

Condition Monitoring of Rope-less Elevator Braking System Based on Wavelet Denoising

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Abstract—The rope-less elevator driven by Permanent Magnet Linear Synchronous Motor (PMLSM) is a new technology for high-rise buildings. In the practical operation, PMLSM inevitably encounters various kinds of turbulences which directly affect the rope-less elevator's operation. The braking system is important for rope-less elevator safe and steady operation. Usually, the ordinary inspections are not able to detect some early stage faults in the elevator braking system. Based on the analyzing of braking system common faults, the article proposes a rope-less elevator braking system monitoring scheme and presents a method that uses air gap sensor, hydraulic pressure transducer and disc spring pressure sensor in order to detect running condition of braking system. The sampling signals are inevitably influenced by noise, which degrades the accuracy and precision of an analysis. De-noising by soft-thresholding is a new signal inspection method in wavelet analysis. On the base of briefly introducing wavelet de-noising theory, a wavelet de-noising analysis method is presented. The study shows that the useful information reflecting the condition of braking system can be effectively extracted from highly noised signals by soft-thresholding de-noising method.

Index Terms—Rope-less Elevator, Braking system, Signal acquisition and processing, Wavelet denoising

I. INTRODUCTION

Many skyscrapers have been built so far in the world, where the high-speed elevators have been developed in order to meet the demand. The typical elevators employ the rope-hoisted method. With the continuous increase in building height, the rope weight may exceed the limit of the strength of the rope itself if the rope length becomes larger than 1,000m. Therefore rope-less elevators are required to realize a high-rise skyscraper elevator system with sufficient transport capacity [1-3]. Permanent Magnet Linear Synchronous Motor (PMLSM) has the

characteristics of larger thrust, high efficiency, high power factor, is the ideal driving source for rope-less lifting system. It drives the elevator car directly without wire rope and breaks the limitations of rope-hoisted method. Supported by the National Natural Science Foundation of China, we have been carrying out search work in the modeling, driver, safe operation strategy of PMLSM, and constructed a rope-less elevator system driven by PMLSM with multi-segment primary [4-9]. The braking system is important for rope-less elevator safe and steady operation. The security and reliability of rope-less elevator have closed relation with its braking system. Therefore, it's important to make real time monitor and diagnose of the braking system in rope-less elevator [11, 13-18].

The sampling signals of braking system are often corrupted by noise in their acquisition or transmission. The goal of denoising is to remove the noise while retaining as much as possible the important signal features. There are different possible approaches to signal denoising and one of the most recent methods is based on the wavelet transform. Wavelets are a new family of basis functions, well localized in both time and frequency domains. Due to their local character, the representation of a signal in the wavelet domain is sparse and allows signal compression and denoising. Donoho and Johnstone and Donoho have developed a method known as the wavelet shrinkage to estimate an unknown smoothed signal from data with noise [10].

In the paper, we described the structure and features of rope-less elevator, introduced the function and structure of disk braking system. Based on the analyzing of braking system common faults, the article proposes a rope-less elevator braking system monitoring scheme and presents a method that uses air gap sensor, hydraulic pressure transducer and disc spring pressure sensor in order to detect running condition of braking system. De-noising method based on wavelet is applied to dispose the acquisition signals of braking system.

II. DESCRIPTION OF ROPE-LESS PMLSM ELEVATOR

The rope-less elevator driven by Permanent Magnet Linear Synchronous Motor (PMLSM) is a new technology for high-rise buildings. Fig.1 shows the

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configuration of the rope-less elevator experimental apparatus. It has been driven by a single sided PMLSM. The specification of which is shown in Table1.



Figure 1. Rope-less elevator driven by single sided PMLSM

TABLE I.
SPECIFICATION OF ROPE-LESS ELEVATOR

Name	Value
Driving mode	Single sided PMLSM
Rated power	1.5 [kW]
Rated load	260[kg]
Mass of cage	70[kg]
Mass of rated load	190[kg]
Movable height	4 [m]
Rated velocity	0.3 [m/s]

A permanent magnet type secondary has been mounted to the cage. The guide rail has been equipped with primary, which faced to the secondary. The cage has been supported with a set of wheels so as to move up and down and to keep the air gap between the primary and secondary member. The attracting force adsorbs the mover on the track, which can make the elevator car stable.

For long stator configuration, the length of the stator sector to be energized has a direct effect on the number of converters and on the resulting efficiency. The optimum is a traffic performances and an economical trade-off, requesting simulations of the full system. Long stators will be constructed by placing unit armatures in rows along the guide way. Driving power is only supplied to the armatures facing permanent magnets and the other armature windings are shorted circuit. In case of interruption in the power supply, the cage will go down at slow speed by energy consumption braking.

III. CONDITION MONITORING FOR BRAKING SYSTEM

A. Braking system for ropeless elevator

The braking system is normally designed to operate with a controlled braking force to ensure the same retardation levels during all operating situations, regardless of the direction of travel, speed, load or other factors. This greatly improves the safety performance of the rope-less elevator. Normally, there are two braking modes: stopping from creep speed to full stop level (service braking), controlled braking during an emergency situation (emergency stop/safety braking). In case of emergency, the butterfly spring will generate positive braking pressure and arrest the fall of the elevator car. The hydraulic disc brake is shown in Fig.2.



Figure 2. Braking system for rope-less elevator

The working principal of braking system is shown in Fig. 3. With the increase of the oil pressure, the thrust F_2 generated by oil increased, which push the piston compressed disc spring. Spring force will be overcome, which can make the brake pads leave the brake disc. When open the solenoid valve, oil pressure decreases, disc springs forces will move the brake pads to the brake disc to produce the positive braking force and arrest the fall of the elevator car.

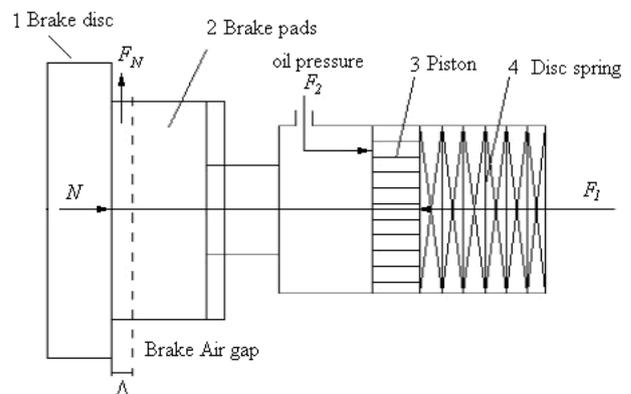


Figure 3. Sketch diagram of disk brake working

According to the working principle of disc brake, we can derive each braking pressure as follows [11-12]:

$$F_N = 2N\mu n \tag{1}$$

Where μ is the friction coefficient between brake pads and brake disc, n is pair number of brake, N is positive pressure.

$$N = F_1 - F_2 \tag{2}$$

Normal retardation of rope-less elevator from full speed to stop is accomplished electrically with the motor and elevator control system. The hydraulic braking system generally functions as a parking brake at still stand. However, in case of loss of motor power, over speed, over travel or any other emergency situation, the

braking system serves as the ultimate means for safely bringing the elevator to a full stop with the retardation rate complying with the specific safety regulations. The hydraulic braking system is therefore vital for the safe and reliable operation of a rope-less elevator. At an emergency stop the oil pressure quickly drops from full pressure to the upper control limit. It is then further reduced following a ramp function in the control system until the required retardation setpoint is obtained. The hydraulic diagram is shown in Fig. 4.

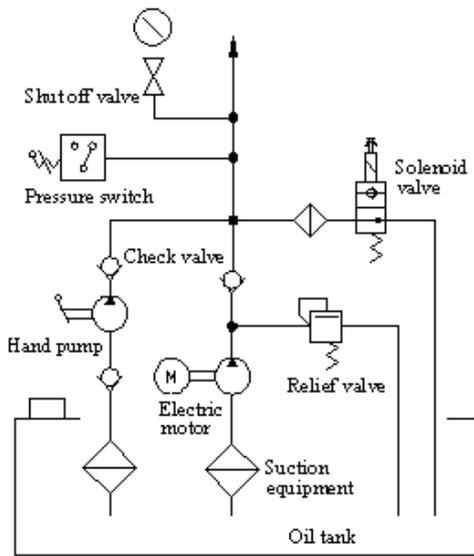


Figure 4. Hydraulic diagram of fail-safe disc brakes

The hydraulic power unit contains an electrically driven variable displacement piston pump mounted under the oil tank with all necessary valves and apparatus required to control the hydraulic brake units. To ensure high safety and reliability, the hydraulic control unit has two parallel valve systems for pressure control. There are three hydraulic connections in the hydraulic station, one to pressurize the brake units and two for the controlled return oil from the brake units. The two separate and independent oil return branches ensure reliable operation of the brake system in case of a fault in one of the branches. An analog hydraulic pressure transducer connected to the elevator control system continuously monitors the system pressure and ensures the proper operation of the disc brake system. The valve test unit is used mainly for maintenance purpose and can be electrically connected to individual valves in the hydraulic station for function control. It can also be used to maneuver the hydraulic brake units while adjusting the air gap sensors or circulating the oil through the filter. The control system of disc brake is shown in Fig.5.

B. Condition Monitoring of Braking System

The braking system is important for safe and steady operation. The security and reliability of rope-less elevator have closed relation with its braking system. If it's failed to brake in the working process, equipments will be damaged, even make death. The common faults of braking system are as follows [13-15]:

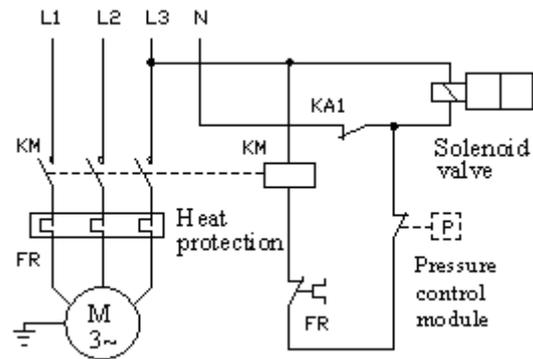


Figure 5. Control system diagram of hydraulic disc brake

(1) Brake does not open. The reason is no oil or hydraulic oil shortage.

(2) The brake can not brake. The reason is hydraulic or brake damage, caused by stuck.

(3) Long braking time, braking distance is long slide, a small braking force.

So the brake monitoring system need to measure the air gap, hydraulic pressure and disc spring pressure [16-19]. The monitoring scheme of brake monitoring system is show in Fig.6

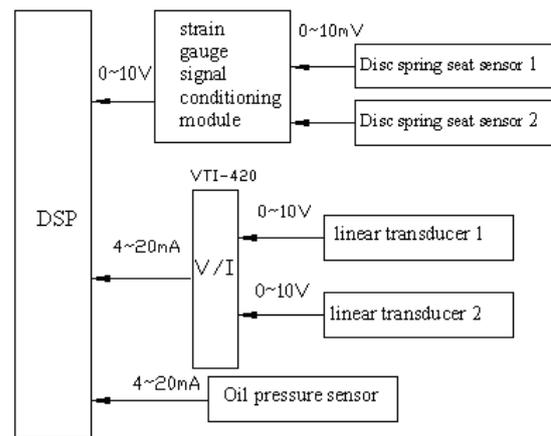


Figure 6. Scheme of brake condition monitoring system

The brake system condition, such as, the air gap, hydraulic pressure and disc spring pressure, is supervised and maintained by MS320F2812 DSP controller. It integrates the necessary hardware and software modules. It is provided with a battery back-up to allow full operation during a short power failure.

(1) Air gap detection

The air gap influences the hydraulic brake unit's clamping force and is very important for the reliable performance of the rope-less braking system. If the air gap increases, the clamping force will reduce. We use linear transducer to detect real-time air gap of brake shoe clearance. The sensor is installed by qualified personnel on the bracket in consideration of all relevant safety regulation. First, storage the value s_0 when the brake closing. After a period of time t the brake open, measured the new value s_t . The difference between the two values is the brake air gap. In order to improve the anti-interference ability, we use 4~20mA to transmit signal.

The schematic diagram of signal conditioning circuit is shown in Fig.7.

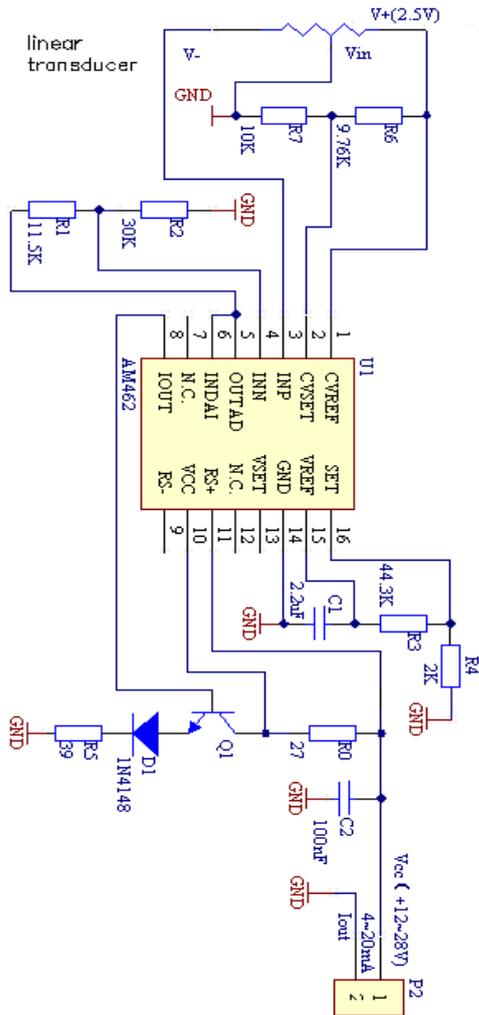


Figure 7. Schematic diagram of linear transducer conditioning circuit

AM462 is a universal V/I converter and amplifier IC with a number of additional functions. The IC basically consists of an amplifier, whose gain can be set externally, and an output stage which can convert voltage signals referenced to ground to industrial current signals. An additional reference voltage source for the supply of external components is also included in the device. A further operational amplifier can be connected up as a current source, voltage reference or comparator. One of the main features of the IC is its integrated protective circuitry. The device is protected against reverse polarity and has a built-in output current limit. Converter IC AM462 enables industrial current loop signals (e.g. of 0/4–20mA) to be produced relatively easily. The IC can be connected up to a processor for signal correction.

M462 has a constant voltage source which supplies the linear transducer. The voltage is calculated by (3).

$$V_{CVREF} = V_{BG} \left(1 + \frac{R_6}{R_7} \right) = 1.27V \left(1 + \frac{R_6}{R_7} \right) \quad (3)$$

In the system, the input voltage is set to 2.5V. The values of R_6 and R_7 can be calculated by (4).

$$\frac{R_6}{R_7} = \frac{V_{CVREF}}{V_{BG}} - 1 \approx \frac{2.5}{1.27} - 1 = 0.97 \quad (4)$$

Taking into account the range of resistors, we select $R_7 = 9.7 \text{ k}\Omega$ and $R_6 = 10 \text{ k}\Omega$.

Output current is calculated by (5).

$$I_{OUT} = V_{INP} \cdot \frac{G_I}{8R_0} + I_{SET} = V_{INP} \cdot \frac{G_{GAIN}}{8R_0} + 4 \text{ mA} \quad (5)$$

The output current range is set to 4...20mA. When $R_0 = 27$ and $I_{SET} = 4 \text{ mA}$, we can get:

$$\frac{R_3}{R_4} = \frac{V_{REF}}{2R_0 I_{SET}} - 1 = \frac{2.5V}{2 \cdot 27 \Omega \cdot 4 \text{ mA}} - 1 \approx 10.57 \quad (6)$$

The amplification of AM462 inbuilt operational amplifier OP1 is expressed by (7) and (8).

$$G_{GAIN} = 8R_0 \frac{I_{OUT \max} - I_{SET}}{V_{INP}} = 8 \cdot 27 \Omega \cdot \frac{16 \text{ mA}}{2.5V} = 1.3824 \quad (7)$$

$$G_{GAIN} = 1 + \frac{R_1}{R_2} \quad (8)$$

$$\text{So, } \frac{R_1}{R_2} = 1.3824 - 1 = 0.3824$$

According to the range of the value of external components, the value of each component as follows:

$R_1 = 11.5 \text{ k}$, $R_2 = 30 \text{ k}$, $R_3 \approx 44.3 \text{ k}$, $R_4 = 2 \text{ k}$, $R_0 = 27$, $R_5 = 39$, $C_1 = 2.2 \mu\text{F}$, $C_2 = 100 \text{ nF}$.

(2) Disc spring pressure detection

Disc spring force as an intermediate quantity, but it's a very important monitoring parameter. Through the monitoring of spring force, we can calculate the braking force. In the process of disc spring force acquisition, we can monitor rope-less elevator braking force in the whole running process. Through the changes of braking force, we can determine whether braking force is too big or too small. In addition, if combined with the spring force signals and other related parameters, such as, air gap, oil pressure; we can calculate the size of the coefficient of friction [12, 19]. According to the related parameters, we can diagnose braking system running condition.

The schematic diagram of disc spring pressure signal conditioning circuit is shown in Fig.8. Disc spring pressure is measured by strain gauge sensor, which is installed in the disc spring seat. The output signal of strain gauge sensor is 0~10 mV. It needs process by isolated strain gauge signal conditioning module.

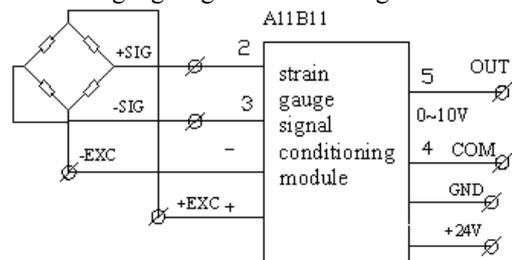


Figure 8. Schematic diagram of gauge signal conditioning circuit

IV. WAVELET DENOISING

A. Continuous Wavelets Transform (CWT)

The CWT - $Wf(s, \tau)$ - is the inner product of a time-varying signal $f(t)$ and the set of wavelets $\psi_{s,\tau}(t)$ given by [20-21]:

$$Wf(s, \tau) = \langle f, \psi_{s,\tau} \rangle = \frac{1}{\sqrt{s}} \int f(t) \psi^* \left(\frac{t-\tau}{s} \right) dt \quad (9)$$

The scaling and shifting the mother wavelet (ψ) with factors of s and τ (with $s > 0$), respectively, generate a family of functions called wavelets given by:

$$\psi_{s,\tau}(t) = \frac{1}{\sqrt{s}} \psi \left(\frac{t-\tau}{s} \right) \quad (10)$$

B. Discrete Wavelet Transform (DWT)

A very common discretization of the CWT, which is a very redundant representation, consists of setting the scale and shift value as: $s = s_0^i$ and $\tau = k\tau_0 s_0^i$ with i and k are integers and is a real value > 1 . A practical choice of τ_0 and s_0 consists on setting s_0 to 2 and τ_0 to 1 that is $s = 2^i$ and $\tau = k \cdot 2^i$. This is called dyadic wavelet transform. In this case, the wavelet functions become [22]:

$$\psi_{i,k}(t) = 2^{-i/2} \psi(2^{-i}t - k) \quad (11)$$

Y. Meyer has demonstrated that this setting form of scale and shift parameters constitutes an orthonormal basis for $L^2(\mathbb{R})$ that is [22]:

$$d_{i,k} \equiv \langle f(t), \psi_{i,k}(t) \rangle \equiv \int f(t) \psi_{i,k}(t) dt \quad (12)$$

and

$$f(t) = \sum_i \sum_k d_{i,k}(t) \cdot \psi_{i,k}(t) \quad (13)$$

The DWT consists of applying the discrete signal to a bank of octave band filters based on low and high pass filters $l(n)$ and $h(n)$ respectively; more precisely, the function $f(t)$ would be expressed as follows [23-24]:

$$f(t) = \sum_{k \in \mathbb{Z}} a_L(k) \phi_{L,k}(t) + \sum_{j=1}^L \sum_{k \in \mathbb{Z}} d_j(k) \psi_{j,k}(t) \quad (14)$$

with:

$$d_j(n) = \langle f, \psi_{j,n} \rangle = \sum k g'(2n-k) a_{j-1}(n) \quad (15)$$

$$a_L(n) = \langle f, \phi_{L,n} \rangle = \sum k h'(2n-k) a_{L-1}(n)$$

where $\phi(t)$ is called the scaling function associated to the wavelet function $\psi(t)$ governed by the following condition:

$$\int \phi(t) dt = 1 \quad (16)$$

C. Wavelet Denoising Theory

The underlying model for the noisy signal is basically expressed by [24-26]:

$$s(n) = f(n) + \varepsilon \cdot e(n) \quad (17)$$

Time n is equally spaced. In the simplest model we suppose that $e(n)$ is a Gaussian white noise $N(0, 1)$ and the noise level ε is supposed to be equal to 1. The denoising objective is to suppress the noise part of the signal s and to recover f .

In braking system condition monitoring application, the useful signals are usually in the form of low-frequency signal or signals of more stable, while the

noise signals are usually in the form of high-frequency signals, so we can start on the noisy signal wavelet decomposition, for example, decomposition of three-layer. Wavelet decomposition process of three layers is shown in Fig.9.

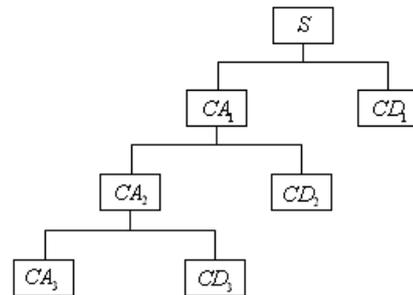


Figure 9. Wavelet decomposition process of three layers

$$\begin{aligned} S &= cA_1 + cD_1 \\ &= cA_2 + cD_2 + cD_1 \\ &= cA_3 + cD_1 + cD_2 + cD_3 \end{aligned} \quad (18)$$

Where, cA_i is approximate part of decomposition, cD_i is decomposition of the detail section, noise usually contained in the detail section, threshold is used for wavelet coefficients processing, through the signal reconstruction we can achieve the purpose of noise reduction.

Choose an appropriate threshold value is the key problem to threshold processing. If threshold value is too small, after denoising, the noise continues to exist. Conversely, if it's too large, some important signal characteristics will be filtered out, causing deviations. Intuitively, for a given wavelet coefficients, noise higher, threshold larger. Majority threshold selection process is for a group of wavelet coefficients, that is, according to a team of statistical properties of wavelet coefficients, calculates a threshold value. Donoho and Jonhstone proposed the universal 'VisuShrink' threshold [24-30]:

$$Thr = \sigma \sqrt{2 \log(N)} \quad (19)$$

In the case of white noise, its standard deviation can be estimated from the median of its detail coefficients (d_j), with $j=1 \dots L$, and is computed by [24-30]:

$$\sigma = \frac{MAD(d_j)}{0.6745} \quad (20)$$

MAD is the median absolute deviation of the corresponding sequence.

Two algorithms of thresholding exist: Hard and Soft. Hard thresholding can be described as the usual process of setting to zero the elements whose absolute values are lower than the threshold. Hard thresholding function is shown by (21).

$$\eta_H(w, t) = \begin{cases} w, & |w| \geq t \\ 0, & |w| < t \end{cases} \quad (21)$$

It is possible to perform non linear denoising by threshold the wavelet coefficients. This allows to better respect the sharp features of the signal.

Soft thresholding is an extension of hard thresholding, first setting to zero the elements whose absolute values

are lower than the threshold, and then shrinking the nonzero coefficients towards 0. Soft thresholding function is shown by [24-34]:

$$\eta_s(w,t) = \begin{cases} w-t, & w \geq t \\ 0, & |w| < t \\ w+t, & w \leq -t \end{cases} \quad (22)$$

The wavelet based denoising process is summarized as follows: the resulting discrete wavelet transform detail coefficients are thresholded by either shrinkage (soft) or crude (hard) strategy. Reconstructing the original sequence from the thresholded wavelet detail coefficients leads to a denoised (smoothed) version of the original sequence. The hard thresholding function and soft thresholding function is shown in Fig. 10.

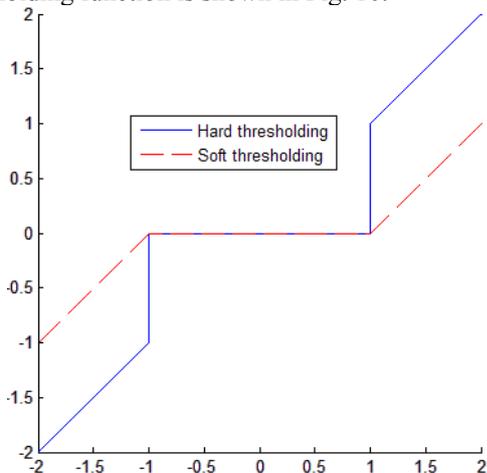


Figure 10. Hard thresholding function and soft thresholding function (Threshold is set to 1)

D. Simulation

The simulation is build in Matlab 7.0. Select signal 'noisbloc' which contains noise as the original signal, using FFT and Wavelet analysis method to denoising the signal. Using wavelet sym8, decomposition level is 5, the results as shown in Fig. 11.

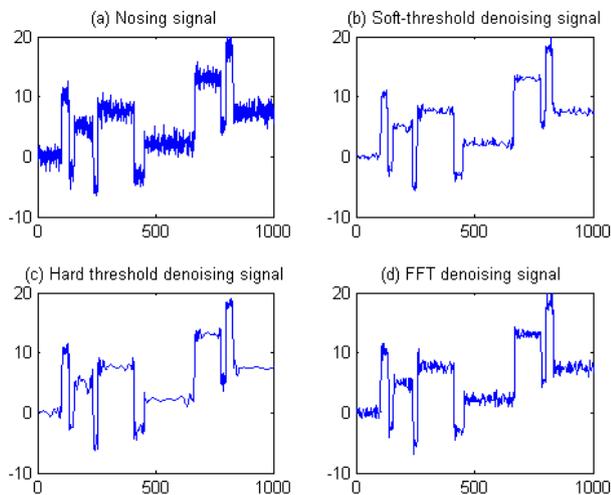


Figure 11. Simulation result

From Fig.11, we can see that denoising using Wavelet analysis much better than the result of Fourier transform, which is due to the Fourier transform can only be expressed in the frequency domain scope, and the coefficient handling method relatively single. While using wavelet decomposition, several method of calculating can be select. On the signal noise suppression, wavelet is more flexible.

For more accurate representation of signal denoising results, we can calculate signal to noise ratio (SNR) and the mean square error (RMSE) of the denoising signal. The RSN and RMSE of several methods of denoising are shown in Table II.

TABLE II.

RSN AND RMSE OF SEVERAL METHOD OF DENOISING			
	rigrsure	sqtwolog	FFT
SNR	41.2376	37.6389	24.9344
RMSE	0.9600	1.1493	2.1692

As SNR of signal is higher, the mean square error between the original signal and denoising signal get smaller, and the denoising signal is closer to the original signal, denoising effects is better.

Table II shows the SNR and RMSE results of three denoising methods, from the result, we can see that the Wavelet analysis denoising results are better than the FFT.

The program is as follows:

```
load noisbloc;
x=noisbloc;
subplot(2,2,1);
plot(x);
title('(a) Nosing signal')
xd=wden(x,'rigrsure','s','sln',5,'sym8');
subplot(2,2,2);
plot(xd);
title('(b) Soft-threshold denoising signal')
p1=1/length(x)*norm(x)^2;
p2=1/length(x)*norm(x-xd)^2;
snr1=10*log(p1/p2)
RMSE1=sqrtm(p2)
xd=wden(x,'sqtwolog','h','sln',5,'sym8');
subplot(2,2,3);
plot(xd);
title('(c) Hard threshold denoising signal')
p1=1/length(x)*norm(x)^2;
p2=1/length(x)*norm(x-xd)^2;
snr2=10*log(p1/p2)
RMSE2=sqrtm(p2)
wc=0.3;
N=5;
[b,a]=butter(N,wc);
xd=filter(b,a,x);
subplot(2,2,4);
plot(xd);
title('(d) FFT denoising signal');
p1=1/length(x)*norm(x)^2;
p2=1/length(x)*norm(x-xd)^2;
snr3=10*log(p1/p2)
RMSE3=sqrtm(p2);
```

V. CONCLUSION

(1) The braking system is designed to work at two braking modes: service braking and emergency stop/safety braking. In case of emergency, the butterfly spring will generate positive braking pressure and arrest the fall of the elevator car.

(2) Through the inspections of the air gap, hydraulic pressure and disc spring pressure, we can detect some early stage faults in the elevator braking system, which can protect the rope-less elevator safe and stable operation.

(3) Air gap inspection selects linear transducer. The V-I converting circuit convert the voltage signal into 4~20mA current signal, which has strong anti-interference ability.

(4) De-noising method with wavelet theory was applied to dispose the sampling signals. Wavelet denoising is much better than the result of Fourier transform.

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