signal for use as the control variable, the further processing being in accordance with:

$$F_{n_1,n_2} = \sqrt{\frac{1}{n_2 - n_1 + 1}} \sum_{n_1}^{n_2} f_n^2 ,$$ where

F_{n_1,n_2} is the signal for use as the control variable,

fn is the Fourier amplitude over a specified azimuthal segment of blade rotation, and

n_1 and n_2 are frequency limits based on n per full revolution.

10. A method as in claim 9 wherein the values of n_1 and n_2 are initially determined by wind tunnel measurements for a particular set of test conditions simulating descent and are subsequently correlated with BVI far field acoustic sound pressure levels for the same set of test conditions.

11. A method as in claim 10 wherein n_1 and n_2 are substantially 24 and 32 respectively.

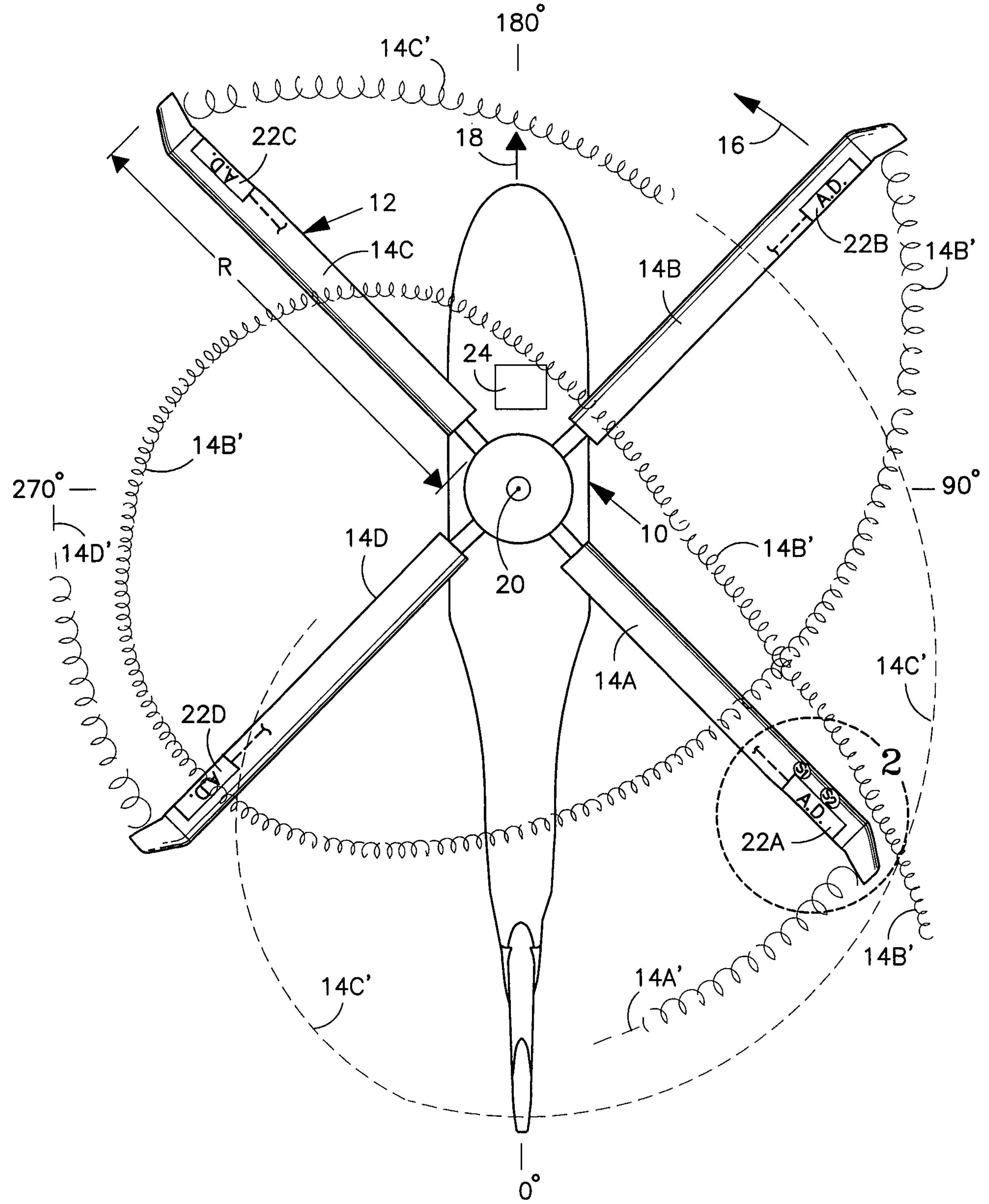
12. A method as in claim 9 wherein the measuring step and the conditioning step are performed repetitively, multiple times for each revolution of the blade to provide a substantially continuous signal for use as the control variable.

13. A method as in claim 8 wherein the filtered pressure measurements are further processed to provide the signal for use as the control variable, the further processing being in accordance with:

$$F_{n_1,n_2} = \sqrt{\frac{1}{n_2 - n_1 + 1} \sum_{n1}^{n2} f_n^2}\text{, where}$$

F_{n_1,n_2} is the signal for use as the control variable,
fn is the Fourier amplitude over a specified azimuthal segment of blade rotation, and
n_1 and n_2 are frequency limits based on n per full revolution.

FIG.1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18
16
22C
12
R
14C
22B
14B'
14B
24
14B'
270°
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14C'
14A'
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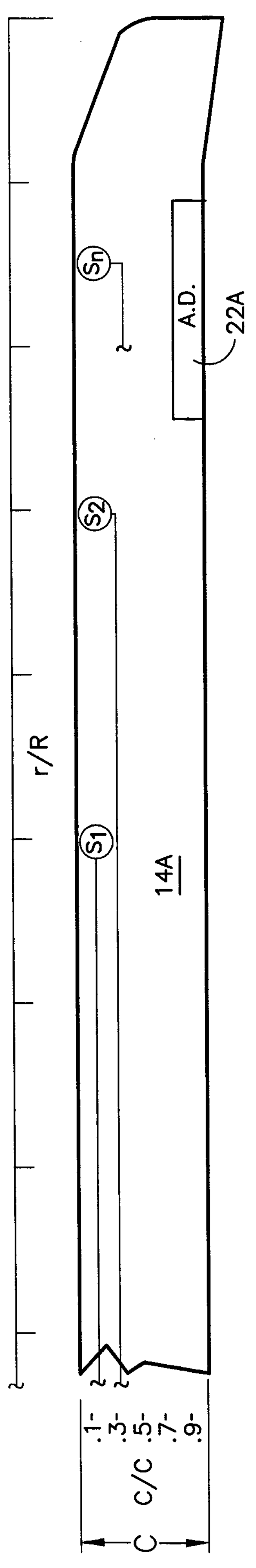
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.65
.60
Sn
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14A
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.3-
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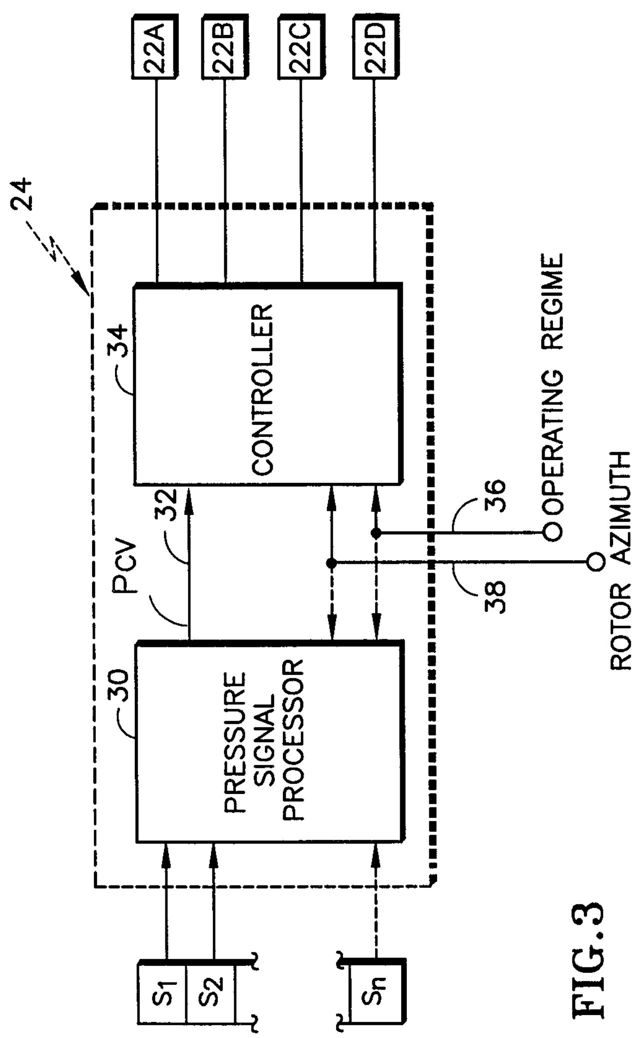
.7-
.9-
C/C
C

FIG.2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22B
22C
22D
24
34
CONTROLLER
30
PRESSURE SIGNAL PROCESSOR
PCV
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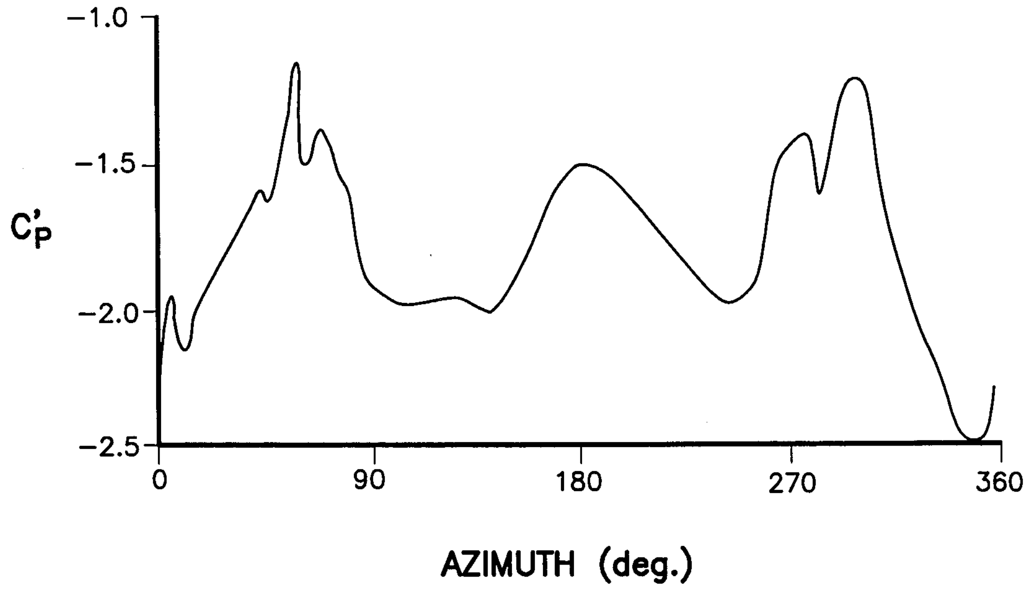
OPERATING REGIME
38
ROTOR AZIMUTH
S1
S2
Sn

FIG.3

FIG.4A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-2.5
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270
360
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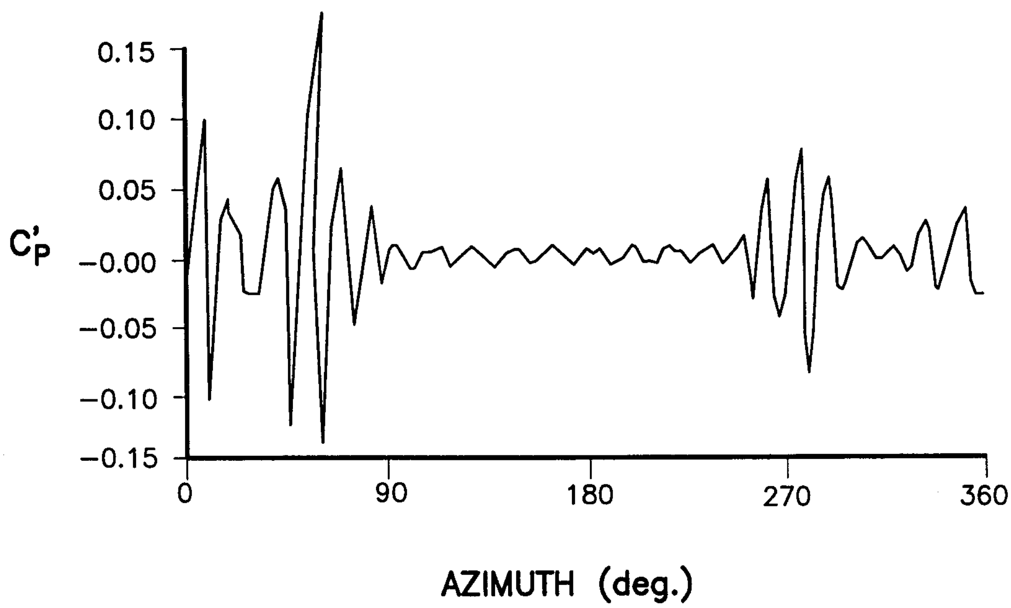
FIG.4B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0.05
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-0.15
C'P
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270
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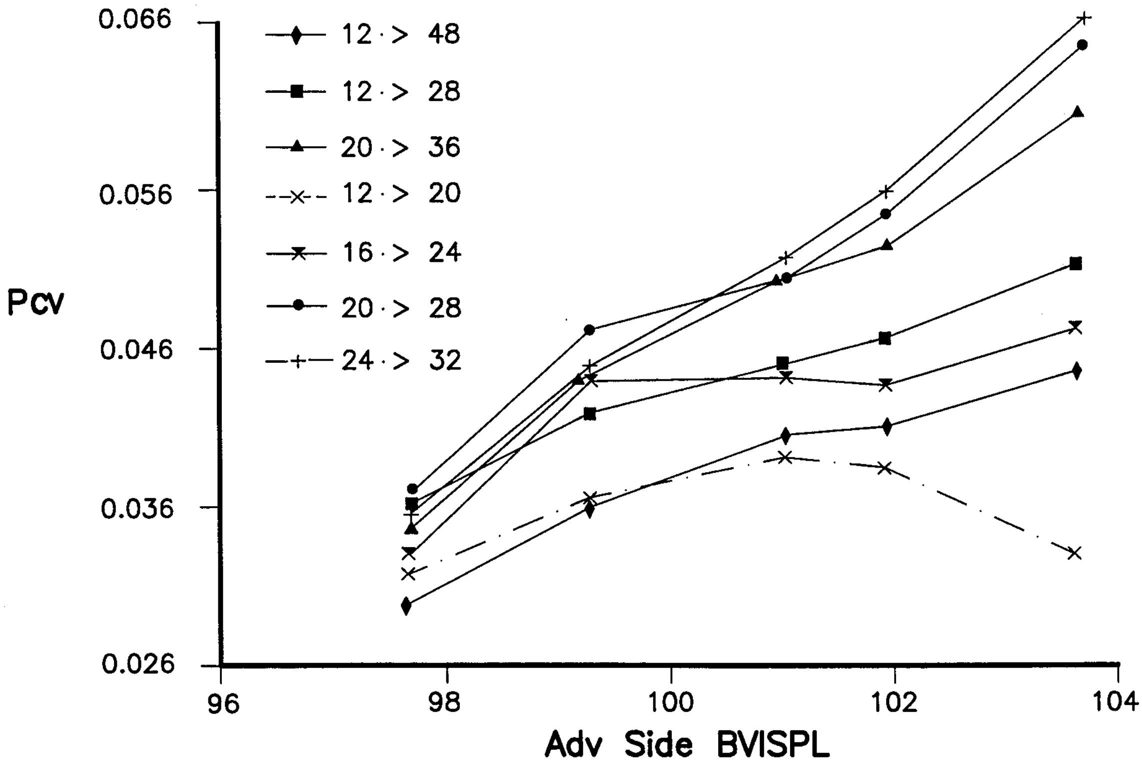
AZIMUTH (deg.)

FIG.5A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0.056
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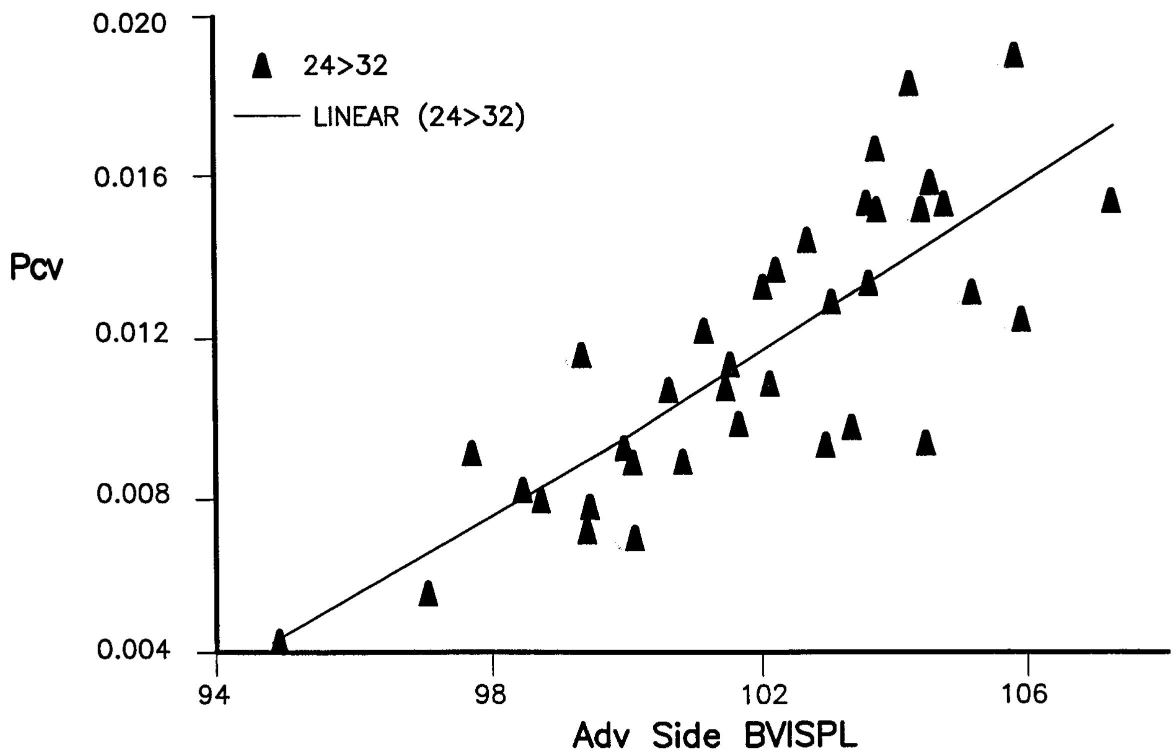
Pcv
12 > 48
12 > 28
20 > 36
12 > 20
16 > 24
20 > 28
24 > 32
96
98
100
102
104
Adv Side BVISPL

FIG.5B


0.020
0.016
0.012
0.008
0.004
Pcv
24>32
LINEAR (24>32)
94
98
102
106
Adv Side BVISPL