PHOTONIC SENSORS / Vol. 4, No. 4, 2014: 359–365

Design of Linear Sweep Source Based on DDS Used in Readout System for Wireless Passive Pressure Sensor

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Abstract: This paper proposes the design and research on the high bandwidth linear frequency sweep signal source involved in the readout unit module of the wireless passive pressure sensor in high temperature based on the principle of mutual inductance coupling which is applied widely at present. The operating principle of the linear sweep frequency source based on the direct digital frequency synthesis (DDS) technology is introduced, and the implementation method of the hardware circuit and logic sequential control process required in our system has been realized utilizing this technology. Through the experiments under different conditions of the step value, the sweep range and other related design indicators, the influence on the extraction method of resonance frequency information, extraction accuracy, and others during the readout system of the mutual inductance coupling sensor are analyzed and studied. The design of the linear frequency sweep signal source is realized with a resonance frequency change resolution of 6 kHz, a minimum step value of 1 kHz, and a precision of frequency for 0.116 Hz within the sweep width of 1 MHz – 100 MHz. Due to the use of the integrated commercial chip, the linear sweep frequency source is made small in size, high working frequency, high resolution and low step values for the readout unit modularized of a higher application value.

Keywords: Direct digital frequency synthesizer, LC resonant sensor, resonant frequency, pressure test

Citation: Yingping HONG, Tingli ZHENG, Ting LIANG, Qun CAO, Hairui ZHANG, and Jijun XIONG, "Design of Linear Sweep Source Based on DDS Used in Readout System for Wireless Passive Pressure Sensor," *Photonic Sensors*, 2014, 4(4): 359–365.

1. Introduction

In harsh environments for engineering applications such as high temperature, high pressure or humidity, the traditional sensing method to test pressure by wire connection has been unable to complete the dynamic distribution timely test due to the parameter drift and system functional or structural failures. Along with the increasing demand of pressure measurement under harsh environments [1], it is high time to design a new reliable method of pressure detection in order to realize the precise measurement and real-time monitoring. Therefore, the coming out of the passive wireless inductance coupling sensing method [2, 3] has solved the technical problems and provides an innovative thought for the signal readout. The

Received: 14 July 2014 / Revised version: 4 September 2014

DOI: 10.1007/s13320-014-0212-1
Article type: Regular

inductance and capacitance (LC) resonant sensor [4] is essentially a resonant circuit composed of an inductance and a variable capacitance being sensitive to the outside testing environment in order to prevent circuit failures or wiring degradation and does not require the direct signal electrical connection and power supply.

Xiong *et al*. made lots of efforts in the high temperature and pressure testing processes and have already achieved great results in the design and fabrication of the sensitive device and readout unit [5, 6]. Despite the high-performance of the frequency source produced by the Agilent signal generator and impedance analyzer, the instruments are unsuitably applied in harsh engineering practical occasions outside the laboratory environment on account of its expensive price and heavy size. To realize the miniaturization of the circuit and wider industrial occasion applications of the passive wireless inductance coupling LC resonant sensor, it is very imperative to develop an adjustable frequency sweep source with the smaller size, higher bandwidth, and higher precision used in the readout unit.

Among various frequency synthesis technologies, the direct frequency synthesis technology holds the lead due to its numerous advantages, such as the wide frequency range and the short conversion time. However, effective measures are difficult to take to curb the output harmonics, noise, and spurious frequency as well as its complex hardware structure, large volume, and high cost. The phase-locked frequency synthesis technology [7] has the advantage of the wide frequency range, yet the weakness of long frequency conversion time and hardly achieving small frequency interval [8] make it difficult to be widely applied.

With the widespread use of digital techniques in instrumentation and communication systems, a digitally-controlled method of generating multiple frequencies from a reference frequency source has evolved the called direct digital synthesizer (DDS). The generated sweep frequency signal based on this technology has the high frequency resolution, and the output frequency points can be up to 2^N (N for phase accumulator digits). It also has the fast frequency switching speed in the magnitude of μs, continuous phase when the frequency conversion, broadband orthogonal signal and low phase noise make the linear sweep source work efficiently and reliably. All of the above features make it easier to improve the phase noise of the reference frequency source and to be integrated, featuring small volume, light weight, and fully digital implementation.

As shown in Fig. 1, in the wireless passive inductance coupling system designed in this research, the sine sweep signal sweep frequency source based on the DDS technology on one end provides the reading antenna driving signal which couples with the LC resonant sensor inductively and modulates the resonance frequency to the reading antenna, then the other end inputs to the readout unit as the standard carrier signal for the overall readout circuit. Note that, in the entire measuring unit the generated sweep frequency source using the DDS technology is the basis reference source and frequency information source of the whole working system, and the different bandwidth values and step values will have an effect on the frequency information extraction of the wireless passive resonant LC sensors. Based on the former research, this paper mainly focuses on the design of a high precision linear sweep source with a high bandwidth on the basis of the DDS technology. The source is controlled in a digital way by the master chip field programmable gate array (FPGA) inside the readout system, then the output is driven by a power amplifier circuit. This paper will focus on the design and research of the high precision and bandwidth linear sweep frequency source based on the DDS technique, simultaneously make corresponding analysis for the readout of the passive wireless sensor LC resonance frequency.

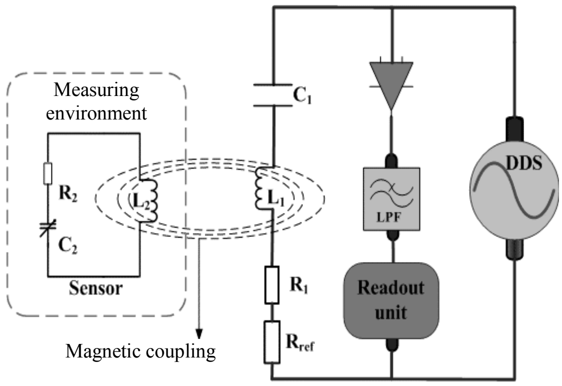

Fig. 1 Model diagram of the inductance coupling frequency readout system based on the DDS sweep frequency source.

2. Design of linear sweep source

2.1 Model of the linear sweep source

As shown in Fig. 2, the fundamental principle of AD9858 sweeping frequency contains an additional frequency accumulator. The DDS is mainly composed of the phase accumulator, data storage, D/A converter, and low pass filter. The data storage is mainly employed to memory the sine signal amplitude value by sampling. After the system clock triggering, the phase addresses are obtained through the accumulation of the phase accumulator and frequency control word, and the digital address is acquired corresponding to the sine signal amplitude value address in the data storage, then we get the analog amplitude by the D/A converter.

The phase accumulator outputs a periodic stepladder sine wave when an overflow occurs, then gains the required sine wave through the low-pass filter. Assuming that the frequency control word is M, K is for the phase accumulator digits, the system clock frequency is f_c, the output sine signal frequency can be derived as $f_o=(Mf_o)/(2^K)$, and the frequency resolution is Δf_o–$f_o/(2^K)$.

In addition, the DDS performs appropriately and effectively in realizing the function of fast sweeping frequency of the wireless passive inductance coupling system due to the ability of high speed frequency jumping (can reach nanosecond).

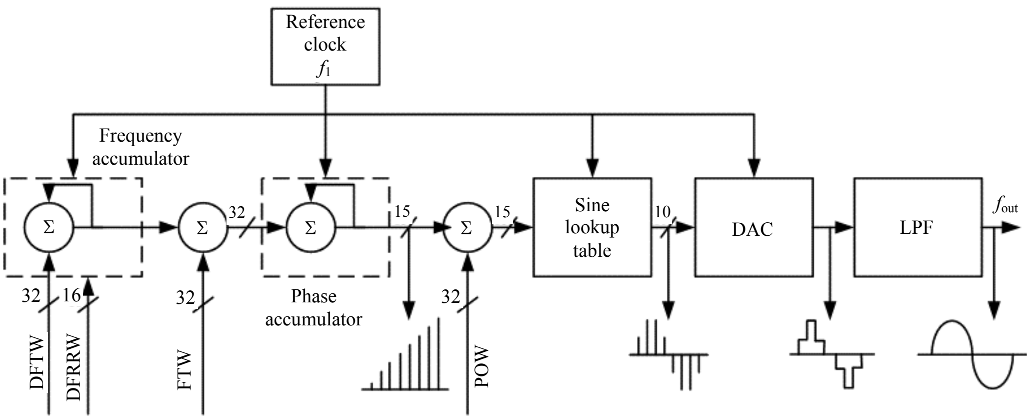

Fig. 2 Structure of direct digital synthesis.

To meet the comprehensive consideration for testing, AD9858 of ADI Company is selected to complete the design of the sweep frequency source. The DDS frequency sweep source of this type is digitally controlled by the central control unit and writes the required frequency control parameters to the chip register according to the design requirements. There are several key register control parameters: *FTW*, *DFTW*, and *DFRRW*, where the *FTW* indicates the frequency control word, *DFTW* indicates the stepping frequency control word, and *DFRRW* indicates the stepping frequency slope control word. They can be calculated by the following formulas:

$$FTW=\frac{2^N\times f_o}{SYSCLK} \tag{1}$$

$$DFTW=\frac{2^{31}\times\Delta f}{SYSCLK} \tag{2}$$

$$DFRRW=\frac{DFTW\cdot T\cdot SYSCLK^2}{2^{35}\times(f_F-f_S)}. \tag{3}$$

In (1), (2), and (3), *SYSCLK* expresses the system reference clock, 500 MHz is chosen in this research, and N is for the phase accumulator digits. The designed linear sweep frequency source in this study has a few key parameters as follows: the the starting sweep frequency f_S, the ending sweep frequency f_F, the sweep frequency step Δf, and the sweep frequency cycle T. This chip employs the FPGA as the digital central control unit, and the DDS unit is set to sweep pattern firstly during the process of initialization, at the same time, the corresponding *FTW*, *DFTW*, and *DFRRW*'s binary code values are calculated by (1), (2), and (3) according to the parameters of f_S, f_F, Δf, and T which are required by the reaout system, then writes the relevant registers based on the reading and writing control timing of the DDS sweeping frequency unit.

After sweeping frequency in one cycle, the frequency control word is fed to the phase accumulator, then the designed linear sweep frequency source outputs a sine wave, combined with the new frequency control word generated by the accumulator on the impact of triangular frequency control word and triangular frequency slope, followed by recycling until the terminal frequency control word. The sweep frequency source's accuracy can reach 0.116 Hz, and the minimum step value is 0.233 Hz calculated by (1) – (3).

2.2 Linear sweep source circuit

The system hardware structure mainly consists of the reference clock source, DDS chip, FPGA central control unit, amplification circuit, filtering and conditioning circuit, and computer control terminal, and the hardware composition diagram is shown in Fig. 3. The 500 MHz standard clock source is on the basis of phase-locked conditioning of the crystal oscillator with a 10 MHz reference clock. The crystal oscillator phase noise is less than or equal to –135 dBc/Hz@1 kHz, and the reference clock phase noise is measured by the spectrum analyzer Agilent. The DDS chip is a direct digital frequency synthesizer with 10 bits DAC and 1 GSPS designed and produced by ADI company, and AD9858 forms a digital programmable and complete frequency synthesizer with an internal high speed and a D/A converter with the excellent performance by the use of the advanced technology, which can generate a sine analog output up to 400 MHz simultaneously providing the rapid frequency sweep and fine adjustment resolution (32 bit frequency control word). The main function of the FPGA control unit is to realize the output of AD9858's digital control timing and write the related frequency control word by which the readout unit is designed for the chip control registers according to the agreed sequence. As the output ability of AD9858 is not enough to drive the antenna inductance coil and sensors being coupled with each other in the wireless passive sensing system, therefore, a power amplifier and a low-pass filter circuit are designed at the output port. The output signal of the DDS is amplified by AD8009 and guarantees a output power (⩾6dBm) which is enough to drive the inductance coil at the antenna terminal for remotely mutual inductance coupling with the sensor and realize reliable information extraction of sensor resonance frequency, then proceeding low-pass filtering after power amplification. The designed sweep signal bandwidth in this study is 1 MHz – 100 MHz, and the resistance and capacitance (RC) low-pass filter is chosen for the design with R of 50 Ω, cut-off frequency of 100 MHz, and C for 31.8 pF obtained by (4):

$$C = \frac{1}{2\pi \cdot R \cdot f_H}. \tag{4}$$

The designed digital control chip is XC3S1400AN made by Xilinx Company, the starting frequency of the linear modulation signal generated by controlling program is 1 MHz, the ending frequency ranges from 1 MHz to 100 MHz adjustable with the step values of 1 kHz, 10 kHz, and 100 kHz.

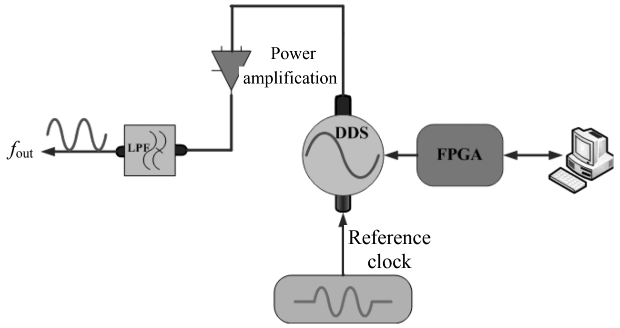

Fig. 3 Diagram of system hardware composition.

The controlling process is shown in Fig. 4. After receiving the start signal, the system can write control word to control the function register (CFR), *FTW*, *DFTW*, and *DFRRW* in turn with the contents calculated by (1) – (3). Following the control word written into the register, it would wait for the arrival of the frequency updated control signal (FUD), whose role is to import the written control word in the register into the DDS chip and to make the DDS start work in accordance with the new configuration at the same time. The controlling update signal FUD is an external excitation signal given by the control chip FPGA with the rising edge effective. The above operation is completed in one frequency sweep cycle of 1 ms.

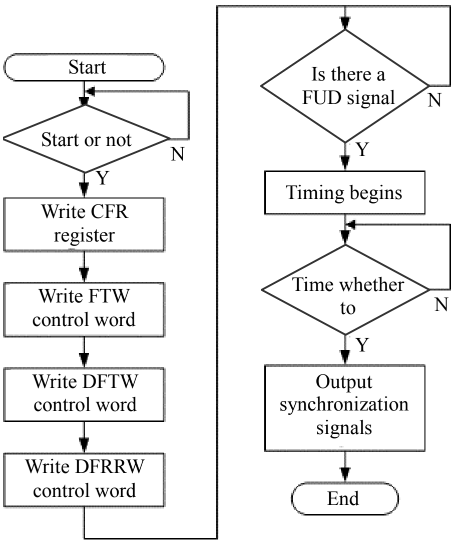

Fig. 4 Digital control flow chart of the frequency sweep source controlling process.

3. Design of a readout unit for an LC resonator

As shown in Fig. 5, the resonant frequency of the sensor can be detected by measuring the various phases of input impedance which is a function of frequency due to the electromagnetic waves transmitted to the sensor through the reading antenna in a wireless passive mutual inductance coupling sensor measurement system consisting of an LC resonator sensitive device and a inductance reading antenna. Taking advantage of the transformer theory, the sensor's resonance and its inductive coupling to the reading antenna are modeled with a two-port network.

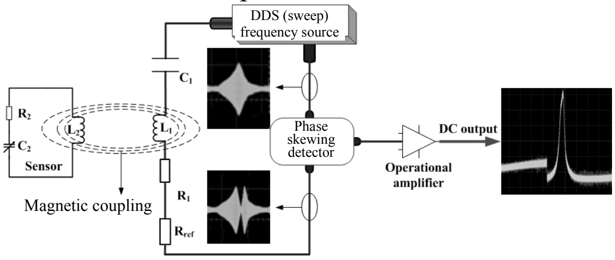

Fig. 5 Scheme of hardware for phase difference testing.

The figure shows that the analog front-end for the phase difference value testing consists of a DDS sweep frequency signal source, a phase difference detector, and a direct current (DC) output amplifier for conditioning, and all units have been implemented using the commercial integrated circuit. The sweep frequency source generates a 1 MHz – 100 MHz high bandwidth linear sweep signal output using a DDS through a logic working timing controlled by the FPGA. The phase difference detector (AD8302) can complete the detection of phase shift within the 2.7 GHz bandwidth of the radio frequency signal range and generate a DC output to indicate the phase difference between the signal inputs *A* and *B*. The sweep signal is input to the inductance of the reading antenna coupled with the remote sensor on one end, and the other end is fed to Port A of the detector AD8302. Then the remote sensor modulates the sensitive information to linear sweep signal of the reading antenna through the inductance coupling, which is input to Port B of AD8302. The output DC signal phase difference value extracted from Ports *A* and *B* of the detector in real time represents the change in the remote resonant frequency since the signals are from the same source with the same frequency and phase. After magnified by the operational amplifier, the DC output is exported to the back-end digital signal processing module for extracting the resonant information of the remote sensor.

4. Experimental results for sweeping source used in readout unit

In this research, the designed linear sweep frequency source was applied to the wireless passive mutual inductance coupling readout unit cooperated with the measured LC resonant sensor in a pressure testing system to demodulate the pressure variation in the environment by reading the changes in sensor's resonance frequency.

The different step values, bandwidths, and driving capacities (power value) generated by the linear output frequency sweep source based on the DDS technology will bring various influences on the test results of the LC resonant pressure sensor. The output power of the main functional chip AD9858 of the linear sweep source power is too low to drive the radio frequency cable and antenna inductance coil in this system inductively coupled with the pressure sensor working remotely, therefore, a power amplification circuit was designed at the output end of AD9858 in order to improve the output driving capability of the DDS sweep frequency signal. By means of measurements, the sweep frequency signal could achieve 6 dBm to meet the demand of the system testing completely after power amplification, and then the quality of the signal has been improved by eliminating the high frequency harmonic components through low-pass filtering.

The designed linear sweep frequency source in this work also studied how linear sweep signals of different step values affect the testing results. As we can see from Fig. 6, the phase difference value of the resonant frequency DC curve was obtained by the readout unit under a series of five different step values for 1 kHz, 10 kHz, 20 kHz, 50 kHz, and 100 kHz. Note that, when the step value becomes smaller, the measured phase difference peak curve carrying the resonant sensor information turns into smoother and closer to the real resonance frequency value of the sensor. On the contrary, the greater the step value of the sweep frequency source designed is, the more interference of the measured phase difference peak curve appears which is not beneficial from extracting the sensor's resonant frequency.

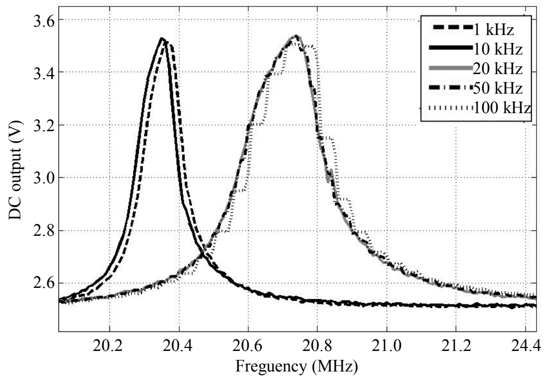

Fig. 6 Sensor's resonant frequency with various steps in the sweeping source.

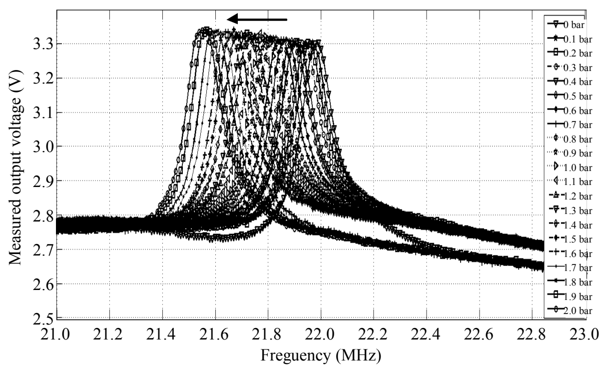

Fig. 7 Measured output voltage versus frequency from 0 to 2 bar.

In addition, the measured phase difference peak curve shown in Fig. 7 shows the performances of the sensor under the pressure condition of 0 – 2 bar, and the test results indicate that the sensitivity of the sensor was about 225 kHz·bar^{-1}. Since 20 test points were chosen ranging from 0 – 2 bar, namely the variation value between two points was approximately 10 kHz if the step value of the sweep frequency source was designed for more than 5 kHz, that is to say, in the case of poor signal to noise ratio, it will be hard to test sensor's sensitive changes.

During the measurement of the sensor, as the starting frequency and ending frequency values were different, in other words, the range of the sweep frequency bandwidth was selected not the same, different resonant peak curves measured by the phase difference readout unit have been intercepted.

We can find that the resonance information peak curve extracted from the readout unit becomes smoother and more accurate when the range of starting and ending frequencies are chosen more narrowly. Otherwise, it is hard to extract resonance frequency information when taking a larger frequency range due to the numerous noises contained in the testing peak curve.

5. Conclusions

In this paper, a high bandwidth linear sweep frequency signal source designed and applied in the testing system of the wireless passive mutual inductance coupling resonant sensor is studied. The basic principle of the linear sweep frequency source and realization method of hardware and sequential control process have been introduced systematically. Simultaneously, the extraction method of phase difference peak resonance information for the passive wireless mutual inductance coupling sensor is expounded.

Through a series of experimental verifications and measurements, the influence on the extraction method and extraction accuracy of the resonant frequency for the wireless LC resonance sensor at different step values, output powers, and sweep ranges are analyzed. This work provided an innovative design method and reference frame for the readout circuit modularity of the LC resonant sensor and design of the sweep frequency source during engineering approaches with the application value of practical engineering.

Acknowledgment

This research was supported by the National Basic Research Program of China (973 Program) under the Grant of No. 2010CB334703. Additionally, the research was also supported by the National Natural Science Foundation of China under Grant of No. 61335008.

References

[1] T. George, K. A. Son, R. A. Powers, L. Y. Delcastillo, and R. Okojie, "Harsh environment microtechnologies for NASA and terrestrial applications," in *Proceedings of IEEE Sensors*, CA, USA, October, 30, pp. 1253–1258, 2005.

[2] M. A. Fonseca, J. M. English, M. von Arx, and M. G. Allen, "Wireless micromachined ceramic pressure sensor for high-temperature applications," *Journal of Microelectromechanical Systems*, 2002, 11(4): 337–343.

[3] Y. Wang, Y. Jia, Q. Chen, and Y. Wang, "A passive wireless temperature sensor for harsh environment applications," *Sensors*, 2008, 8(12): 7982–7995.

[4] R. Nopper, R. Niekrawietz, and L. Reindl, "Wireless readout of passive LC sensors," *IEEE Transactions on Instrumentation and Measurement*, 2010, 59(9): 2450–2457.

[5] J. Xiong, Y. Li, Y. Hong, B. Zhang, T. Cui, Q. Tan, *et al.*, "Wireless LTCC-based capacitive pressure sensor for harsh environment," *Sensors and Actuators A: Physical*, 2013, 197: 30–37.

[6] J. Xiong, S. Zheng, Y. Hong, J. Li, Y. Wang, W. Wang, *et al.*, "Measurement of wireless pressure sensors fabricated in high temperature co-fired ceramic MEMS technology," *Journal of Zhejiang University Science C*, 2013, 14(4): 258–263.

[7] R. Nopper, R. Has, and L. Reindl, "A wireless sensor readout system-circuit concept, simulation, and accuracy," *IEEE Transactions on Instrumentation and Measurement*, 2011, 60(8): 2976–2983.

[8] J. Coosemans, M. Catrysse, and R. Puers, "A readout circuit for an intra-ocular pressure Sensor," *Sensors and Actuators A: Physical*, 2004, 110(1–3): 432–438.