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A New, Available High-Precision CCD Angle-measuring Sensor in Aeronautics and Astronautics

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ABSTRACT

A new photoelectric angle-measuring sensor is presented, in which the linear array charge coupled device (CCD) TCD106C is used as the key sensitive component. Moreover, the high-speed data collecting system, digital signal processor (DSP) and optical modulating plate are used to achieve the desired results. The sensor introduced here has advantages in high precision, good dynamic performance, small bulk, absolute ±360° angle measurement, to name only a few. It can be widely applied to many angle-measuring fields of aeronautics & astronautics. The key techniques comprising of the structure design, the dump dual sampling principle, the interpolating algorithm and the angle measuring method are introduced in the paper.

INTRODUCTION

High-precision angle measurement plays an important role in geometric variable measurement of aeronautics and astronautics. The control and measure precision of aviation and spaceflight vehicles, such as airplane, missile, and satellite, mostly depends on the precision of the measurement and control instruments. Among these, there are many instruments in which the angle measuring sensors are used, such as revolving stage, inertial platform, space telescope, digital theodolite, star tracker, radar, and so on. Along with the development of technology in aeronautics, astronautics, measurement and control, problems such as failure in high precision, low reliability, large bulk, high cost occurred in the application of the present angle measuring sensors.

In this paper, a new photoelectric dynamic angle-measuring sensor is described, in which the key sensitive component is linear array charge-coupled device (CCD). Moreover, the high speed data collecting system, digital signal processor (DSP), optical modulating plate, and the techniques of dump dual sampling, micro-control direct memory access (MCDMA), and interpolating algorithm, are used to achieve the desired results. The sensor introduced here has advantages in high precision, good dynamic performance, small bulk, absolute ±360° angle measurement, to name only a few. Thus, it can be widely applied to many angle-measuring fields of aeronautics, astronautics, measurement and control. The verified performance of the sensor is excellent by the application in the dynamic test revolving stage of inertial attitude sensor.

ARCHITECTURE

The sensor's physical configuration consists of a sensor head (SH) and electronic box (EB) separated by a distance of approximately 1m.

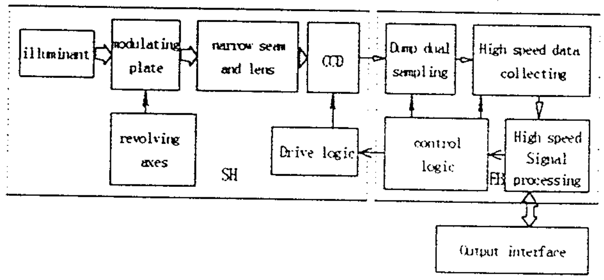

Fig.1. Schematic Representation of CCD Angle-measuring Sensor

As a novel high-precision angle-measuring sensor, its many features are different from those of other sensors, such as mechanical structure, parameters of instrument, techniques of machining, and et. al. The system will be totally modularized, standardized, and has expandability.

SENSOR HEAD

The sensor head is fixed on the revolving axes and revolves with it. Its architecture shows in Figure 2.

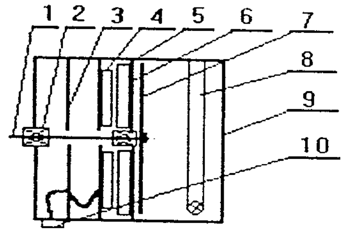

Fig.2 Sketch Map of SH Structure

where, 1 — revolving axes; 2 — precise bearing; 3 — signal regulator; 4 — CCD and its drive circuit; 5—semi-cylinder lens; 6—narrow seam; 7 — optical modulating plate; 8 — cool light source; 9—crust; 10—outlet.

The sensor head consists of a cool light source, optical modulating plate, narrow seam, semi-cylinder lens, linear-array CCD, CCD drive circuit board, video signal regulating circuit board, revolving axes and mechanical components, and crust. In order to achieve high precision and good dynamic performance, the requirement of evionment and mechanical structure in the sensor is much strict. For example, the radical and axis vibration magnitude of bearing must be minimal, all parts of the sensor are rigidly connected, and the interference of surrounding shock is much small. In this sensor, special double CCD structure and symmetrical typical curves of the modulating plate are designed and introduced. Thus, the random error caused by relative changing of any components' position is lotmost minished. In addition, many other factors, such as the mechanical shock, axes vibration, heat produced by illuminant, and et.al. , should be considered simultaneously.

ILLUMINANT & OPTICAL SYSTEM

For a given optical system, if the output signal is certain, more high the sensibility of CCD spectral response, more short the integral time is required by CCD. In order to improve signal to noise ratio, we usually choose the illuminant which has similar peak wavelength of spectral response to that of CCD. Here, the linear-array CCD, TCD106C is used. Its peak wavelength of spectral response is 500nm,and its character of spectrum response shows in Figure 3. In this sensor, we choose an 11W, three-basic-color fluorescent light sousе as the illuminant. It is driven by a high frequency electronic regulator to ensure its light intensity is stable. The illuminant's peak wavelength of spectral response is 545nm, which is similar to that of CCD, and its character of spectral response shows in Figure 4.

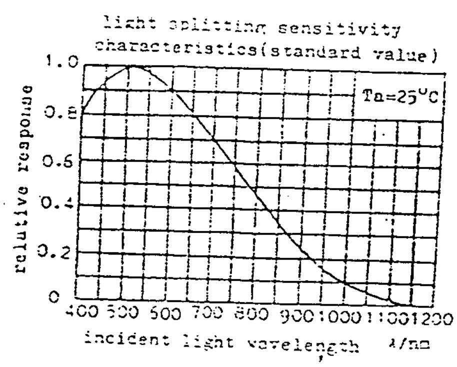

Fig.3 Spectral Response Character of TCD106C

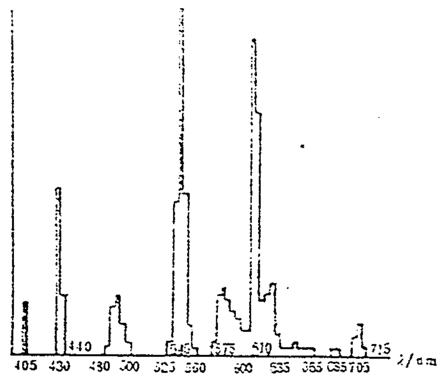

Fig.4 Relative Spectrum Distribution of H-type Three Basic Color fluorescent light source

Following the theory of Fourier optics, the distribution of light field on back focal face T(XOY) (frequency field XOY) is planar Fourier transform of that on the front focal face t(XOY) (space field XOY) in the planar Fourier optical system which takes a spherical lens as the lens of Fourier transform, i.e.:

$$T(X,Y) = A\iint_{-\infty}^{+\infty} t(x,y)\,p(x,y)\exp[-2\pi\cdot j(ux+vy)]\,dxdy \tag{1}$$

where, u=X/λf; v=Y/λf; A is amplitude value of planar light beam; p(x,y) is the aperture function of Fourier lens, here assumed as 1; λ is wavelength of light beam; f is focus of optical system; u,v is two mutual vertical space frequency; t (X,Y) is permeation of lens' front focal face input function.

Eqn.1 shows, the dynamic measuring error would have been produced between the planar Fourier space frequency spectrum and the linear array of CCD image sensing elements, as the light beam passed a spherical lens.

Whereas, a cylinder lens is a parallel straight line along meridian direction (Y direction), its meridian focus f2 is infinite. Thus, cylinder lens acts as Fourier optical transformer just along radial direction. Its spectrum in frequency field is linear distributed, and its character of transform could be denoted as:

$$G(X,Y) = A\int_{-\infty}^{+\infty} t(x,y)\exp(-2\pi jux)\,dx \tag{2}$$

A special short focus semi-cylinder lens is tantamount to a combinative lens consisted of a spherical lens and a cylinder lens. As Fourier transform system is forever linear space system, the frequency spectrum of the semi-cylinder lens along Y direction is linear aligned, and is superposition of linear-array CCD elements. So, we place a short focus semi-cylinder lens on the light sensing face of CCD, and the angle measuring precision and dynamic performance of this sensor are effectively improved.

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OPTICAL MODULATING PLATE AND ITS SPECIAL CURVES

The design of optical modulating plate and its special curves require easy machining, and the precision of the sensor must be ensured. In the practice, the modulating plate is a circular transparent glass plate on which a thin layer of film is plated, and then two kinds of transparent curves which width are respectively 10mm and 20mm, are etched on the film. It ensures the measurement precision and easy machining, simplifies the angle measuring method and reduces the time of calculation.

HIGH SPEED DATA COLLECTING SYSTEM

CCD high-speed data collecting system (Figure 5) is designed to realize dynamic and wide range measurement. The system is based on the double buffers, which are alternately work under the control of parallel synchronism address generator and drive logic circuit. Under the control of digital signal processor (DSP), the high speed dump dual sampler and holder synchronize and collect the video signal of CCD with high speed, the parallel synchronism address generator gives the address which the collected data should be stored in. The different frame data of CCD out from high speed A/D converter is respectively stored into two RAM by two sets of parallel data buffers. At any time, at least one frame static data is always ready to provide for DSP. DSP will do a series of data processing consisted of filter, interpolating, and calculating of angle value. This method has not any limit of dynamic data transfer rate. This effectively improved the collecting speed of CCD output data.

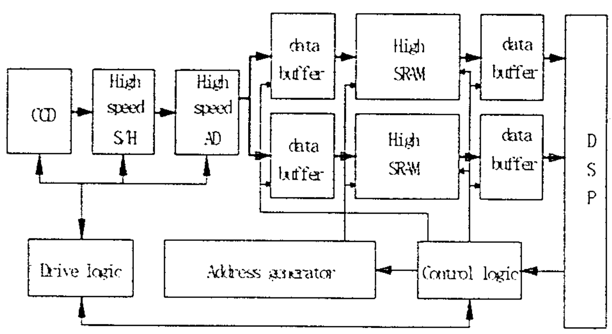

Fig.5 CCD High Speed Data Collecting System

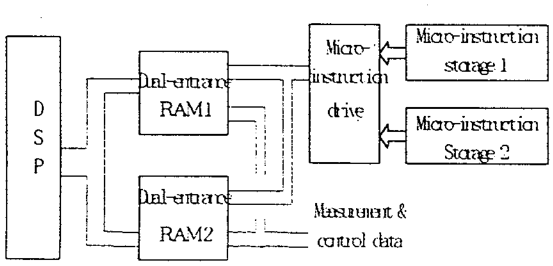

Fig.6 Schematic Representation of Intelligent Control Structure of Data Collecting

In addition, an intelligent control structure of data collecting based on firmware is designed and used in this sensor. Its schematic representation shows in Figure 6. As the core of this firmware scheme is micro-instruction, and two new control mechanisms - "staring" and "focusing" are adopted, this scheme has great versatility, self-adaptability and ability of intelligent control over complex data collecting realized in hardware-level. Since data processing and data collecting are well balanced, good performance of whole system is ready.

MACHANISM OF ANGLE MEASUREMENT

As measuring angle displacement or rotating speed using the CCD angle-measuring sensor, the stable and well-distributed light is first modulated by the optical modulating plate, passes through the narrow seam and the semi-cylinder Lens, becomes four light points, and then form images on the image sensing elements of linear-array CCD. Thus, the angle displacement is transformed to line displacement of the light point moving along the direction of CCD sensing elements array. Under the control of drive circuit, CCD accomplishes an exposure sequence that consists of the following states: idle, flush, expose, transfer, and data readout. The video signal from CCD is regulated by preamplifier and dump dual sample processor, and then converted to digital data by a 12-bit A/D converter. Under the intelligent of MCDMA (micro-control direct access memory) hardware, the collected data is transferred to RAM, and then the precise point's position is achieved by filtering and interpolating. Using the position difference of two points produced by the first kind curve of the modulating plate, the rough value of revolving angle (α) can be Figure out. Moreover, the value of small relatively revolving angle (β) can be calculated out using the position difference of two points produced by the second kind curve of the modulating plate, then the precise revolving angle value of the modulating plate ($\alpha+\beta$) is achieved. As the modulating plate is fixed with revolving axes, the precise revolving angle value of the axes is also ($\alpha+\beta$).

DATA PROCESSING METHODS

Continuous integrating of light intensity of every image-sensing element forms the video signal from CCD. The geometry size of CCD image sensing elements is quite accurate and the sensing elements are well distributed. If interpolating process is exerted on the video data, the position resolution could reach to one percent of the sensing element's geometry size. It is to say, if we select a data window consisted of appropriate number elements' output, and make an interpolating calculation on these data according to the following Eqn.3, the precise light intensity center position could be achieved.

$$X_c = \frac{\sum_{i=0}^{n} E_i (X_0 + i)}{\sum_{i=0}^{n} E_i} \qquad (3)$$

Where. Xc is the center position; Ei is the output value of the (X_0+i) image-sensing element; X0 is the first sensing element in the interpolating window; n is the number of data in the interpolating window.
From Eqn.3, the deviation(vibration) of interpolating result could be obtained:

$$\sigma_{xc} \cong \frac{\theta}{S/N} \qquad (4)$$

Where. θ is the number of CCD sensing element; S/N is the signal to noise ratio of accumulating charge of CCD video signal.

In Eqn.4. it is assumed that the voltage value of CCD signal is higher than that of CCD background noise. Thus. with raising the interpolating precision or reducing the interpolating error. it is necessary to improve the signal to noise ratio.

It is difficult to achieve fine result of eliminating the noise using the common method of filter. Whereas. the integrated and dump dual sample processor can effectively remove kinds of noise, such as KTC, 1/f. 1/f2. and et. al., and improve the signal to noise ratio using the irrelevance of noise. Thus. the integrated and dump dual sampling is rather an ideal processing method for CCD video signal. The signal waveforms in front and behind of dump dual sample processing show in Figure 7.

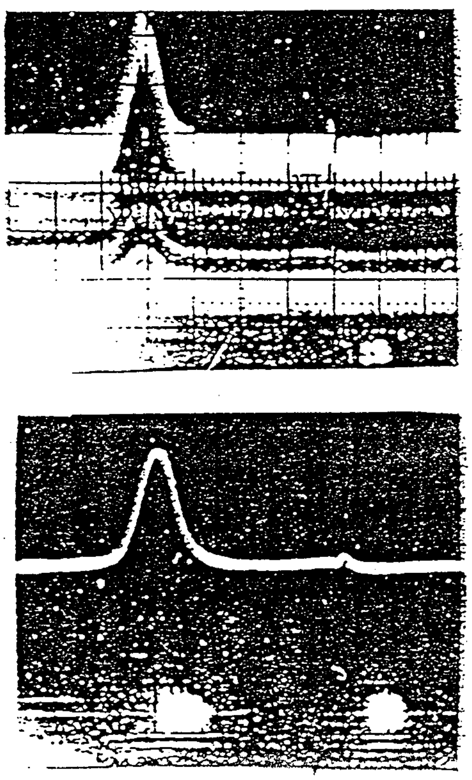

Fig. 7 Signal Waveform in front and behind Dump Dual Sampling process

From Eqn.3. it is clear that. the interpolating algorithm requires the signal waveform in the interpolating window is symmetrical and signal waveform in a frame is stable. In the interpolating window. the burr data caused by few defect CCD sensing elements should be get rid of. because the burr data obviously influence the precision of interpolating result. The white noise caused by system factor should be also eliminated or reduced. as it will increase interpolating error. For these reason. the following processing method should be also adopted:

(a)Take the peak value in a frame of CCD signal as the center of interpolating window. the size of window is about 10 to 20 data.
(b)Eliminate the burr data in the interpolating window using the method of program judgement and median filter.
(c)Eliminate the white noise using nonlinear wavelet analyses method.

Using the common filter to reduce noise. it results the waveform is spreaded out and partly distort. Whereas. nonlinear wavelet analyses method takes the fluctuate threshold value. which the criterion is signal energy. as the wavelet coefficients to discriminate the signal contaminated by noise. With changing of noise energy. the threshold value fluctuates. The wavelet coefficients which is equal to or lower than the threshold value is given up. and the original signal is recovered just using the coefficient which is above the threshold value. In this way. greatpart of white noise is removed. and the waveform isn't obviously distorted.

HARDWARE FEATURE

At present. modularization. standardization and expandability are the mother current of the testing system development. In the described sensor. the hardware structure is designed and completed according to above three principles. Thus. the sensor could work normally under circumstance of using just the same hardware (CPU. data collecting and processing module. etc.) with other measurement and control system together. It can also accomplish different function by loading corresponding software. The measured and calculated result can be displayed on the "soft display panel" which is created by executing corresponding software.

In addition. the function module of the sensor is designed according with the standard of VXI bus. and various of interfaces. such as GPIB. standard PC. is prepared.

SUMMARY

The presented CCD angle measuring sensor used a new angle measuring mechanism, high resolution linear array CCD. special mechanical structure. standardize modulate expansion hardware design. integrated and dump dual sampling processor. intelligent controlled

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high-speed data collecting system, and signal processing methods of filter, interpolate, and so on. All of the above make the sensor has many good performance, such as high precision, good dynamic performance, small bulk, absolute ±360° angle measurement, and so on. The sensor has been applied to the dynamic test revolving stage of inertial attitude sensor. It verified that the sensor has advantages over other angle measuring sensors. Thus, it can be widely applied to many angle-measuring fields of aeronautics, astronautics, measurement and control.

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