

USPTO PATENT FULL-TEXT AND IMAGE DATABASE

(10 of 23)

United States Patent
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Thermal anemometer airstream turbulent energy detector

Abstract

A turbulence sensor whose signal output is processed to substantially reduce accumulated turbulence signal bandwidth and provide a permanent stored record in which maximum information content is preserved while a minimum of data samples are recorded. Both turbulence energy and turbulence intensity sensors are disclosed. Aircraft mounting of multiple sensors together with correlation monitoring relating to airframe structural integrity prediction is disclosed. A turbulence energy sensor for ground monitoring of conditions such as wake vortex and wind shear turbulence as well as cyclonic system detection in remote geographic areas is also disclosed. An aircraft turbulence sensor, combining a fast response thermal anemometer airspeed transducer together with a ducted thermal anemometer direction transducer sensing angle-of-attack is disclosed.

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Field of Search: 73/170.12,170.14,170.02,182,183,861.65,861.85,204.22,204.24,204.25

References Cited [Referenced By]**U.S. Patent Documents**

2701474	February 1955	Goudy
3079758	March 1963	Vogel et al.
3251057	May 1966	Buehler et al.
3402295	September 1968	Astheimer

3407688	October 1968	Babson et al.
3604261	September 1971	Olin
4070908	January 1978	Newell
4184149	January 1980	Baker et al.
5195046	March 1993	Gerardi et al.
5233865	August 1993	Rossow
5357795	October 1994	Djorup
5385069	January 1995	Johnson

Other References

Flomenhoft, "Brief History of Gust Models for Aircraft Design", J. Aircraft, vol. 31, No. 5: Engineering Notes (pp. 1225-1227). .

Ducvharme, et al., "The Feasibility of Using a Hot-Film Anemometer in the Rain", American Meteorological Society, (Oct. 1994) (pp. 1415-1419). .

David Hughes, "Design, Checks Cited in Crash", Aviation Week & Space Technology (Nov. 1, 1993), (pp. 39-42). .

Edward H. Phillips, "New Sensors Reduce Wind Shear Risks", Aviation Week & Space Technology (Oct. 18, 1993), (p. 53). .

Frederic M. Hoblit, "Gust Loads on Aircraft: Concepts and Applications", AIAA Education Series (1988). .

Ralph E. Huschke, "Glossary of Meteorology", American Meteorological Society, Boston, MA (1959). .

Richard J. Goldstein "Fluid Mechanics Measurement", Hemisphere Publishing Corp. (1983). .

Houbolt, et al. "Dynamic Response of Airplanes to Atmospheric Turbulence Dincluding Flight Data on Input and Response", NASA, Washington, DC (Jun., 1964). .

Kitchin, et al. "RMS To DC Conversion Application Guide, 2nd Edition", Analog Devices, Inc. (1986). .

"Special Linear Reference Manual", Analog Devices, Inc. .

Lumley, et al. "The Structure of Atmospheric Turbulence", Interscience Publishers (1964). .

Tennhekes, et al. "A First Course in Turbulence", The MIT Press, Cambridge, MA (1972). .

Omega Complete Flow & Level Measurement Handbook and Encyclopedia, vol. 28. copyright 1992..

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Claims

What is claimed is:

1. A turbulence sensor comprising:

thermal anemometer airspeed transducer means providing fast response airspeed signal output;

means.

8. The turbulence sensor as defined in claim 2, 3, 4 or 5, wherein:

said second storage section of said digital storage means comprises continuous magnetic tape storage means.

9. The turbulence sensor as defined in claim 2, 3, 4 or 5, wherein:

said digital storage means comprises disc storage means.

10. A turbulence sensor according to claims 1, 2, 3, 4 or 5 comprising:

an aircraft on which are located plural thermal anemometer turbulence sensors exposed to longitudinal airflow at widely separated mounting points,

correlation means to determine degree of correlation between said turbulence sensor signals from said plural turbulence sensors, and

means indicating degree of correlation determination.

11. The turbulence sensor of claim 3 or 5, further comprising:

means for permanently recording a single numerical value of stored said time history taken by said microprocessor computation means as a cumulative weighted arithmetic total representing all stored and accumulated said turbulence values, said numerical value being continually updated as said turbulence sensor is operated, thereby providing a turbulence exposure summary indicator.

Description

TECHNICAL FIELD

The invention relates generally to improved airspeed transducer apparatus for determining and reporting turbulence energy and turbulence intensity for use on aircraft and in the ground environment. The invention discloses a turbulence sensor whose signal output is processed by either analogue or digital means to substantially reduce accumulated turbulence signal bandwidth and provide a permanent stored record in which maximum information content is preserved while a minimum of data samples are recorded. A time-history is thus obtained of the lifetime exposure of an airframe to in-flight atmospheric turbulence disturbances that may occur only for a very small portion of total flight time. Such a time-history can facilitate structural inspection and fatigue prediction. The invention further discloses aircraft mounting of multiple turbulence sensors together with correlation monitoring to provide warning of a possible impending loss of a portion of airframe structural integrity. Both turbulence energy sensors and more complex turbulence intensity sensors are disclosed. The simpler turbulence energy sensor may be applied in the ground environment to airport runway wake vortex and low level wind shear measurements as well as cyclonic system detection in remote geographic areas.

BACKGROUND ART

A considerable amount of time and effort has been expended respecting atmospheric turbulence

measurement and attempts at prediction of atmospheric turbulence by many commercial, civil, and military organizations since all aircraft are affected by turbulence while they are operating. Many different sensing and signal acquisition techniques have been used, ranging from radar to laser radar, from laser velocimetry to Lidar, from hot wire anemometry to pressure tube anemometry, from passive to active acoustic sounding, from infrared to microwave radiometers, and on. Most equipment thus far is very costly, is highly complex, and is usually too large and cumbersome for general field usage or aircraft installation. Relatively little has been done respecting actual exposure monitoring of an aircraft to inflight turbulent airflow and most aircraft presently use near center-of-gravity located remote reading accelerometers for such measurements, recording continuous data on a flight recorder or its equivalent.

A summary of the current state-of-the-art of turbulent velocity measurements from aircraft, used in present day aircraft design practice, is given on pages 22, 23, 62, 63 and 170 of the book entitled "Gust Loads on Aircraft: Concepts and Applications", by Frederic M. Hoblit, published in 1988 by the American Institute of Aeronautics and Astronautics, Inc., Washington, D.C., ISBN 0-93403-45-2.

A flow direction sensor for aircraft that senses angle-of-attack and sideslip by means of a served sphere with pressure difference ports is disclosed by U.S. Pat. No. 3,079,758. Fluctuating changes in indicated attitude with respect to aircraft motion has been used in computing turbulence from the vertical and lateral components.

A ground-based air-turbulence detection system using radar techniques is disclosed by U.S. Pat. No. 3,251,057.

An airborne infrared process for spectral scanning of the atmosphere ahead of an aircraft is disclosed by U.S. Pat. No. 3,402,295. At that time it was disclosed that temperature discontinuities could be measured as an aid in locating turbulent air.

A turbulence indicator for aircraft that used inertial displacement of a mass within the indicator is disclosed by U.S. Pat. No. 3,407,668.

An airframe is an elastic non-linear mechanism and atmospheric turbulence sensing apparatus at or near the center-of-gravity or center-of-motion sees the aircraft's response to a random disturbance input through a constantly changing non-linear filter, the aircraft structure itself. Variables, such as aircraft speed, wing loading, fuel consumption, flight attitude, passenger and cargo load changes, wing lift-curve slope, and the like, all contribute to the non-linear characteristics of the elastic airframe. These variables affect the inaccuracies of an indirect measurement of turbulence exposure.

Historically, qualitative pilot reports are used to describe the characteristics of in-flight turbulence and different pilots in the same aircraft can report different results. Research turbulence instrumentation, true gust instrumentation, generally utilizes boom-mounted angle-of-attack and sideslip vanes for accurate time-histories during turbulence encounters. Such systems are not economically feasible when continuous measurement is desired during routine flight operations for long term observation of structural integrity as a contributor to flight safety. It is desirable that turbulence variations are sensed so that the aircraft operator may benefit from a time-history of the aircraft's exposure to randomly encountered turbulence during normal flight operations for the service life of the aircraft. The same aircraft type on two different repetitive routes can see wildly different total accumulated exposure to en-route turbulence. Flight over large land masses with mountain ranges and varied terrain, such as across the continental United States, can be quite different than long transoceanic flights although the flight durations may be the same. Presently, airframe useful life is determined linearly by totalizing the number of flight hours and by counting the number of takeoff-landing cycles. Inspections are carded on in linear fashion as well, ignoring the fact that the aircraft operates in a non-linear environment, a

u is eddy velocity or turbulence, and

U is mean wind speed or mean airspeed.

Simply put, turbulence intensity is equal to turbulence energy divided by mean airspeed.

Two approaches to the implementation of the invention are disclosed where these, in turn, are accomplished by analogue computation means and by digital computation means. The first approach discloses a turbulence energy sensor that uses the numerator of the above expression. The second approach discloses a turbulence intensity sensor that solves the entire equation. On the ground it is appropriate to apply the measurement of turbulence energy thereby avoiding zero wind condition calculations and infinite values of turbulence intensity. In aircraft operations it can be equally appropriate to use either turbulence energy or turbulence intensity as indicators of exposure to disturbed air since a mean airspeed component is always present.

Most airspeed transducers have non-linear response characteristics and whether one chooses to use raw airspeed signals in a piecewise linear look at turbulence values or use linearized airspeed signals to obtain a truer measurement is a matter of choice that depends also on the turbulence disturbance range. Early aircraft design criteria used much smaller values of turbulent airspeed components but more recent flight experience has shown a need to use significantly larger values that sometimes approach mean airspeed readings in extreme cases. This suggests that linear airspeed data are to be preferred for comparisons between different airframes and different aircraft types.

The instant invention also discloses successive stages of bandwidth reduction, measuring energy and energy accumulations over a period of time, for storage and recording purposes in order to reduce the total amount of data needed to be stored without losing the energy exposure time-history. It is shown that the entire life history of an aircraft fitted with the disclosed sensor or sensors can be contained in a very small storage device like an IC or integrated circuit chip.

The invention further discloses means for correlation of the output of plural turbulence sensors, mounted on different places on an aircraft that experience similar airflow, which serve to detect changes in the airframe structure that can cause a failure for sensor outputs to correlate in the expected fashion when the airframe is intact. Such failure to correlate sensed outputs can be caused by fatigue cracking in major structural members such as lifting surface attachment forgings, engine pylon attachment elements and the like.

In a further embodiment a basic form of turbulence energy sensor is used to detect rapid local wind motion changes near the ground, as an alarm. Such changes are experienced in the presence of different turbulence forms, as in the case of airport runway wake vortex turbulence generated by aircraft operations, low level wind shear which can be brought about by squall lines, downdrafts and microbursts against the ground, and similar phenomena where turbulence energy increases are sudden and often unpredictable. On a much larger scale, a network of simple turbulence energy sensors, often kilometers apart along uninhabited coastal regions, for example, can be used to signal passage of disturbed air masses in the absence of more costly conventional weather reporting stations.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a block diagram of the essential components of a turbulence energy sensor made in accordance with the principles of the present invention.

FIG. 2 is a diagram showing a typical transfer function for a thermal anemometer transducer.

averages that are accurate only for sine wave inputs. Modern RMS-to-DC converters, such as the Analog Devices, Inc. AD637, are particularly well suited to such measurements and the AD637 can be easily adapted to the very low frequencies that are typically encountered at the output 17 of bandpass filter 16. Measurement of frequencies between 0.09 cps and 5 or 10 cps can be accomplished with the AD637 connected in a way to greatly reduce the size of the required averaging capacitor and this is shown under the section "Low Frequency Measurements" by FIG. 15 on page 4-30 of the manufacturer's data sheet Rev. A, included within the Analog Devices "Special Linear Reference Manual", dated 1992.

Airspeed transducer 14 electronics, bandpass filter 16, and root-mean-square measuring circuit 18 can be constructed, using modern off-the-shelf integrated circuit and electronic components, to occupy a volume of about 50 cubic centimeters or three cubic inches. Such physical sizing permits the electronics to be located close to pylon 13 or it may even be included within pylon 13 support structure itself as a self-contained unit with power in, root-mean-square measured airstream turbulence signal out.

It is helpful to refer to the "RMS to DC Conversion Application Guide", 2nd Edition, by Charles Kitchin and Lew Counts, published by Analog Devices, Inc. in May 1986, for a thorough review of RMS measurements.

Output 19, as a measurement of turbulence energy, is in a condition where the enormous data bandwidth of inflight encountered atmospheric turbulence is in a manageable form for later recording, computation, or data processing. Root-mean-square turbulence energy 19 can also be used in real time to signal the level of local turbulence activity as it is sensed while turbulence energy sensor 10 is operated on the ground as a fixed sensor. Operating bandwidth is determined in much the same fashion as for an aircraft installation. It is helpful to assign a lower velocity threshold limit to the measurement as an aid to bandpass filter 16 design since a zero velocity measurement of local wind speed has little meaning in the context of turbulence energy measurement.

FIG. 4 is a simplified block diagram illustrating a second embodiment of the instant invention disclosing a turbulence intensity sensor. Analogue signal processing is shown for measurement of turbulence energy, as in FIG. 1, and further computation is accomplished together with data storage to provide a record of turbulence exposure time-history.

Bandpass filter 16 provides turbulence signal 17 from airspeed transducer 11 output 15 which is a composite signal containing mean airspeed and turbulence components. Lowpass filter 23 provides a mean airspeed signal 24 from airspeed transducer output 15. The cutoff frequency of lowpass filter 23 is chosen to be equal to or less than the lower cutoff frequency setting of bandpass filter 16 so that no turbulence is present in mean airspeed signal 24 in the form of short term fluctuations. Divider 25 denominator input signal 24 is mean airspeed and numerator input 19 is turbulence energy taken from root-mean-square measurement 18 of bandpass filtered turbulence signal 17. Quotient 26 is fed to electrical integrator 27 that integrates a continuous analogue measurement of turbulence intensity. Integrator 27 reset timing is under control of microcontroller 31 which also controls analogue-to-digital converter 29, abbreviated as ADC, providing digital data 30 to digital storage 33.

Sampled data theory postulates that at least two samples per cycle are required to define a varying signal. When airspeed transducer bandpass filter output 17 is sampled, using the above aircraft example, 10.30 samples per second are required to define a 5.15 cycle per second signal. Clearly, continuous sampling and recording can accumulate an enormous amount of data. Integrator 27 can accumulate measured turbulence intensity 26 for several minutes or even several hours, depending on the quality of the integrating capacitor and other components used in integrator circuit construction. If a sample is used to represent a portion of the aircraft's flight history, a one minute sample of turbulence exposure corresponds to 17 kilometers travelled distance, five minutes corresponds to 85 kilometers, and ten

minutes corresponds to 170 kilometers travelled, by a Boeing 747-357 at maximum airspeed. With a single sample taken of integrator 27 output 28 every ten minutes, some 240,000 samples are needed to disclose 40,000 hours time-history for a particular airplane's total flight operations. Each sample represents the total energy exposure of the aircraft for the duration of the integration period. In smooth flight the energy sample will be negligible. During turbulent flight the energy sample becomes significant.

Analogue-to-digital converter 29 periodically samples the integrator 27 output 28 under control of microcontroller 31 which resets integrator 27 to zero when each sample is converted to digital form. Microcontroller 31 is used in this embodiment mainly to provide timing and control functions.

The sampled digital output 30 is fed to storage 33 which can be in two parts, 34 and 35, where the first part 34 is dynamic memory that can be in the form of RAM, random-access-memory, and the second part 35 is permanent storage in the form of ROM, or read-only-memory. It should be noted that with longer integration time less dynamic memory capacity is needed for temporary storage before the permanent storage is loaded with a sample. Long integration times require expensive component parts and careful construction. Turbulence sensor ambient environmental requirements may suggest shorter integration times, minutes, not hours.

The permanent storage 35 includes periodic samples of the aircraft flight history and a single storage unit can be interrogated periodically during maintenance periods to aid in aircraft inspection and servicing. Storage 35 can be a small thumbnail sized programmable read-only-memory module or ROM, CD-ROM or compact disc ROM, optical disc storage, continuous magnetic tape or similar rugged storage device. It is helpful, where a permanent record is desired, to use only recording devices that are written once per sample location and are not erasable.

FIG. 5 is a simplified block diagram illustrating a third embodiment of the instant invention, disclosing a turbulence intensity sensor. Digital signal processing is shown for measurement and computation of turbulence energy, division of turbulence energy by mean airspeed, and digital storage of the result.

As in FIG. 4, airspeed transducer 11 output 15 is followed by bandpass filter 16 and lowpass filter 23, and their outputs, 17 and 24, are converted to digital signals 38 and 39, respectively, by analogue-to-digital converter 36. Analogue-to-digital converter 36 can either be comprised of two converters, one for each input signal, 17 and 24, or one converter preceded by a two input multiplexer, with converter 36 providing turbulence signal 38 to root-mean-square measurement 37, thence to a divider stage 41 where mean airspeed signal 39 is divided into turbulence energy signal 40. Divider 41 output 42 is fed to storage 43 for entry into a permanent record as described in the above disclosed second embodiment. Microprocessor 32 provides timing, control, and computation for all functions following airspeed signal component inputs 17 and 24. Intermediate data sample accumulation and integration is accomplished digitally so as to obtain the reduced bandwidth time-history result obtained by the above disclosed second embodiment of the invention.

FIG. 6 discloses an embodiment of the invention that combines the turbulence energy sensor 10 of FIG. 1 with signal 19 integration and storage disclosed in the embodiment illustrated by FIG. 4, including integrator 27, analogue-to-digital converter 29, multi-part storage 33 and microcontroller 31. Analogue signal handling is shown until turbulence energy output 17 is digitized, preparatory for digital storage. As above, microcontroller 31 is used as a controller for timing, ordering of digitized data into storage 33, and integrator 27 resetting, readying integrator 27 for the subsequent sample period in turbulence energy signal accumulation.

FIG. 7, like FIG. 6, discloses an embodiment of the invention that combines the forward portion of

magnitude becomes significantly large enough to adversely affect aircraft operation. Detection and measurement of inflight variations in horizontal airstream gradients contribute to airframe structural integrity predictions that are based on actual dynamic turbulence energy exposure time histories.

FIG. 9 illustrates a simplified block diagram of an aircraft reporting and alarm display system made in accordance with the principles of the instant invention. Using the notation of FIG. 8, for example, airplane fuselage 50 mounted turbulence sensors 51 and 52 feed output signals to correlator means 56 that can be as simple as a difference amplifier together with output signal level comparators, whose output 57 in turn can be fed to an alarm circuit 58 and also a display 59. Space on an airplane cockpit instrument panel is limited and it is doubtful whether such a display would be installed since the longitudinal correlation information obtained is of greater significance to maintenance personnel. In the case of lateral correlation, between wing tip mounted sensors 54 and 55, immediate knowledge of increasingly sharp gradients can be used by the pilot to initiate evasive action when needed. In this latter instance a cockpit display 59, together with alarm circuit 58, becomes of great significance respecting safety of flight.

A helpful discussion of atmospheric turbulence spectra and correlation can be found in pages 175-197 of a book entitled "The Structure of Atmospheric Turbulence", by John A. Lumley and Hans A. Panofsky, published in 1964 by Interscience Publishers, a division of John Wiley & Sons, New York, Library of Congress Catalog Card Number 64-14991. A more recent general discussion can be found in pages 29-32 and 207-211 of a book entitled "A First Course in Turbulence", by H. Tennekes and J. L. Lumley, published by The MIT Press, Cambridge, Mass., 1972, ISBN 0 262 200 19 8.

FIG. 10 depicts a structure for airspeed transducer pylon 13 that supports and orients thermal anemometer transducer sensing element 12 in respect to impinging airflow. Fabrication is customarily of stainless steel, for pylon 13 and mounting flange 60, and hard anodized aluminum alloy for the tip portion 61 housing sensing element 12. It is preferred to protect exposed sensing element 12 with a sheath such as stainless steel, dense aluminum oxide, or a vitreous refractory material that is able to withstand continuous particle carrying airstream abrasion in order to avoid erosion caused dimensional changes. Dimensional changes can adversely affect heated sensing element 12 heat transfer coefficients, thereby changing airspeed transducer calibration. A semi-resilient material could also be used, such as Teflon (a trademark), which has been experimentally verified confirming resistance to such abrasion.

In a further embodiment of the instant invention, it should be noted that by a combination of a turbulence sensor having sensing element 12 together with a ducted thermal anemometer transducer, a determination of fast response airspeed, with measured turbulence, as well as angle-of-attack is facilitated.

Further, in respect to FIG. 10, ducts 63 and 64 are shown illustrating inclusion of ducted thermal anemometer structure used for concurrent angle-of-attack or impinging flow direction sensing.

FIG. 11 is an elevational section view showing ducted thermal anemometer structure illustrated in FIG. 10 through pylon 13, taken along the line 2--2 thereof, and looking in the direction of the arrows. Orthogonal duct pair 63 and 64 are shown, oriented in the plane of incident airflow, with paired thermal anemometer resistive sensing elements 65 located at or near their midpoints. For clarity, paired elements are not shown pictorially across duct 64, lying underneath and alongside duct 63. A plane parallel to the longitudinal axes of ducts 63 and 64 is perpendicular to the longitudinal axis 62 of thermal anemometer airspeed transducer sensing element 12 illustrated in FIG. 10.

It should be noted that when a mean airspeed component is always present, as against an aircraft in flight, duct 63 and 64 reverse airflow cannot occur. Therefore, in yet a further embodiment, paired

sensing elements 65 may be replaced by a single transverse sensing element in ducts 63 and 64 to detect duct airflow.

Low speed aircraft, helicopters in particular, as well as VSTOL aircraft (vertical or short take-off and landing aircraft), benefit by use of the above disclosed embodiments of a combination turbulence sensor, including both airspeed and direction sensors, serving as a low speed airspeed sensor that is capable of making airspeed component determinations to near zero airspeed. These instrument characteristics augment the disclosed embodiments defining turbulence sensor measurements of turbulence energy and turbulence intensity.

The more general case of higher speed aircraft is also well-served in that, from angle-of-attack determinations made by a coherent or very closely situated sensor, airspeed turbulence vector component magnitudes can readily be computed, thus aiding after-the-fact investigation of aircraft operations.

The ultimate turbulence energy bandwidth reduction can be demonstrated in the form of a single numerical value. If all accumulated and stored measured turbulence energy exposure values are integrated or summed, a single number can be obtained to describe the individual aircraft's cumulative turbulence exposure during its entire prior flight history. In this way a turbulence exposure summary indicator or index can be determined for a particular aircraft that may be used to describe a type or class of aircraft when historical performance, relating to aircraft safety, is to be considered or compared from airframe to airframe.

The above description presents the best mode contemplated in carrying out the invention. The invention is, however, susceptible to modifications and alternate constructions from the embodiments shown in the drawing and described above. Consequently, it is not the intention to limit the invention to the particular embodiments disclosed. On the contrary, the invention is intended and shall cover all modifications, arrangements and alternate constructions falling within the spirit and scope of the invention, as expressed in the appended claims when read in the light of the description and drawing.

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