AN ULTRASONIC ANGULAR MEASUREMENT SYSTEM

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ABSTRACT

An original design is presented for a system capable of measuring the relative angle of a flat surface using reflected ultrasonic wave pulses. No physical contact with the surface is necessary. The measurement range is from 0 to 54 degrees. Theoretical resolution is 5 minutes of arc, with actual measured resolution of approximately 20 minutes of arc. The system has performed successfully in limited flight tests, is capable of rates up to 80 angle measurements per second, and has a solid-state memory recording capacity of 24,000 bytes. The measurements are time-tagged as they are recorded and may be transferred to a personal computer at a later time over a standard RS-232 serial communications link. The system is small (approx. 6 by 4 by 1.5 inches) and uses two standard 9-volt batteries as its power source.

KEY WORDS

Angular Measurement, Ultrasonics, Non-contact Angular Measurement, Inclinometers, Tip-off Angle Measurement

INTRODUCTION

Various methods have been proposed to measure angular displacement at close range using optical or ultrasonic methods. Optical angular measurement devices have been demonstrated involving reflective surfaces, optical code plate sensors, encoded diffraction gratings [1] [2], and photodiode arrays [3]. These optical methods all require modification of the object to be measured (such as attaching mirrors) or contact with the object (such as connection to a shaft). Ultrasonic methods have proven more useful in applications where contact with (or modification of) the object to be measured is not possible [4]. Limitations of non-contact ultrasonic angular measurement systems which have been reported in the past [5] include limited angular range (less than 20 degrees), large size, and complexity. The system described in this paper overcomes many of these limitations.

The original purpose of this project was to find a method to measure the tip-off angle of a cargo pallet as it is being extracted in flight from a C-17 aircraft (Figure 1). The tip-off angle is defined as the angle between the deck of the plane and the cargo pallet. Some of the requirements for the system were: minimal modification to the aircraft, accuracy of at least 0.5 degrees, ability to use the system with any arbitrary pallet (no pallet modification allowed), a measurement rate of at least 50 measurements per second, and data recording capability. The system described in this paper was designed to meet these requirements and test results show that, in most cases, it was successful.

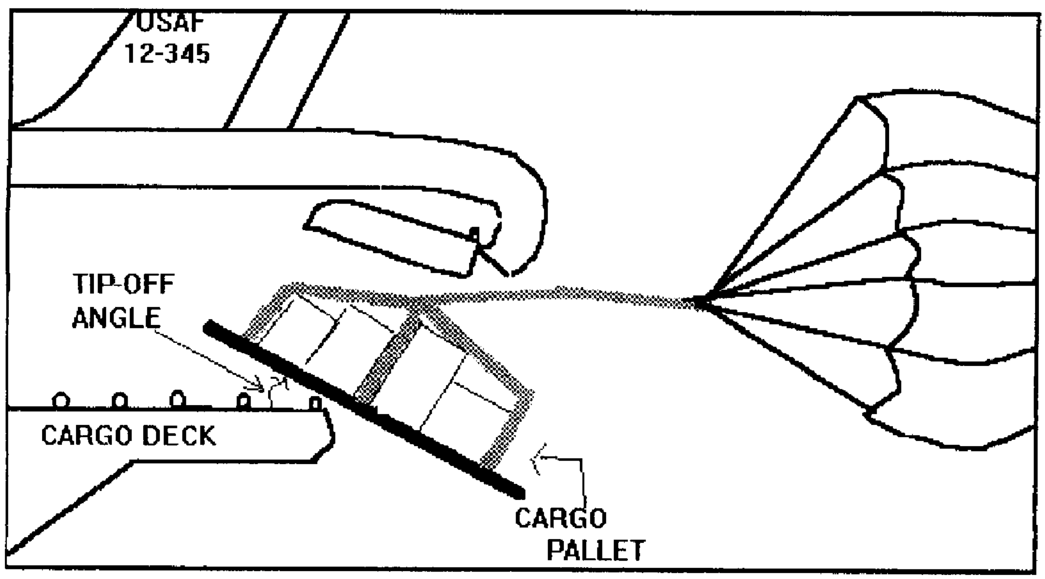

Figure 1. Cargo Pallet Extraction from an Aircraft

SYSTEM DESCRIPTION

The ultrasonic angular measurement system can be divided into three parts: the control box, the ultrasonic transducer, and the reflector block (Figure 2). The system transmits pulses of ultrasound from the transducer which bounce off the cargo pallet, then a reflector block, then back to the pallet, and finally return to the ultrasonic transducer. By measuring the time difference between the transmitted pulse and received echo, the distance that the pulse traveled can be calculated using the speed of sound in air. The system must measure the air temperature since the speed of sound is dependent on temperature. The distance traveled by the pulse of ultrasound is linearly related to the angle in question. Following is a description of each of the three parts of the system.

The control box receives software instructions from a personal computer, provides system control, records the data, and sends the data back to the personal computer. The heart of the control box is a commercially available printed circuit (PC) board which contains a 6303 microprocessor, an analog to digital (A/D) converter, timers, a universal asynchronous receiver/transmitter (UART), read only memory (ROM), and random access memory (RAM). Also included in the control box are RS-232 serial communications driver circuits, power switches, light emitting diode (LED) status indicators, an ultrasonic driver module, a thermistor temperature sensor, and two standard 9-volt batteries. Software is loaded into the control box from a personal computer via the RS-232 serial communications port (after loading the software the personal computer may be disconnected). The two power switches control power on/off and standby/operate modes (standby mode keeps memory active but shuts off all other power in order to save the batteries). The three LEDs indicate low battery power, memory remaining, and data recording mode (stopped, waiting for target, or recording target data). The thermistor temperature sensor puts out an analog voltage proportional to the air temperature and the voltage is then digitized by the A/D converter and used for calculation of the speed of sound. The ultrasonic driver module generates high amplitude electrical pulses of 150 KHz waves which are used to drive the ultrasonic transducer. The ultrasonic driver module also senses the return echo signal from the transducer. One of the 9-volt batteries supplies the ultrasonic driver module and the other supplies the rest of the electronics.

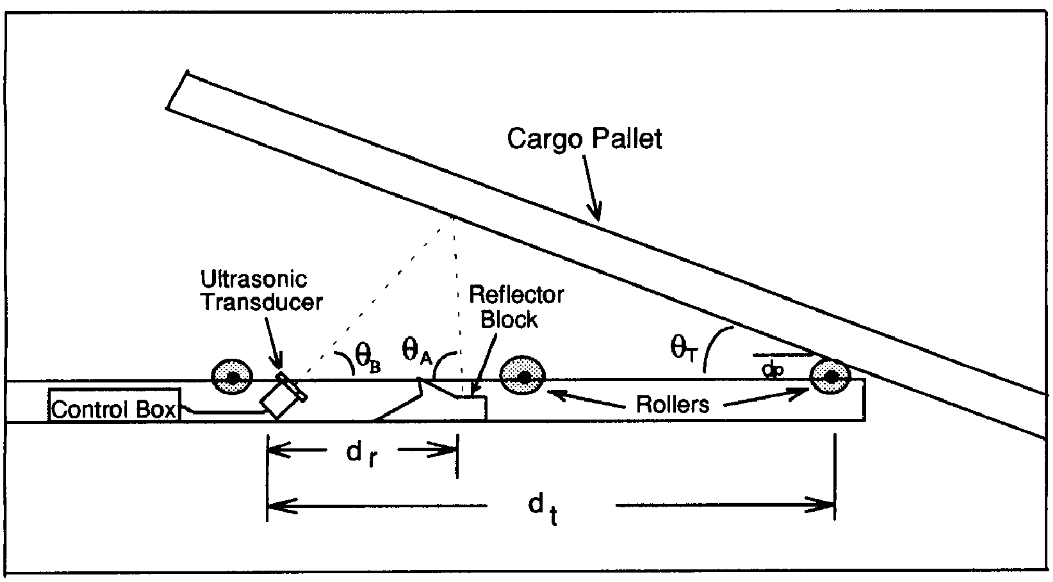

Figure 2. The Ultrasonic Angular Measurement System

The ultrasonic transducer is a piezoelectric device which operates at 150 KHz It has a beam width of ten degrees and no sidelobes. It converts electrical pulses generated by the control box into ultrasonic waves. It also generates electrical signals when excited by ultrasonic waves (echoes of the transmitted waves).

The reflector block is the most unique part of the system. It enables the measurement of a wide range of angles. The block is machined from a solid piece of aluminum and has various angled surfaces designed to reflect the ultrasonic pulses back in the same direction they came from (see Figure 3). The block is divided into two parallel halves, with each half optimized for a different angular range. The geometry of the system and theory of how the reflector block works are discussed in the following sections.

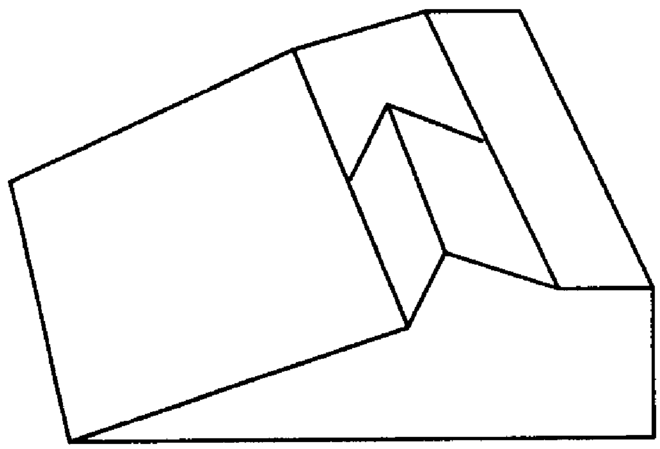

Figure 3 The Reflector Block

SYSTEM OPERATION

In order to understand how the system operates, it is first necessary to understand the geometry. Figure 2 is a side view diagram of the angular measurement system which shows the path of the ultrasonic pulses from the time they leave the transducer until the echoes return to the transducer. This geometry is based on the specific application of measuring the tip-off angle of a cargo pallet being extracted from an airplane, but the method may be generalized to measurement of the relative angle of an arbitrary flat surface. Two assumptions are necessary in order for the system to function: 1) the angle between the plane in which the transducer is mounted and the plane of the surface whose angle is being measured (cargo pallet) may be varied in only one dimension (no twist or tilt except the angle being measured) and 2) The intersection between the two planes must be a fixed line (for example, it would be a violation of this assumption to maintain the relative angle between the two planes while changing the distance between them). These assumptions are valid for the aircraft application since the cargo pallet slides on rollers a fixed distance above, and parallel to, the cargo deck and tips about the constant pivot line at the edge of the cargo deck as it leaves the airplane (see Figure 1). In the tip-off angle application, the angular measurement system is mounted to the cargo deck of the aircraft at a fixed distance from the edge of the deck and the pallet slides on rollers above the system.

The transducer is mounted at a 48-degree angle relative to the aircraft cargo deck. This angle is chosen to optimize angular range, system compactness, and the pulse travel distance versus tip-off angle relationship. The ultrasonic pulses travel at the initial 48-degree angle until they contact the bottom side of the cargo pallet. The pulses are reflected from the bottom of the pallet at an angle determined by the tip-off angle θ_T of the pallet. The pulses arrive at the cargo deck at a distance d^r from the transducer, and at an angle θ_A relative to the deck. Both d_r and θ_A are functions of the tip-off angle. The reflector block is shaped such that at any given distance d_r, the angular surface of the block will be approximately perpendicular to the angle θ_A. The result is that pulses striking the reflector block are reflected back along the same path that they came from. Pulses returning from the reflector block strike the bottom of the pallet along their original path and are reflected back to the transducer. (Approximations in the angles of the surfaces of the reflector block are compensated for by the fact that the beam width of the ultrasonic pulses is 10 degrees, so that the ultrasonic pulses actually travel at approximately plus or minus 5 degrees from the beam center.) As the pallet tip-off angle increases, the pallet eventually becomes perpendicular to the path of the pulses emitted by the transducer, at which point the pulses are reflected directly back to the transducer instead of to the reflector block. By measuring time difference between the transmitted pulse and the return echo, and with knowledge of the speed of sound, the distance traveled by the ultrasonic pulses can be calculated.

The velocity of sound in air varies with the square root of temperature as shown by the following equation:

$$V_S = 13{,}044\,(273 + T_A)^{1/2} \qquad (1)$$

where V_S is the velocity of sound in inches per second, and T_A is the ambient air temperature in degrees centigrade. It is necessary to correct the speed of sound for temperature in order to obtain sufficient measurement accuracy. In the ultrasonic angular measurement system the control box contains a thermistor temperature sensor which is read under software control in order to make this correction.

The distance traveled by the ultrasonic pulses as a function of tip-off angle can be derived mathematically. Neglecting path length changes due to the reflector block (assuming that all pulses are reflected at the level of the cargo deck) the distance equation is given by

$$S = \frac{[d_t \sin\theta_T + d_p \cos\theta_T]}{\sin(\theta_T\ \theta_B)} \times \frac{[1 + \sin\theta_B]}{\sin(2\theta_T + \theta_B)} \qquad (2)$$

where S is the distance traveled in inches, θ_T is the tip-off angle in degrees, θ_B is the angle of the transducer relative to the cargo deck in degrees, d_t is the distance of the transducer from the pivot line in inches, and d_p is the vertical distance between the transducer and the bottom of the pallet in inches when $\theta_T=0$. In the application described in this paper, θ_B = 48 degrees, d_t = 22 inches, and d_p = 1 inch. It should be noted that equation (2) applies to angles θ_T of less than 29 degrees. For angles of 29 degrees or greater, the path (as mentioned earlier) is from transducer to pallet and directly back to transducer (bypassing the reflector block).

Operation of the ultrasonic angular measurement system is controlled by the system software. The software is written such that the system is always in one of three modes: waiting for valid data, recording data, or halted due to a full data buffer. In the waiting for data mode, pulses are sent out and the system waits until valid echoes are detected. Once a valid echo is detected the system changes to the data recording mode. In the data recording mode, time, temperature, and intervals between transmitted pulses and echoes are recorded. New pulses are transmitted at the rate of 80 pulses per second. When non-valid echoes are detected the system reverts back to the wait mode, or, if the data buffer becomes full, the program halts. System mode, data buffer status, and battery status are indicated by light emitting diodes under software control.

TEST RESULTS

Tests performed on the angular measurement system include laboratory calibration and check out as well as limited flight tests. Laboratory calibration was accomplished using a test fixture which simulated the aircraft installation. The fixture included mounting brackets for the control box, transducer, and reflector block. The pallet was simulated by a hinged flat plate with screws that could be tightened in order to hold it at a fixed angle. The angle of the hinged plate was measured visually using a protractor. The plate was moved in one degree increments throughout the entire range of the system and the measured distances corresponding to each angle were recorded. The data measured in this test are plotted in Figure 4.

The relationship between distance and angle is approximately linear between 4 and 28 degrees and 29 and 54 degrees. The 4 to 28 degree relationship is based on the mode of operation where the ultrasonic pulses travel from the transducer, to the pallet, to the reflector block, and back. The 29 to 54 degree relationship is based on the mode of operation where the ultrasonic pulses are reflected from the bottom of the pallet directly back to the transducer. Linear regression methods show a good linear fit in each of the two angular regions (standard error of 0.32 degrees in the low angle region and 0.49 degrees in the upper angle region). Resulting equations for the two regions are:

$\theta_T(L) = (1.777)S - 8.242$ (3)

$\theta_T(U) = (3.562)S - 12.934$ (4)

where $\theta_T(L)$ is the tip-off angle in the low angle (4 to 28 degree) region, $\theta_T(U)$ is the tip-off angle in the upper angle (29 to 54 degree) region, and S is the measured ultrasonic pulse path distance. Equation (3) agrees approximately with the geometrically derived Equation (2) and differences are attributed mainly to the fact that Equation (2) did not take into account the finite dimensions of the reflector block.

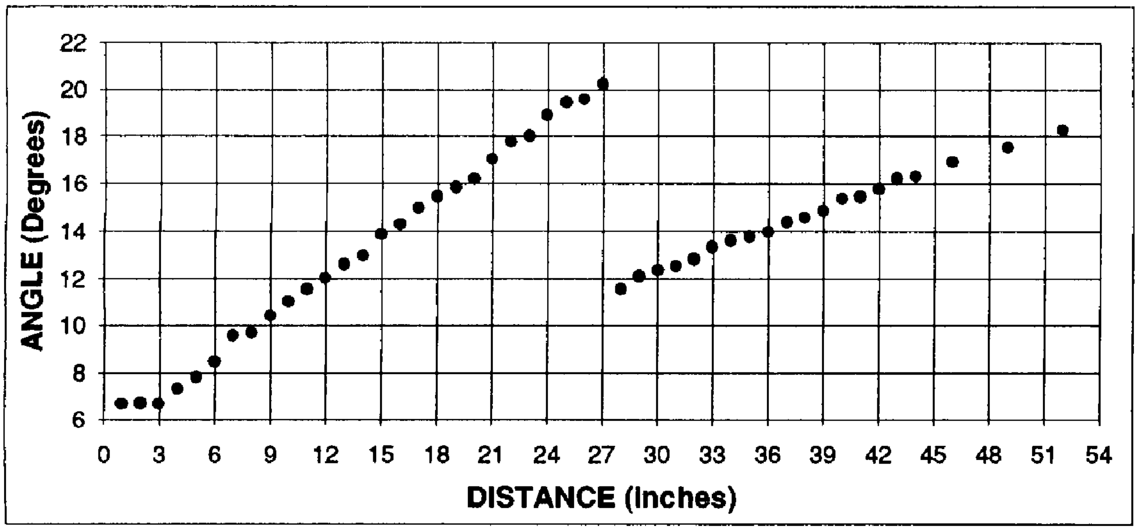

Figure 4. Graph of Distance Versus Angle

Because of the two distinct linear relationships represented by Equations (3) and (4) in the low angle and upper angle regions, it is necessary to keep track of which angular region the system is operating in. The transition between regions can be determined by noting the abrupt change in the slope of distance versus time (dS/dt) which occurs at the transition.

The theoretical angular resolution of the system can be determined by using Equations (3) and (4) along with the rated distance resolution of the ultrasonic transducer. The transducer resolution is rated at 0.04 inches. Changing S in Equations (3) and (4) by 0.4 inches yields a change in measured angle of 0.07 and 0.14 degrees (4.2 and 8.4 minutes of arc) respectively. The angular measurement equipment used in the laboratory calibration (visual measurement using a protractor) was not accurate enough to verify this resolution.

Limited flight tests have been conducted in a C-141 aircraft in order to determine if the system is effected by possible air turbulence and/or ultrasonic noise generated when the cargo doors are opened in flight. This test was done using the laboratory test fixture (in order to vary measured angles along with an oscilloscope to visually monitor noise received by the transducer.) The system was monitored during opening and closing of the cargo doors. Some noise increase was noted when the cargo doors were just slightly open, but this was not judged important since the system is intended to be operated with the doors fully open. Flight tests of the final system with actual pallets have not yet been completed.

CONCLUSIONS

The ultrasonic angular measurement system described in this paper has proven to be an important improvement in the ability to measure angles in an environment where contact with or modification of the surfaces to be measured is not possible. Compared to other reported ultrasonic angular measurement systems [5], this system uses one transducer instead of three while increasing the measurement range and resolution.

FURTHER INFORMATION

More formation on the ultrasonic angular measurement system may be obtained by contacting the author at 416 TS/ENS, 59 N Flightline Road, Edwards AFB, CA 93524-6150, telephone (805) 277-0956 or DSN 527-0956.

ACKNOWLEDGMENTS

This project would not have been possible without tremendous support from the instrumentation division at the Air Force Flight Test Center. Particular thanks go to David Crounse, Kevin Medina, Ted Richardson, Susan Harlow, Mary Pottorff and Tracy Schaerer.

REFERENCES

1. Spillman, W.B.,el al., "Wavelength Encoded Fiber Optic Angular Displacement Sensor," SPIE Proceedings - Fiber Optic and Laser Sensors VIII. Vol 1367, 1990, Pg 197-202.

2. Ami, M., et al., "Optical Method of Measuring Angular Displacement Using a Diffraction Pattern," Applied Optics, Volume 26, Number 14, October 1987, Pages 4310-4312.

3. Sato, K.,et al., "Optical Method of Measuring Angular Displacement Using Four Photodiode Arrays," Applied Optics, Volume 23, Number 23, December 1984, Pages 4450-4452.

4 Canali, C., et al., "A Temperature Compensated Ultrasonic Sensor Operating in Air for Distance and Proximity Measurements," IEEE Transactions on Industrial Electronics. Volume lE29, Number 4, November 1982, Pages 336-341.

5. Marioli, D., et al., "Ultrasonic Distance Measurement for Linear and Angular Position Control," IEEE Transactions on Instrumentation and Measurement, Volume 37, Number 4, December 1988, Pages 578-581.