

A LOW-POWER SURFACE DYNAMOMETER SYSTEM FOR BEAM PUMPING UNITS APPLICATION

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ABSTRACT: A low power data acquisition module of surface dynamometer for beam pumping units application is newly developed. It consists of one control unit, one power management unit and several functional components. The control unit acquires and processes the measurement data from accelerometer and load sensor, and establishes communication with the whole network by Zigbee wireless technology. The power unit utilizes the combined power supply solution of solar cell and rechargeable lithium battery, and uses the boost/buck regulator to provide the stable voltage source for the system. The power cost problem is much considered in the system, not only all the electronic components are low power cost and several power saving strategies are used, but also the data processing algorithm is efficient. Double integral calculation to displacement based on reliable acceleration data has the advantage of less calculation and excellent stability. The experimental results demonstrate that the measurements have minor relative errors and good agreement with other methods, and that the total power consumption is smaller than 200mW when the system is in full working, and it does not exceed 60mW in low power mode. This performance can meet the beam pumping units requirements well.

KEYWORDS: Dynamometer; beam pumping units; low power; accelerometer; double integral method

1 INTRODUCTION

Beam pumping units serve more than two-thirds of artificially-lifted oil wells in the world, and their management level directly influences the oil productivity and economic benefit. Dynamometer card, which indicates the relationship of load and displacement of the polished rod's suspension point, is widely used to analyse the working conditions of pumping units and then to judge whether the production is reliable and efficient. The surface dynamometer is just an instrument that measures the two parameters of load and displacement. The load is relatively easy to measure by load sensor. But for the displacement parameter, considering many disadvantages of the conventional measuring-line method, such as high cost, poor flexibility and inconvenient use, a new method of using acceleration to calculate displacement is developed in these years. So the acceleration and load measurement and the displacement algorithm are the key techniques for this type of dynamometer.

In order to realize the efficient monitoring to beam pumping units for long term, the dynamometer must solve two problems. First, power source must be uninterrupted. Because the dynamometer is fixed on the moving equipment, the

rechargeable battery is suitable for power supply. For longer working life, not only battery capacity improving but also power consumption reducing of the whole system should be more considered. Second, the acquired data can be transmitted to the monitor center in time when needed. Many dynamometers ever transmitted data via mobile network considering easy implementation, which leads to high economic cost and high power consumption. In recent years, with the development of IoT technology, some wireless LAN technologies such as WIFI, Bluetooth and Zigbee are gradually popular in industry.

Oil field is always composed of various groups of oil wells distributed in a large open region. Most distances of the nearest wells are from tens of meters to several hundred meters, which makes it feasible to establish communication network within the group of oil wells through Zigbee technology. If necessary, among the whole oil field, only one or several wells may use Zigbee & GPRS dual communication mode, and GPRS mode is responsible for the long distance communication situation. In addition, the unshielded sunlight in the oil field makes it possible to choose the solar cell as the main power source. In view of the above working backgrounds of beam pumping units, the

scheme of combined power source and Zigbee wireless data transmission is applicable.

2 PRINCIPLE OF DISPLACEMENT CALCULATION

The quality of dynamometer card not only depends on the accuracy of the measurement data, but also has close relationship with the algorithm of displacement calculation. There are various algorithms to calculate displacement by acceleration. For example, the algorithm based on DFT and the calculation method based on Kalman Filter and discrete numerical Integration. In this design, since the accelerometer can guarantee the measurement accuracy because of its perfect performance, the error accumulation is not serious, so the double integral method is applicable.

Because sucker rod moves periodically perpendicular to the ground, the acceleration $a'(t)$ measured by accelerometer can be expressed as

$$a'(t) = a(t) + g \quad (1)$$

where $a(t)$ is the acceleration of sucker rod, and g is the gravitational acceleration and can be regarded as a constant.

Assuming that the period of the reciprocating movement is T , and the velocity of sucker rod is $v(t)$. Combining equation (1), then

$$v(T) = v(0) + \int_0^T a(\tau) d\tau = v(0) + \int_0^T [a'(\tau) - g] d\tau \quad (2)$$

here $v(0)$ stands for the velocity at the hypothetical initial time. For the periodicity there is

$$v(T) = v(0) \quad (3)$$

By contrasting equation (2) to (3), then

$$g = \frac{1}{T} \int_0^T a'(\tau) d\tau \quad (4)$$

Substituting the equation (4) into the equation (1) gives:

$$a(t) = a'(t) - \frac{1}{T} \int_0^T a'(\tau) d\tau \quad (5)$$

Equation (5) indicates the relationship between sucker rod real acceleration and the measured one by accelerometer. In the other words, it expresses how to calculate $a(t)$ through $a'(t)$. Similar to the above derivation, the calculation process about $v(t)$ can be summarized as following

$$v(t) = v(0) + \int_0^t a(\tau) d\tau = v(0) + v_0(t) \quad (6)$$

$$s(T) = s(0) + \int_0^T v(\tau) d\tau = s(0) + \int_0^T [v(0) + v_0(\tau)] d\tau \quad (7)$$

$$s(T) = s(0) \quad (8)$$

$$v(0) = -\frac{1}{T} \int_0^T v_0(\tau) d\tau \quad (9)$$

$$v(t) = v_0(t) - \frac{1}{T} \int_0^T v_0(\tau) d\tau \quad (10)$$

where $v(0)$ is the velocity at the same hypothetical initial time as $a(t)$, and $v_0(t)$ stands for the velocity increase in the span of t .

Equation (6) and equation (10) describe how to calculate $v(t)$ through $a(t)$. Eventually the displacement $s(t)$ is defined as

$$s(t) = \int_0^t v(\tau) d\tau \quad (11)$$

From the above derivation, we can summarize the calculation process of displacement. The sucker rod acceleration $a(t)$ is firstly calculated by the accelerometer reading minus its average number in one period. After integral operation of $a(t)$, $v_0(t)$ is obtained. Then the sucker rod velocity $v(t)$ is calculated by $v_0(t)$ minus its average number in one period. The displacement can be obtained by integral operation of $v(t)$. For the digital sequence $a'(i)$, assuming that there are N sample points in one period, that is $a'(i)$, $i = 0, 1, 2, \dots, N-1$. Then the displacement can be calculated through the following equations

$$a(i) = a'(i) - \frac{1}{N} \sum_{i=0}^{N-1} a'(i), \quad i = 0, 1, 2, \dots, N-1 \quad (12)$$

$$v_0(i) = \sum_{j=0}^i a(j), \quad i = 0, 1, 2, \dots, N-1, j = 0, 1, \dots, i \quad (13)$$

$$v(i) = v_0(i) - \frac{1}{N} \sum_{i=0}^{N-1} v_0(i), \quad i = 0, 1, 2, \dots, N-1 \quad (14)$$

$$s(i) = \sum_{j=0}^i v(j), \quad i = 0, 1, 2, \dots, N-1, j = 0, 1, \dots, i \quad (15)$$

3 LOW POWER SYSTEM DESIGN

The overall architecture diagram of the dynamometer is shown in Figure 1. It consists of the following components: Acceleration sensor, load sensor, main control unit, power management module, real-time clock, and Flash memory, etc. The main controller integrates various peripheral

interfaces and wireless transceiver, all of these resources can satisfy the dynamometer function requirement well. In order to reduce power cost of the dynamometer, the following strategies are employed.

1) Hierarchical management to power supply. Not all the components are powered on simultaneously. When all the sensors' data needn't be acquired, all peripheral components are powered off, only the microcontroller is in active mode.

2) Data transmission in group. In order to reduce power cost of wireless transceiver, the acquired data

is always temporarily stored in FLASH memory and it would be sent out in packet via Zigbee wireless network when the FLASH is full.

3) Utilization of power-saving mode of microcontroller. Not all the components need be working for all time according to oil extraction characteristics, so software controls the hardware circuit running in some appropriate power-saving mode in different period.

4) Electronic components are selected strictly according to their power cost.

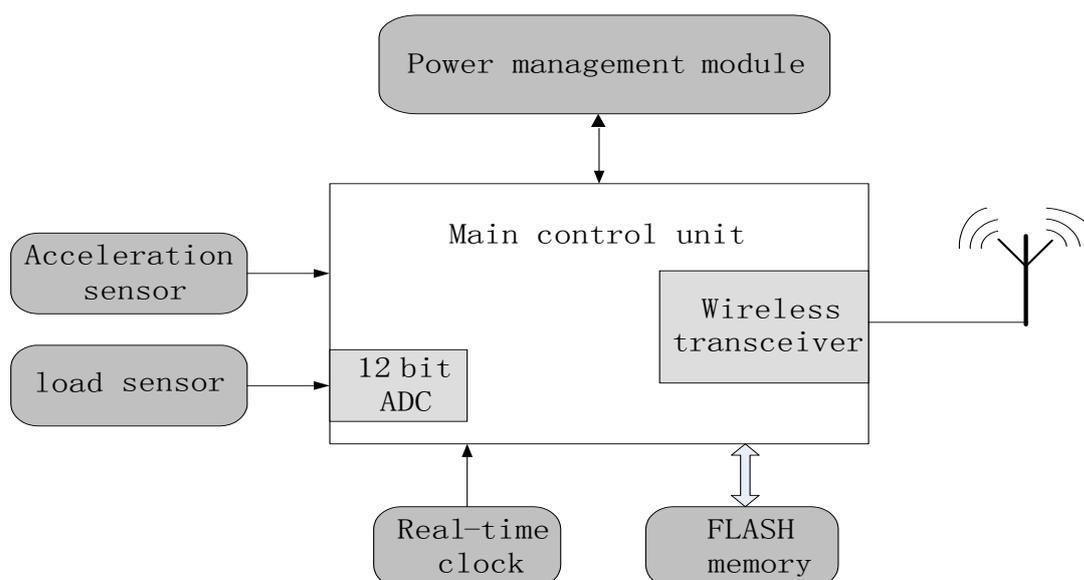


Figure 1. Diagram of the dynamometer

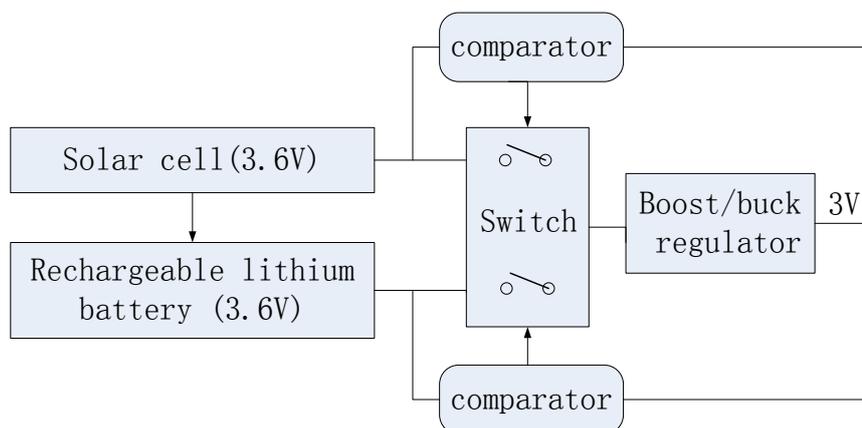


Figure 2. Diagram of the power management

3.1 Power management module

The power management module can be divided into two parts. One part is DC/DC regulators. A boost / buck regulator chip made by LINEAR corporation, with 3V output voltage is used as the main regulator of the whole system. It provides high conversion efficiency of up to 90% over a wide range of load currents, even in boost mode, the conversion efficiency can be more than 85%. In

addition, the ultra low noise regulator REF193 is used as the reference voltage for ADC in the main control unit, greatly improving the measurement accuracy of the load parameter. Finally, in order to further reduce system power consumption, the system utilizes the load management circuit. When there is no need for acceleration sensor and load sensor working, the management circuit will automatically turn off their power supply.

The other part is the power source, including the solar cell, rechargeable lithium battery, the charging circuit and the switch circuit. The dynamometer is fixed on the moving sucker rod, so it is convenient using batteries as power supply. The integral solution of solar cell and rechargeable lithium battery with 3.6V output voltage is used in this design. Besides, the boost/buck regulator can provide stable 3V voltage when its input voltage is in the range of 2.5V-5.5V just as mentioned above. By means of comparing the output voltage of solar cell and lithium battery with the stable 3V voltage, the comparator decides which should be selected as the power source and when the charging circuit should begin to run. All of these power management strategies make the good performance of the power supply module.

3.2 Accelerometer

Low noise, low drift and low power is the most important for acceleration sensor. Equation (4) indicates that displacement is calculated from acceleration, the little error of acceleration will be accumulated gradually and lead to the larger displacement error. ADXL355 from Analog Devices is a 3-axis MEMS acceleration sensor, with $20 \mu\text{g} / \sqrt{\text{Hz}}$ noise density, $200 \mu\text{A}$ measurement current and $0.15 \text{mg} / ^\circ\text{C}$ temperature drift error. It has $\pm 2\text{g}$ measurement range and adjustable bandwidth. There is a 20bit analog-to-digital converter in the sensor, so the acceleration data can be easily read by the control unit through SPI interface and its peripheral circuit is very simple. The ADC uses 1.8V supply as a reference to provide digital outputs insensitive to the supply voltage, and what's more, the 1.8V supply comes from the internal low dropout regulator. The three axis acceleration data are acquired though only the vertical one to the ground is needed in calculation, the other two are mainly used to analyse and judge whether there is some accident disturbance during the measurement process, ensuring the reliability of the operand.

3.3 Load Sensor

Load sensor must have the ability to accurately reflect the pull tension on sucker rod, so its location and installation method is very important. In this design YHYT-MV loading sensor is selected, which features high accuracy of 0.3% and good linearity, easy to be installed, and a fully sealed design. It is made in Mainland China and its measuring range is up to 150kN. It can be connected to the outer circuit by three wires, including power, ground, and signal wire. The output is analog voltage proportional to

load and is converted to digital by the 12-bit ADC built in the main control unit.

3.4 Main control unit

The ultra low power microcontroller CC2530F64 is used as the main controller. It integrates 8051 microcontroller core and RF transceiver compliant with 2.4GHz IEEE 802.15.4 standard. Its working current is less than 30mA when in active mode and $0.4 \mu\text{A}$ when in standby mode. It has one 12-bit 200Ksps ADC with 4KHz bandwidth, which is used as the load sensor signal converter. There are 2 SPI communication interfaces, one is used to connect accelerometer and the other is connected to real-time clock chip DS1302. It can work properly under the wide voltage range of 2.0 to 3.6V. Additionally, it has battery voltage monitoring function and 8KB RAM space. All above features make CC2530F64 suitable for the battery-powered dynamometer design.

4 SOFTWARE DESIGN

The software system is designed based on IAR integrated development environment and Zstack protocol stack of TI. Because the dynamometer card needn't be continuously measured at all time, most of the time the dynamometer factually keeps in power saving mode, and it would be woken up and get into active state again when needed. The application program is mainly responsible for receiving and interpreting the command from the monitor center and controlling the access to accelerometer, load sensor, real time clock unit and FLASH memory. Just as shown in figure 3, Zstack protocol is firstly started, and after a series of system initialization, the application program is executed next according to Zstack's mission polling mechanism.

Definition of movement period according to the measured acceleration data is the first step. Despite perfect performance of the accelerometer, the acquired data need be processed firstly. In this design, the sampling rate of accelerometer is set about 31 per second, and 3720 *3 acceleration data in 3 axes are collected after 2 minutes. Then the reliable data are screened and processed through FIR low-pass filter based on rectangular window function, and then the period can be find according to the data number between two nearest maximum acceleration data.

Then data acquisition are carried out at the preset time or when interrupt from the monitoring center appears.

The data usually are collected only at some specified time, so the program always reads time and begins to acquire and store the data when needed, otherwise it keeps waiting and the peripheral components are power off.

Once the commands are received through wireless, the program will execute the interrupt service routine. There are more than ten different commands and they make the system function more flexible.

As for displacement calculation, the acceleration data are firstly processed as same as that of period

definition above, then according to equation (12) - (15) displacement are calculated. This method overcomes the shortcoming that the bottom dead center of the suspension point must be accurately confirmed in advance through acceleration data processing. In that case, once the dead center is wrongly defined, the dynamometer card would be inconceivable. Furthermore, the less calculation of the algorithm is beneficial for the system power cost.

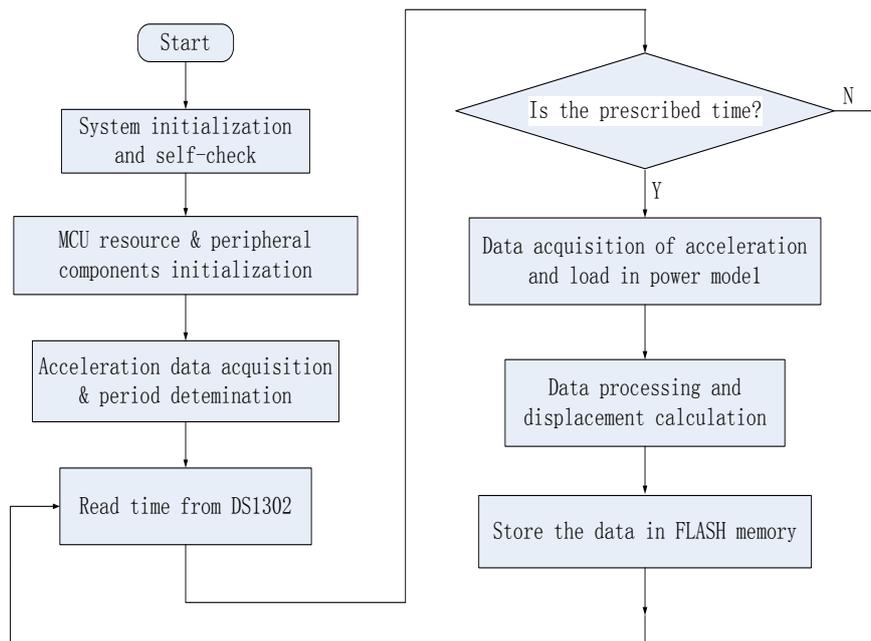


Figure 3. Main flow diagram of software

5 EXPERIMENT

Experiment is implemented by fixing the dynamometer on a beam pumping unit. In order to test the measurement accuracy, the two parameters of stroke and the times of strokes are measured by other methods in advance, as shown in Table 1 and Table 2.

The beam pumping units generally work stable and the parameters wouldn't change seriously in a short time, so after the above tests, the measurement using the designed dynamometer is implemented. As an example, Figure 4 shows the changing curves according to two records at different period. In Figure (a), the horizontal axis represents sampling points number in a given period, the vertical axis indicates load value, and the red curve represents the measured load. In order to conveniently observe the change trend relationship between load and displacement, the change of displacement indicated by the blue curve is also shown in the diagram. It can be seen that the change trend of these two

parameters is reasonable though the load curve is not so smooth.

The Figure (b) is two dynamometer cards corresponding to Figure 4(a). It can be seen that they are approximately consistent with the ideal parallelogram shape. After further calculation, the two parameters of stroke and times of strokes can be easily obtained. As shown in Figure (b), the two measured strokes are 3.92 and 3.94 respectively, the times of strokes are both 5.20. They are very close to the data in Table 1 and Table 2. After repeated measurement for ten times, we find that the measured times of strokes are very stable, they are all 5.20. The measured strokes have some differences at each time, as shown in Table 3, the fluctuation range is smaller than that of measuring line method, and the maximum relative error is smaller than 2.3%.

In addition, the experiment results also show that the power consumption does not exceed 200mW when the system is in full working, and it does not exceed 60mW in waiting state.

Table 1. Stroke measurement for five times by measuring line method

No.	1	2	3	4	5
stroke	4.0m	3.9m	4.0m	3.8m	4.0m
average stroke	3.94m				

Table2. Time of ten periods measurement by stopwatch and average times of strokes

No.	1	2	3	4	5
time of ten period	1'54"	1'55"	1'54"	1'56"	1'53"
average time	1'54"				
calculated times of strokes	5.24/min				

Table 3. Stroke measurement for five times by measuring line method

No.	1	2	3	4	5	6	7	8	9	10
stroke	3.87m	3.95m	3.85m	3.89m	3.97m	3.94m	3.91m	3.92m	3.88m	3.92m
relative error	1.78%	0.25%	2.28%	1.27%	0.76%	0	0.76%	0.51%	1.52%	0.51%

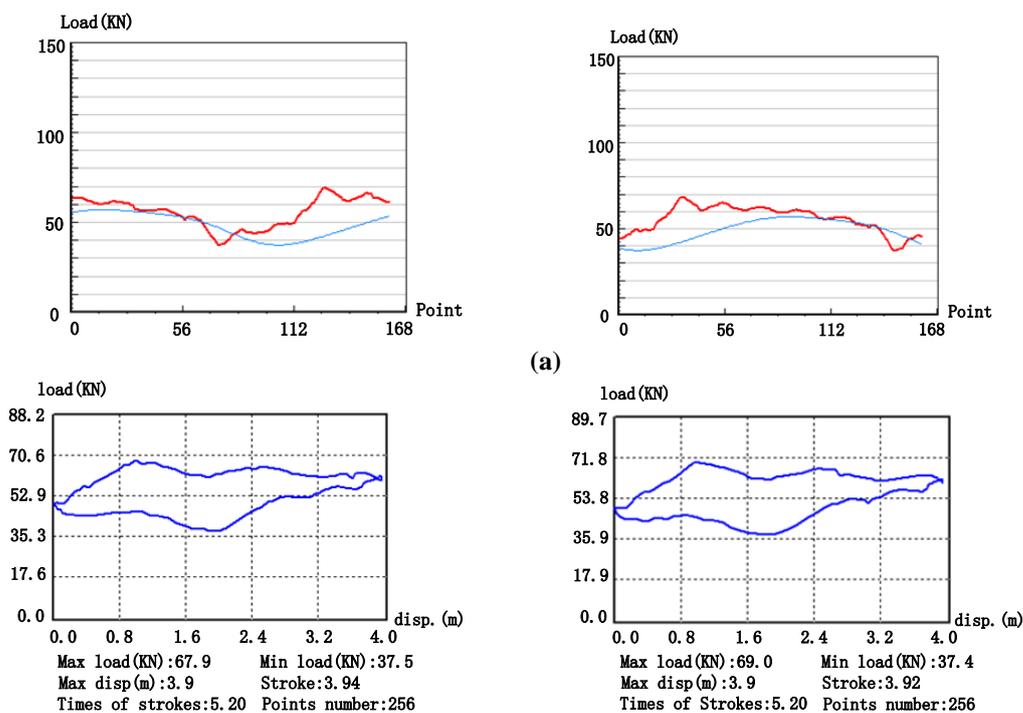


Figure 4. (a) The load changing curve in a period. (b) Two dynamometer cards based on measured data

6 CONCLUSIONS

The special application of surface dynamometer for beam pumping units requires accurate data measurement system with low power consumption. As one of the basic parameters of dynamometer card, displacement can be calculated through double integral of precise acceleration data, and this method has less calculation and excellent stability. As for power consumption, many aspects are

considered, for instance, Zigbee wireless data transmission technology is employed, solar cell and rechargeable lithium battery are used as power supply, and all electrical components are low power cost. Besides, when the dynamometer is in waiting state, the peripheral parts of MCU are power off, and the acquired data are always transmitted to the monitoring center in group, avoiding power waste due to frequent switch of wireless transceiver. Briefly speaking, In this work, the acceleration and

the load data can be acquired efficiently, the dynamometer card can be drawn quite accurately, and the total power consumption are relatively low. However, there is still something need to be improved. In order to execute the command from monitoring center at any time, the microcontroller is always in wireless signal receiving state rather than power saving mode, so the power consumption of the microcontroller is not very low enough. So it needs further study to reduce the total power consumption of the system.

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