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A DYNAMIC RAIL WEIGHING SYSTEM BASED WHEEL MEASUREMENT

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Abstract: A dynamic rail weighing system for weighing a ship (or boat) of passing dike is presented in this paper. The system applies wheel measurement to get weigh signal and model-based measurement processing weigh signal, thus weighing a ship (or boat) of passing dike. A scaling method of the rail weighing system based wheel measurement is proposed. This paper discusses thoroughly that the method of model-based measurement processes weigh signals.
Keyword: Rail Weighing System, Wheel Measurement, Model-based Measurement

1 INTRODUCTION

Across some rivers in China, there are many dikes for water conservancy. When a ship (or a boat) wants to pass a dike, one of the methods is to carry it over the dike by using of a flatcar. How much will it cost to carry a ship over a dike? This cost follows the weight of the ship itself and the goods in this ship. To show the principle of cost exactly and rationally, it is necessary to weigh dynamically a ship passing over a dike. In this paper, the author introduces a dynamic rail weighing system for weighing a ship (or a boat) that is passing over a dike.

Fig. 1 is a sketch of a dynamic rail weighing system for weighing a ship that is passing over dike. By using sensors of pin type and the method based on wheel measurement, the system can measure

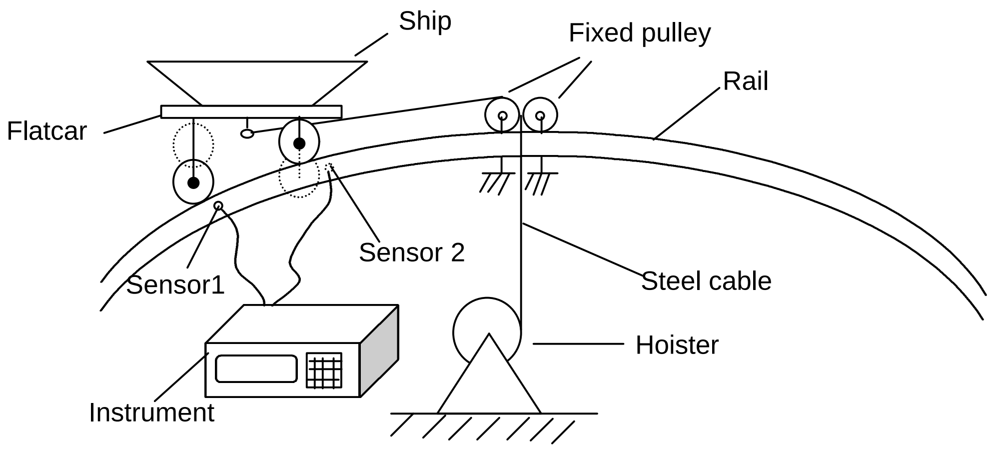

Figure 1. A sketch of a dynamic rail weighing system for weighing a ship

gravity waveforms one by one during the wheels are passing through the sensors on the rail. By the circuit of signal processor in the measurement instrument, the signal of gravity waveforms getting from sensors can be amplified, filtered, and converted from analogue signal to digital signal. The digital signal from analog-to-digital converter goes to a microcontroller in the instrument. The microcontroller processes storage, digital filtration, analyzing and calculating for dynamic signal and identifies the weight of a ship. Because the method of based on wheel measurement is used, it is different between usual weighing system and our weighing system to scale system. We will discuss the scaling method later in section 4, “SYSTEM SCALING”**.** Wheels press through the sense position of a rail in a short time. The dynamic signal wave is in Fig. 6 when a wheel passes a sensor. Because the weighing system uses a model-based measurement, the weighing precision excels that of a average measurement. The signal processing method of a model-based measurement is discussed in section 3, “SIGNAL PROCESSING”.

2 DESIGN OF THE SYSTEM

2.1 Getting gravity signal

By using method of based on wheel measurement the system can obtain weight of the boat, and both of the sensors of pin type which are placed on the side of the rails can collect the gravity signals of wheels passing through the rails. The method of non-axis placement is used to fix the sensor, as shown in Fig. 2. Because two electric analogue switches with low resistance can transfer two signals of two sensors one after another, there is only one channel of amplification and filtration is needed to finish the transmission and collection for the signals. One channel not only reduces the cost of hardware, but also avoid the discretization which is caused by two channels. By means of two electric analogue switches which are controlled by a microcontroller, the gravity signals which are collected by sensor 1 and sensor 2 pass electronic analog switches to exactitude amplifier with a filtration function, as shown in Fig. 3. The amplifier put the signals which have been magnified into analog-to-digital converter. The A/D converter completes an A/D conversion and sampling by the control of the microcontroller in a 200 μS interval, then microcontroller accepts digital signals from the output of an A/D converter.

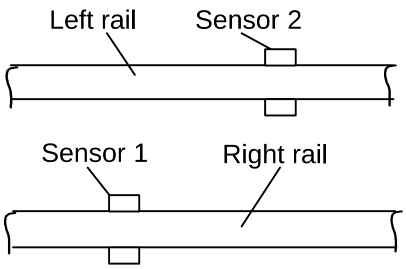

Figure 2. The placement sketch of two sensors

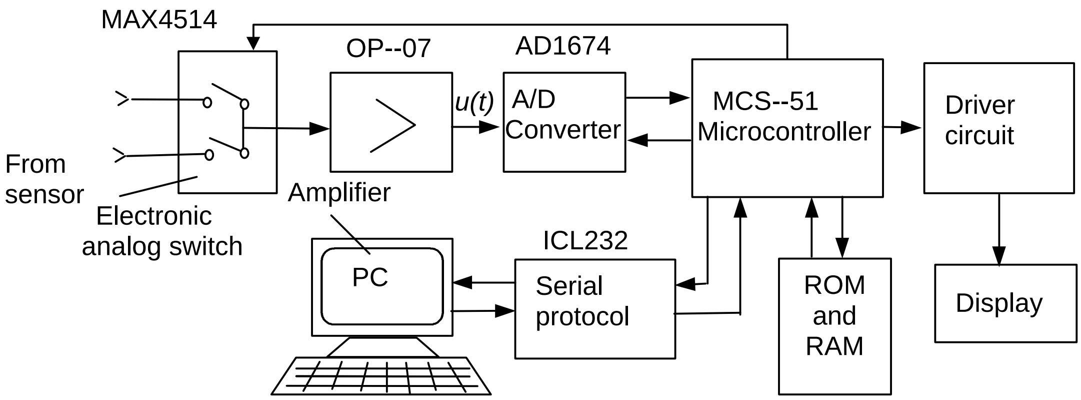

Figure 3. The sketch of the system which collects and processes signals

2.2 Design of the hardware

The diagrammatic sketch of a hardware system is shown in Fig. 3. The integrated circuit OP-37 is chosen in the design of amplifier in order to measure the gravity signal which is a brevity signal, as the signal propagator of OP-37 is 12 V/μS. According to the dynamic response rate of a sensor, we have designed a low-pass filter of cut-off frequency f_0=0.8 kHz. A/D converter AD1674 is selected, which has the maximum sampling rate of 100k SPS (SPS = sampling per second) and signal acquisition time of 1 μS. The dynamic capabilities of AD1674 are fit the needs to transmit and collect the signals in the system. There are 48k×8bit RAMs which are used as storage of temporary gravity signals of four wheels in the microcontroller subsystem. The machine frequency of microcontroller is 11.059 kHz. The microcontroller communicates with PC by RS232 protocol and ICL232 conversion circuit of electrical level.

2.3 Design of the software

The system software includes many program modules such as initialization, display, serial communication, signal collection, digital filter, wheel gravity signals processing and so on. The design idea of signal collection subprogram is that when the measurement instrument accepts the signal which means that the flatcar carrying the ship (or boat) begins to move, then it is begin to collect the signals of sensor 1 and sensor 2, and during the collection the system will keep analyzing whether the wheels are just pressing on the sensors or not; if it is not, then the collecting data are given up; otherwise, keeps the data that can be used by digital filter and wheel gravity signals processing subprogram. The digital filter subprogram begins to run during the sampling interval, and we will discuss the method of digital filter later. After the collection of gravity signals of four wheels have been finished and the digital filter subprogram has completed run, the wheel gravity signals processing subprogram begins to run, and we will also discuss the method of processing wheel gravity signals in later section. After the system finishes the processing of wheel gravity signals, the value corresponding to real weight of the ship (or boat) can be acquired. The real weight of the ship (or boat) can be obtained by calculating digital value of each wheel, which has been scaled in different proportion, and then summing them up. The data of the ship (or boat) weight is delivered to the display subprogram and the serial communication subprogram. The display subprogram can convert the binary data into display code, and the serial communication subprogram can put the data to PC.

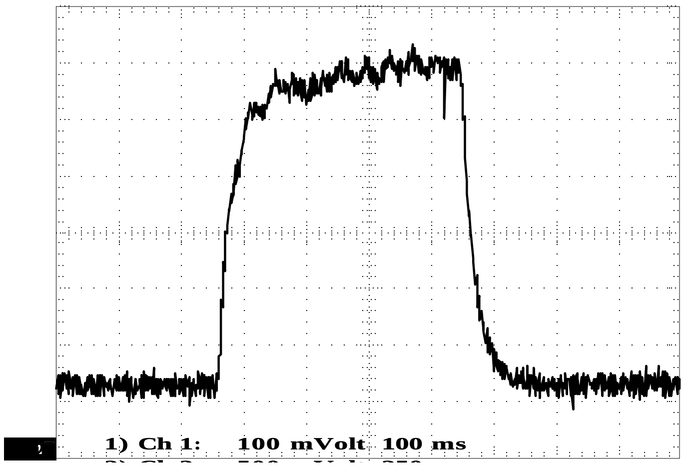

Figure 4. The waveform of the voltage *u(t)* by TDS220 oscillograph obtaining

3 SIGNAL PROCESSING

3.1 Digital signal filter

The signal waveform in Fig. 4 is voltage *u(t)* wave that is acquired by TDS220 digital oscillograph made in Tektronix company of U.S. The *u(t)* is an output wave of the amplifier as in Fig. 3 and the signal of direct ratio to a sensor output. The *u(t)* is consisting of a gravity signal and some noise signals. In order to remove the noise signals, we first apply the median filtering to remove the evidence bias data, and then a second-order recurrence low-pass filtering to remove the other noise signals.

Fig. 5 is an equivalent circuit model of the second-order recurrence low-pass filtering, thus it can be seen:

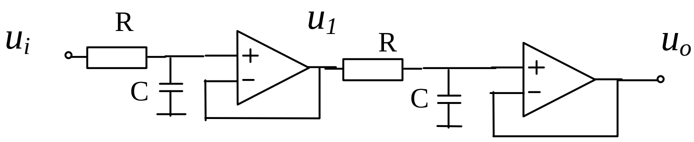

Figure 5. The equivalent circuit model of second-order recurrence low-pass filtering

$$u_i = RC\frac{du_1}{dt} + u_1 \qquad (3-1)$$

$$u_1 = RC\frac{du_o}{dt} + u_o \qquad (3-2)$$

According to Eq. (3-1) and (3-2), the relevant difference equations are

$$u_i(KT) = RC\frac{u_1(KT) - u_1[(K-1)T]}{T} + u_1(KT) \qquad (3-3)$$

$$u_1(KT) = RC\frac{u_o(KT) - u_o[(K-1)T]}{T} + u_o(KT) \qquad (3-4)$$

$$u_1[(K-1)T] = RC\frac{u_o[(K-1)T] - u_o[(K-2)T]}{T} + u_o[(K-1)T] \qquad (3-5)$$

In Eqs. (3-3), (3-4) and (3-5), T is sampling cycle (T=200 μS), K is a sampling order number. If Eqs. (3-4) and (3-5) are used to eliminate $u_1(KT)$ and $u_1[(K-1)T]$ in Eq. (3-3), the result is

$$u_o(KT) = \frac{2RC}{RC+T}u_o[(K-1)T] - \frac{(RC)^2}{(RC+T)^2}u_o[(K-2)T] + \left(\frac{T}{RC+T}\right)^2 u_i(KT) \qquad (3-6)$$

Eq. (3-6) is an expression of the second-order recurrence low-pass filtering. In Eq. (3-6), the RC value is decided by MATLAB 5.2 software analyzing.

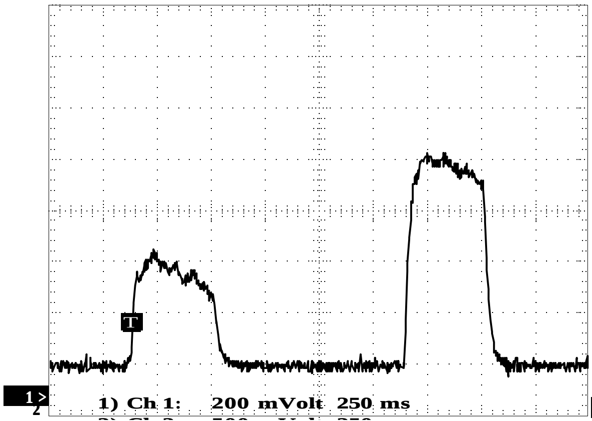

Figure 6(a). The waveform of the right rail's *u(t)*

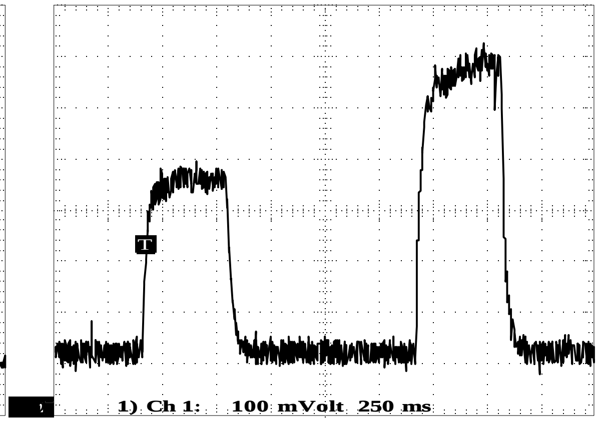

Figure 6(b). The waveform of the left rail's *u(t)*

3.2 Gravity dynamic signal analyzing

In Fig. 6, it is different that waveforms are made by the gravity of wheels. The reasons are

1 The disaccord of sensitivity coefficients between Sensor 1 and Sensor 2, and the disproportion of heavy over wheels;

2 The vibration of the flatcar moving;

3 The disaccord of plainness between the rail plane and the four wheels plane, so Sensor 1 signal is large when wheels begin to press, and Sensor 2 signal is small when wheels begin to press, as in Fig. 6(a) and (b).

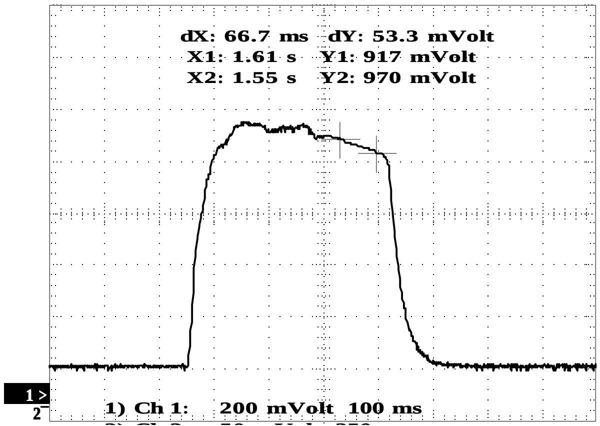

Figure 6(c). The sample figure of calculating "B" value

3.3 System modeling[1] and gravity data obtaining

Fig. 7 is a mechanics model of the weighing sense mechanism. *x(t)* is the strain value of the sensor to be forced, and *u(t)* is the output of the amplifier in Fig. 7. The *u(t)* varies directly proportional to the *x(t)*. The *u(kT)* is a discrete value of *u(t)*. "M" is an equivalent mass when a wheel presses on the sensor; *"f"* is the internal friction coefficient; *"c"* is spring rate.

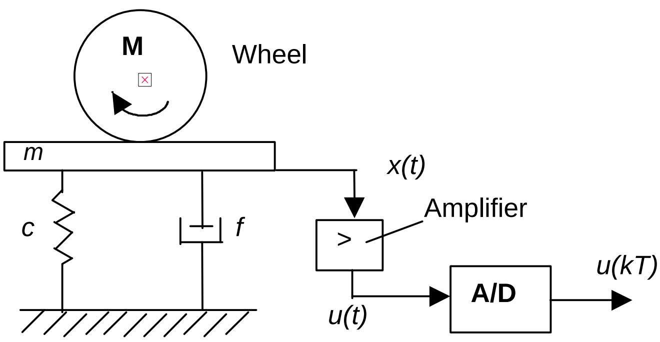

Figure 7. The mechanics model of sense mechanism

According to Fig. 7, when a wheel leaves the station of sense, the dynamics equation is

$$m\frac{d^2x}{dt^2}+f\frac{dx}{dt}+cx=0 \qquad (3-7a)$$

or

$$\frac{d^2x}{dt^2}+\frac{f}{m}\frac{dx}{dt}+\frac{c}{m}x=0 \qquad (3-7b)$$

The solution of Eq. (3-7) is

$$x(t)=A_1e^{p_1t}+A_2e^{p_2t} \qquad (3-8)$$

t 0 in Eq. (3-8), and where

$$p_1=-\frac{f}{2m}+\sqrt{(\frac{f}{2m})^2-\frac{c}{m}} \qquad (3-9)$$

$$p_2=-\frac{f}{2m}-\sqrt{(\frac{f}{2m})^2-\frac{c}{m}} \qquad (3-10)$$

In Fig. 7, after the wheel leaves, under the condition that system is steady (*t*=), it is that *x*( )=0. We consider that the strain is zero, if there is not any heavy on the station of a sense.

According to Fig.7, the initial value of the sensor strain *x*(0+)=*Mg/c*.

Analyzing the mechanics model of the weighing sense mechanism, we consider that the strain rate of a sensor is constant if the wheel leaves instantly. It is that

$$\frac{dx}{dt}\Big|_{x=0_+}=B$$

The initial condition above is accurate and sure. *dx/dt* is infinite if *dx/dt* changes suddenly. But, it is impossible that *dx/dt* is infinite. Therefore, we have

$$x(0_+)=\frac{Mg}{c}=A_1+A_2 \qquad (3-11a)$$

$$\frac{dx}{dt}\Big|_{x=0_+}=p_1A_1+p_2A_2=B \qquad (3-11b)$$

The solution of Eq. (3-11) is

$$A_1=-\frac{B}{p_2-p_1}+\frac{p_2}{p_2-p_1}\cdot\frac{Mg}{c}$$

$$A_2=\frac{B}{p_2-p_1}-\frac{p_1}{p_2-p_1}\cdot\frac{Mg}{c}$$

The autoregressive moving average model of Eq. (3-7) is

$$x(kT)=-a_1x[(k-1)T]-a_2[(k-2)T]+e(kT) \qquad (3-12)$$

In Eq. (3-12), it is that

$$a_1=-\frac{2+\frac{f}{m}\cdot T}{1+\frac{f}{m}\cdot T+\frac{c}{m}\cdot T^2} \qquad a_2=\frac{1}{1+\frac{f}{m}\cdot T+\frac{c}{m}\cdot T^2}$$

The *e(kT)* is an incorrelate stochastic error series. The average value of *e(kT)* is zero.

We apply the least squares estimate to estimate the unknown numbers a_1, a_2 of Eq. (3-12). On condition that we measure *x(kT) (N+n)* times, N equations are formed (*N* 2000). We have

$$\left.\begin{aligned} x(3T) &= -a_1 x(2T) - a_2 x(1T) + e(3T) \\ x(4T) &= -a_1 x(3T) - a_2 x(2T) + e(4T) \\ &\cdots\ \cdots\ \cdots\ \cdots\ \cdots \\ x[(N+2)T] &= -a_1 x[(N+1)T] - a_2 x(NT) + e[(N+2)T] \end{aligned}\right\} \qquad (3-13)$$

The matrix equation of Eq. (3-13) is

$$X(N) = \Phi(N) q + E(N) \qquad (3-14)$$

In Eq. (3-14), we have

$$X(N) = \{x(3T), x(4T), \cdots, x[(N+2)T]\}^T$$
$$E(N) = \{e(3T), e(4T), \cdots, e[(N+2)T]\}^T$$
$$q = [a_1, a_2]^T$$
$$\Phi(N) = [j^T(1), j^T(2), \cdots, j^T(N)]^T$$
$$j^T(i) = \{-x[(1+i)T], -x(iT)\} \qquad i = 1, 2, \cdots, N$$

In Eq. (3-13), each equation may be

$$x[(2+i)] = j^T(i) q + e[(2+i)T] \qquad (3-15)$$

By the estimator $\hat{q}$ of the system parametric vector q , the residual sum of squares of Eq. (3-13) is

$$J = \sum_{i=0}^{N} e^2[(2+i)T] = E^T(N) \cdot E(N) = -2\Phi^T(X - \Phi\hat{q}) = 0 \qquad (3-16)$$

J is quadratic function of $\hat{q}$. To find the minimum of *J*, we have

$$\frac{\partial J}{\partial \hat{q}} = 0 \qquad (3-17)$$

$$\frac{\partial J}{\partial \hat{q}} = \frac{\partial}{\partial \hat{q}} E^T E = \frac{\partial}{\partial \hat{q}}[(X - \Phi\hat{q})^T (X - \Phi\hat{q})]$$

We obtain

$$\hat{q} = (\Phi^T \Phi)^{-1} \Phi^T X \qquad (3-18)$$

It is satisfied in the system that $(\Phi^T \Phi)$ must be nonsingular.

$\hat{q}$ of sensor 1 measurement channels is different from $\hat{q}$ of sensor 2, because it is a contrast between sensor 1 and sensor 2, and between the mechanisms of the left rail and the right rail.

The signal of sensor 1 when a wheel leaves out is smaller than that when a wheel comes in. The signal of sensor 2 when a wheel leaves out is larger than that when a wheel comes in. The slope of a signal augment or diminution determines B in Eq. (3-11b) which is different for different wheels.
Because *u(t)* is proportional to *x(t)*, Eq. (3-7) ~ Eq. (3-18) are equivalent if *x(t)* is replaced with *u(t)*. Therefore in Fig. 6(c),

B = *du* /*dt* = -53.3 mV / 66.7 mS = -O.799 (V/S)

When a wheel leaves instantly, *u(kT)* in Eq. (3-12) also coincides with

$$\frac{u(kT) - u[(k-1)T]}{T} = B$$

The *u(kT)* is a signal when a wheel leaves instantly, and is the wheel gravity signal that we want to obtain. The *u(kT)* is proportional to *Mg/c*. The *"c"* is constant if the weighing sense mechanism is immobile. Therefore, the *u(kT)* is proportional to *Mg* (wheel gravity).

4 SYSTEM SCALING[2]

Because of the disaccord of plainness between the rail plane and the four wheels plane, we get the disaccord of sensitivity coefficients between Sensor 1 and Sensor 2; Each proportion of the wheel measuring value to gravity is unequal to another. Consequently there are different measuring results for same heavy at different locations on the flatcar. Namely, we have the so-called corner error. Wheel measuring values are respectively expressed as: y_A, y_B, y_C, y_D. The first measuring values are respectively expressed as: y_{A1}, y_{B1}, y_{C1}, y_{D1}. Such as, the fourth measuring values are expressed as: y_{A4}, y_{B4}, y_{C4}, y_{D4}. Every time we measure, the scaling weight is placed at a corner in order. The relevant proportion coefficients are respectively expressed as: k_A, k_B, k_C, k_D.

The relation between the mass of a scaling weight and the measuring value at a time are expressed as:

$$\left.\begin{aligned} m &= k_A y_{A1} + k_B y_{B1} + k_C y_{C1} + k_D y_{D1} \\ m &= k_A y_{A2} + k_B y_{B2} + k_C y_{C2} + k_D y_{D2} \\ m &= k_A y_{A3} + k_B y_{B3} + k_C y_{C3} + k_D y_{D3} \\ m &= k_A y_{A4} + k_B y_{B4} + k_C y_{C4} + k_D y_{D4} \end{aligned}\right\} \qquad (4-1)$$

In Eq.(4-1), *"m"* is the mass of a scaling weight.

The solutions of proportion coefficients (k_A, k_B, k_C, k_D) are gotten through solving Eq. (4-1). In fact, the solutions of k_{Ai}, k_{Bi}, k_{Ci}, k_{Di} are solved at each measuring sect, then the averages of *N* groups (k_{Ai}, k_{Bi}, k_{Ci}, k_{Di}) are obtained by the flowing equations.

$$k_A = \sum_{i=1}^{N} k_{Ai} \qquad k_B = \sum_{i=1}^{N} k_{Bi}$$

$$k_C = \sum_{i=1}^{N} k_{Ci} \qquad k_D = \sum_{i=1}^{N} k_{Di}$$

In the way, the nonlinear error is reduced.

5 MEASURING RESULT

The maximum weighing value of weighing system is 90×10^3kg. The measuring error is 1%FS. The weighing system error consists of the identification error, the noise interference, the nonlinear error of the system, the sensor error and the corner error. Among these errors, the identification error is a main error source. Therefore, the advanced and proper identification theories and algorithms will improve the model-based measurement for a dynamic weighing system.

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