第 39 卷第 4 期
2010 年 4 月

光 子 学 报
ACTA PHOTONICA SINICA

Vol. 39 No. 4
April 2010

Article ID:1004-4213(2010)04-0744-4

A Digital Ultrasonic Endoscope System for Medical Imaging*

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Abstract: The development of a novel push-type ultrasonic endoscope is described in which probe rotation is accomplished by a small motor situated near the transducer. A digital FPGA-based ultrasound imaging system is implemented which uses coded excitation to increase the SNR and penetration depth, with probe rotation accomplished by a small motor situated near the transducer replacing the external motor and the long steel wire used in other ultrasonic endoscopes. The apparatus is tested continuously for 300 hours with no obvious problems. The coded excitation, digital quadrature demodulation imaging system can obtain ultrasonic images of higher quality and more information of the echo is preserved compared with the analog imaging system, because the analog digital conversion is moved to the first step of the signal processing. The digital imaging system possesses a higher SNR resulting in a sharp image. Locating the motor near the probe improves the consistency of rotational speed in comparison with external guide-wire rotation, and increases the image quality and life-span of these devices.

Key words: Ultrasonic endoscope; Micro motor; Coded excitation; Digital imaging system

CLCN: TH785.5 **Document Code**: A **doi**: 10.3788/gzxb20103904.0744

0 Introduction

As a noninvasive apparatus, the medical endoscope, since its invention in 1950s, has greatly helped the doctor to be able to examine internal organs directly[1]. However, traditional endoscopes, can only obtain images of the organ surface, which would lead to mis-detection of those precancerous tissues buried in the parenchyma.

As a result, the ultrasonic endoscope was designed and it could obtain ultrasonography images of the inner tissues to find precancerous lesions early[2-3]. The ultrasonic endoscope, which combines an electronic endoscope and a micro ultrasonic imaging system, sends an ultrasonic probe into coelom through biopsy channel of the electronic endoscope and rotates the probe to scan the tissue. However, the commercial ultrasonic endoscopes available currently all use an external motor connected to a 1.5 meter long soft steel wire to rotate the ultrasonic transducer[4]. Because the wire is under a large torque during its revolving, it is easily damaged. Consequently, the life-span of the ultrasonic endoscope is short.

In this paper, a new ultrasonic endoscope is presented which uses a micro ultrasonic motor[5-7] situated at the tip of the endoscope to rotate the transducer. The micro ultrasonic motor replaces the long steel wire utilized in other ultrasonic endoscopes. Since the motor is steady and durable, the life-span of the ultrasonic endoscope using this motor can be extended greatly. The ultrasonic motor also provides following advantages: 1) lower rotating speed with larger output torque; 2) larger output power density; 3) smaller responding time, of the order of ms; 4) higher positioning accuracy; 5) no electromagnetic interference[8].

There is a 90° hard bend at the entrance of the biopsy channel and the diameter of the biopsy channel of the endoscope is only 2.8 mm. Hence, the probe's external diameter should not be wider than 2.2 mm and the length is less than 14 mm.

Because of the very small size of the ultrasonic probe, the area for fixing transducer on the motor's rotor is only 2.52 mm^2 (1.8 mm × 1.4 mm), which results in lower ultrasonic launching power. Consequently, the ultrasonic pulse has lower SNR (signal-to-noise ratio) and shorter penetration depth, leading to the lower imaging quality of the system.

To increase the SNR and the image quality, a novel digital ultrasonic imaging system is

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* Supported by the Project of the Education Department of China(106048), the National High Technology Research and Development Program of China(2007AA04Z339) and the National Natural Science Foundation of China (6082700)

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Received date: 2009-04-29 Revised date: 2009-06-22

designed. In this system, coded excitation[9] is employed and a full digital circuit is used to complete the echo processing, such as pulse compression and demodulation. In this study, the prototype of the ultrasonic motor is presented. And the digital ultrasonic imaging system is evaluated by scanning a glass.

1 System design

1.1 Ultrasonic endoscope design

The main blocks of the medical ultrasonic endoscope system is shown in Fig. 1. It is composed of an electronic endoscope and a micro ultrasonic imaging system. The micro ultrasonic imaging system consists of a micro ultrasonic probe, an ultrasonic signal processing circuit and a computer with images synthesizing software. The ultrasonic probe, which consists of a micro ultrasonic motor and an ultrasonic transducer, is connected to the signal processing circuit with a 1.5 m longsoft guide wire.

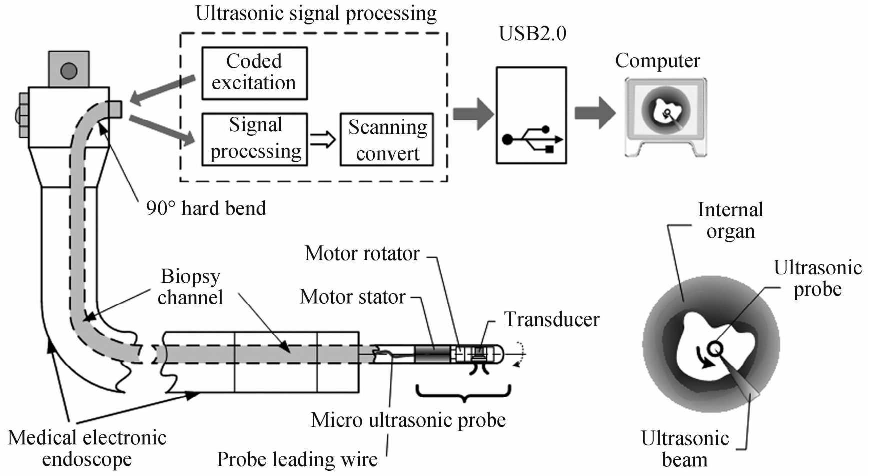


Fig. 1 Overall diagram of the medical ultrasonic endoscope

When diagnosing lesions in organs in vivo, the doctor observes the surface of the alimentary canal by the CCD imaging system first. Then, the ultrasonic probe is sent into coelom through the biopsy channel of the electronic endoscope with the transducer rotated by the ultrasonic motor. While the transducer is revolving, it is driven to launch ultrasonic pulses by the ultrasound excitation circuit. The pulses are reflected by each layer of the organs. The echos are received by the same transducer and transformed into electronic signals which are captured by the signal processing circuit. The model of the signal channel of the ultrasonic imaging system is shown in Fig. 2. Using the theory of linear system, the electronic signal can be simply written as

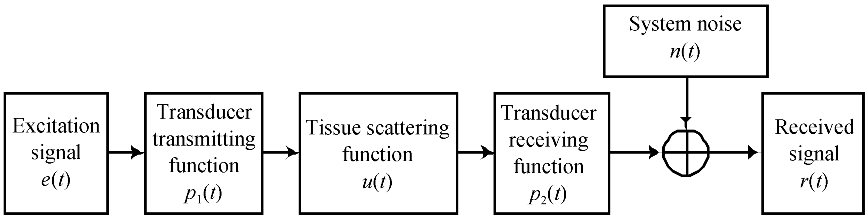


Fig. 2 Model of the signal channel of the ultrasonic imaging system

$$r(t) = e(t) * p_1(t) * u(t) * p_2(t) + n(t) \quad (1)$$

where $n(t)$ is the noise of the system and is usually a Gaussian white noise. Since the transducer is a significant component of the imaging system, it should be of broad bandwidth and sensitive to weak signal. And the bandwidth of the transducer determines the bandwidth of the received signal and the sampling frequency of the entire imaging system.

Finally, the image signals are transferred to computer for real time display through USB2.0 interface. As a result, the doctor can obtain the images of the surface and the inner tissue simultaneously.

In our system, the coded excitation technique is used to increase the ultrasonic pulse′s average power. The coded excitation technique uses a coded pulse, such as Barker code and Chirp code, to excite the transducer to launch a coded ultrasonic pulse. The length of the excitation pulse is much longer than the impulse response time of the transducer, making the ultrasonic pulse having much energy[10]. To maintain the axial resolution, the echo must be compressed in the signal processing circuit which is implemented by a FPGA. If the length of the coded signal is T, and the bandwidth of the coded signal is B, then the gain in SNR (GSNR) for coded excitation using matched filter is

$$\mathrm{GSNR}=\mathrm{TB} \tag{2}$$

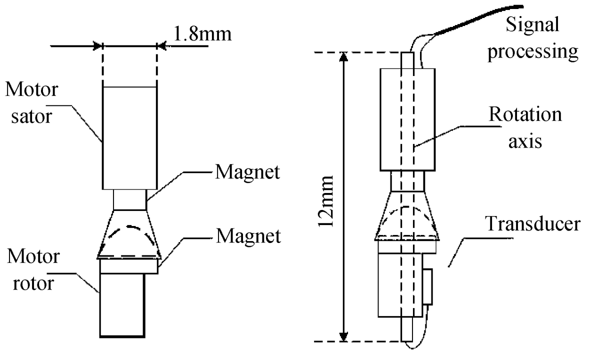
Obviously, the longer the length of the coded signal is, the batter SNR will be obtained. However, the ultrasonic endoscope is designed for diagnosing the internal organs specially, whose wall thickness is usually in the order of a few millimeters, the length of the coded pulse should not be so long that echoes from adjacent layers overlap. As a result, a 4-chip Barker code is selected as the excitation pulse.

1.2 Ultrasonic probe

Since all the commercial ultrasonic endoscopes available currently all use an external motor connected to a 1.5 m long soft steel wire to rotate the ultrasonic transducer, the wire is under a large torque during its revolving, and it is easily damaged. Based on statistical data collected by the TIANJIN MEDICAL UNIVERSITY GENERAL HOSPITAL, the average life-span of FUJINON's ultrasonic endoscope is only approximately 50 hours. Furthermore, it is difficult to control the revolution speed of the probe. To improve the image quality and life-span of these devices, we developed a novel push-type ultrasonic endoscope in which the probe rotation has been accomplished by a small ultrasonic motor[11] situated near the transducer with the motor's diameter only 1.8 mm.

Fig. 3(a) shows the schematic diagram of the micro ultrasonic motor which is composed of a stator and a rotor[12]. During scanning, the motor is reversed with the rotor sucked on the stator by the suction force between the magnets situated in them respectively . The surface of the stator is covered with piezoelectric ceramics. When the stator is switch on, the piezoelectric material will oscillate and generates a friction between the stator and the rotor, driving the rotor to revolve.

By fixing a micro piezoelectric ceramic transducer on the rotor of the ultrasonic motor, a micro ultrasonic probe is completed, which is shown in the Fig. 3(b). With the transducer fixed, the barycenter of the rotor is balanced to the axle of the probe. One of the transducer's electrodes is joined together with the rotor and connected to the external driving circuit through the stator by a sliding contact. The other electrode is connected to the external driving circuit through the central rotating axis in the ultrasonic motor.



(a) The micro ultrasonic motor (b) The micro ultrasonic probe

Fig. 3 The schematic diagram of the motor and the probe

1.3 Digital ultrasonic imaging system

For improving quality of the ultrasonic image, a fully digital ultrasonic imaging system[13] is designed, which is composed of coded excitation module, demodulation unit, digital scanning converter and USB2.0 interface. The schematic diagram of the imaging system is shown in Fig. 4. In this system, the transducer is excited by a coded pulse to increase the launching power. The echo captured by the transducer is sampled by a high speed A/D circuit placed at the front of the receiving circuit immediately. Then the digital echo is processed by field programmable gate array (FPGA) which performs pulse compression, quadrature demodulation, coordinate converting and data transferring. In the whole ultrasonic imaging system, only the excitation circuit and the amplifier are implemented by analog circuits and others are all implemented by digital circuits which has a higher SNR.

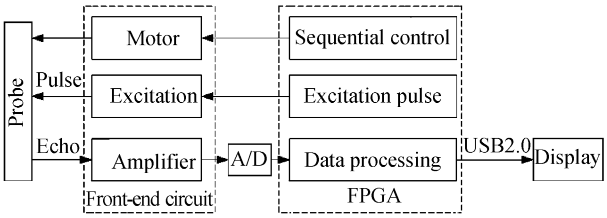


Fig. 4 The schematic of the digital ultrasonic imaging system

Basically, the ultrasonic endoscope is a kind of B-mode imaging equipment, which creates a gray-scale image using the amplitude of the echo. Hence, using Altera IP (Intellectual Property) cores, a digital quadrature demodulator is designed in the FPGA to obtain the amplitude of the echo.

After demodulated, the digital ultrasonic signals are stored in polar form firstly. Then, according to a coordinate conversion table, the stored signals are read out to form a new image in rectangular form. The new image has many leak points, especially at the far field. So, it is necessary to fill up the image using interpolation methods. In the system, a round interpolation is used which abandons the data in diameter direction while only interpolating the points in arc direction.

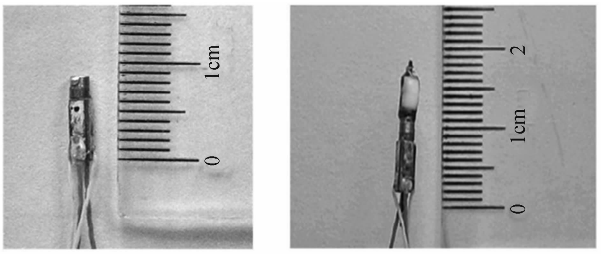
The USB2.0 interface is utilized to transfer image data from the FPGA to a general computer to display the ultrasonic image.

2 Result and discussion

2.1 Ultrasonic probe

At present, we have finished a prototype of the micro ultrasonic motor, which is shown in the Fig. 5(a). In order to enter the coelom through the 2.8 mm diameter biopsy channel of the electronic endoscope, the diameter of the prototype is 1.8 mm. The unloaded rotating speed of the stator is lower than 600 rpm and the stalled torque is up to 10 μN · m.

By fixing a micro piezoelectric ceramic transducer on the rotor of the ultrasonic motor, a micro ultrasonic probe is completed, which is shown in Fig. 5(b).



(a) The motor (b) The probe

Fig. 5 Picture of the ultrasonic motor and the probe

In the prototype experiment, the ultrasonic motor can revolve continually with the small transducer fixed for about a month. Considering the problems arising from the application, such as encapsulation and coupling, it is believed that the ultrasonic endoscope with this motor can work for 300 hours or more.

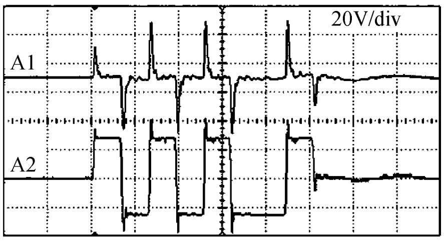
2.2 Coded excitation

The coded excitation circuit is implemented by a MD1211 and a TC6320, which are Supertex Company's chips. The MD1211 is a high speed dual MOSFET (Metal Oxide Semiconductor Field Effect Transistor) driver. The TC6320 is a special transmitting chip integrating an N-channel MOSFET and a P-channel MOSFET for medical ultrasonic imaging.

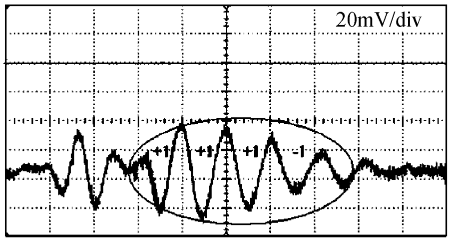
The coded signal is produced by FPGA and is driven into the transducer by the coded excitation circuit.

In the experiments of the coded excitation, a 4-chip Barker code [+1+1+1−1] was used to excite the transducer. And in order to increase the emission efficiency, the code is modulated to improve the energy coupling within the transducer's bandwidth.

The coded excitation signal captured by an oscilloscope is shown in Fig. 6(a). The channel A2 is the modulated signal output from the TC6320 with each chip of the code represented by a positive pulse and a negative pulse. The duration of each pulse (positive or negative) is $1/2f$, where f is the transducer's operating frequency, 5MHz. The channel A1 is the driving signal on transducer after being matched by a RC circuit. Within the 8 pulses of channel A1, the left 6 pulses represent the first 3 chips of the 4-chip Barker code, [+1+1+1]. And the right 2 pulses represent the last chip [−1].



(a) 4-bit Barker code excitation signal



(b) Echo of the 4-bit Barker code excitation

Fig. 6 Waveform of coded excitation captured by a oscilloscope

Fig. 6 (b) shows the echo from a single reflector excited by the coded signal mentioned above. The first 3 chips [+1+1+1] of the 4-chip Barker are included in the first 3 cosine pulses. The bit -1 is included in the last cosine pulse which lasts longer.

2.3 Scanning imaging

The performance of the digital ultrasonic imaging system is validated by an experiment of rotating scan of the wall of a glass. The center frequency of the transducer used in the experiment is 5 MHz and the bandwidth is 1 MHz. The sampling frequency of the A/D converter is set to 20 MHz. Fig. 7 shows the glass used in the experiment which is filled up with ultrasound coupling liquid. The transducer, which is rotated by a mechanical motor with a rotate speed of 100 circles per minute, was immerged in the coupling liquid and scanned the glass wall.

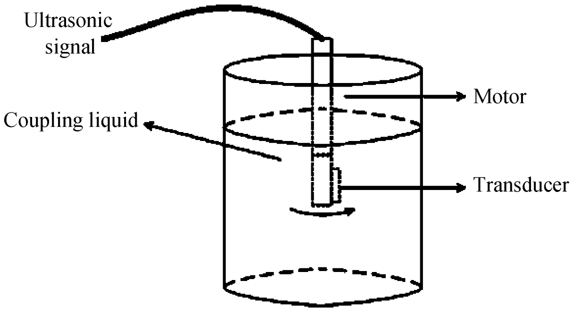
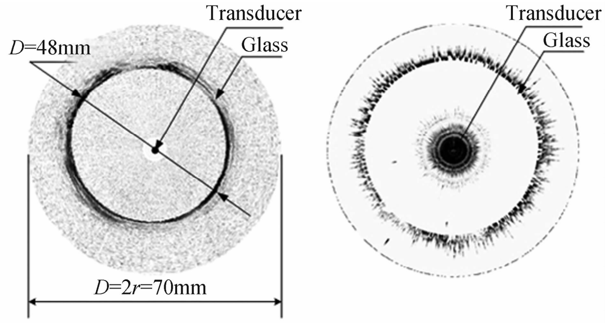


Fig. 7 Target of the scanning imaging experiment

Fig. 8(a) shows the image of the glass obtained by the system. The black circle is the glass wall detected by the ultrasound. There is no reflection in the coupling fluid, which is the white area in the image. In the picture, r is the system′s detecting depth 35 mm and d is the diameter of the glass 48mm.

Fig. 8(b) shows the image of the glass obtained by an analog imaging system designed by our group previously[14]. It is obvious that the digital imaging system can obtain ultrasonography images with higher quality, compared with the conventional analog imaging system. Because the echo is sampled at radio frequency in the digital imaging system, more information of the echo can be preserved compared with the analog imaging system. Furthermore, the digital imaging system possesses a higher SNR. As a result, a sharp image can be obtained.



(a) The digital imaging system (b) The analog imaging system

Fig. 8 Comparison of images obtained by digital and analog system

3 Conclusions

In this paper, a novel digital medical ultrasonic endoscope was designed for diagnosing precancerous cells in the internal organs of human. Considering that the diameter of the biopsy channel of electronic endoscope is only 2.8 mm, the probe′s external diameter is 1.8 mm and the inflexible length is less than 14 mm.

With a micro ultrasonic motor situated at the tip of the endoscope, our design will have a much longer life-span comparing with commercial available ultrasonic endoscope. Besides, the ultrasonic motor has many other advantages, such as stabilization and durability. For the moment, a prototype of the micro ultrasonic probe has the rotating speed up to 100 cycles per minute. Furthermore, the ultrasonic motor can revolve continually with the small transducer for about a month.

In order to increase detecting depth and imaging quality of the ultrasonic endoscope, a digital ultrasonic imaging system was built which is composed of coded excitation, digital quadrature demodulation, digital coordinate converter and USB2.0 interface. The performance of the digital imaging system has been tested by the image of a glass.

However, the equipment, designed to increase the life-span of the ultrasonic endoscopes, is still at the prototype stage. Plan is in place to move to clinical trial soon.

Acknowlegment: *The author would like to thank Prof. Zhou Tie-Ying at Tsinghua University for the discussion on the ultrasonic motor and the ultrasonic probe. The author would also like to thank Dr. Wang Bang-Mao at Tianjin Medical University General Hospital for the information of the ultrasonic endoscope in the clinical diagnosis.*

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数字式超声内窥成像系统

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摘　要:介绍了一种采用前置微型电机的新型推拉式超声内窥镜的研制方法.在该内镜系统中,采用FPGA实现成像处理功能,运用编码激励技术以提高系统的信噪比和探测深度,使用了微型前置探头取代了目前商用超声内镜中所采用的钢丝连接以驱动换能器进行旋转扫描.该仪器在300 h的连续工作测试中能够正常运行.相较模拟成像系统,数字系统将模数转换置于信号处理的最前端,从而能够保留回声的更多信息.这使得编码激励、数字式正交解调系统获得更高的成像质量.将电机前置于探头附近,能够较外部导线牵引旋转方式获得更大的旋转稳定性、更高的超声图像质量和更长的使用寿命.

关键词:超声内窥镜;微型电机;编码激励;数字成像系统

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