The auto-monitoring of geo-technical centrifuge operating state based on weighted data fusion

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Abstract—There are many parameters which could reflect the operating state of geotechnical centrifuge. However, only one parameter is detected generally; this is insufficient and unsafe for the running of the geotechnical centrifuge. This paper put forward an auto-running state monitoring method which is based on the multi-parameters’ weighted data fusion. The way by multi-sensor acquiring the running state data of the geotechnical centrifuge, then processing the data with weighted data fusion could produce the comprehensive running state parameter, which feed forward to the control system to keep the equipment running in a safe manner. The method in this paper could be implemented automatically and the result for safety monitoring is sufficient, the effect is much more efficient.

1. Introduction
The geotechnical centrifuge modeling Earth gravity with inertial force, could be used by putting a 1/n size model on the swing bucket of the centrifuge which will give a n times acceleration of the earth, to study the stress state and strain state of foundations which is always grand in volume and subjected to gravity. The centrifugal test is very useful to the geotechnical structure design and geo-mechanics study.

The running safety monitoring is done by sensors which are used widely in industrial equipments, but the auto-warning systems are not used[3]. For the geotechnical centrifuge, the operating safety state monitoring of the geo-centrifuge is mainly done by detecting the unbalance of the revolving arm. The unbalance sensed by two groups of force transducer which fixed equally in distance with the spindle in one line was calculated to reflect the centrifuge balance state, then it was compared with the unbalance threshold, to estimate the safety state. In addition to the unbalance monitoring, video monitoring is always used as a compensational way for the running safety monitoring which is exhausting for its concentration needed and the decision making timely by the watching worker.

When geo-centrifuge running, the revolving speed is high, and load is heavy, once there is any trouble, it will lead to unsafe consequences even catastrophe, so the auto-monitoring of the operating state is necessary. For the condition of the monitoring parameters’ number is low with a lower automation level, this paper put forward a way monitors more parameters which processed by data fusion to achieve the automatic state monitoring, then keep the geo-centrifuge running safe mostly.

2. Geo-centrifuge running monitoring model
Geo-centrifuge is often running with heavy testing sample often several hundred kilograms(even tons) in a high g level(e several hundrad gs) centrifugal field, which featured by unbalance force, high
spindle revolving speed and the arm’s high structure stress intensity, sometimes companied by the whole structures vibration. One of the above parameters exceeds its threshold for a safety running case may cause catastrophe, then geo-centrifuge running state monitoring is necessary.

The operating state monitoring could be conducted by monitoring parameters such as: structure stress, balance state, operating state, the base vibration and revolution speed which is used as a benchmark for state recording. The geo-centrifuge running safe monitoring scheme is showed in figure 1.

![Figure 1. Geo-centrifuge running state monitoring scheme](image)

Figure1. Geo-centrifuge running state monitoring scheme

The structure stress is usually measured by strain gauges bonded on the surface of the structure. For effective measuring, a full bridge circuits is recommended\(^4\), and temperature compensate strain gauge in the measuring circuits must be included; and to reduce the line resistance the whole line should be as short as possible.

Unbalance monitoring is usually conducted by two groups of force sensors fixed between the arm and the spindle in a radial line\(^5\)(as showed in figure 3). When the centrifuge is running, each group of the force sensors will measure a radial force in one side, then the difference of the two groups of forces is the unbalance in the g level which reflects the unbalance state. In order to detect the unbalance correctly, the force sensors should be pre-loaded appropriately avoiding gap growth in the centrifuge running. For a certain detecting condition the force sensors chosen are a compromise of its accuracy and range.

Operating state often means the running state of the geotechnical centrifuge, which is monitored directly by high speed filming and then helps the operators determined whether the centrifuge state is normal or not. Video monitoring’s importance is never emphasized too much, for a loosen nut may flyed away and penetrated some steel plate even it happened scarcely. In the other hand the state monitoring video record is always used to playback to check the testing program as a auxiliary anlysis way.

The base vibration is usually a result of many things such as the characteristic frequencies and its modal, the residual balance forces, and the base mounting inclination errors and so on. The much intense the much danger of the centrifuge, so the base vibration is detected by sensors. A vibration sensor choose must have a greater frequency range than the running frequency.

The last monitoring parameter is the revolving speed which is fundamental and determines the other four parameters, and is always used as a background for the other four parameters interpretation.

3. Geo-centrifuge state monitoring data fusion model

Each kind of the geo-centrifuge monitoring signals only reflect one aspect of its state, and the whole state is unknown. In the other hand, effective state estimation is usually subjected to comprehensive
estimation of multi-parameters. The multi-parameters comprehensive estimation must be data fused to get comprehensive result reflecting the equipment’s running state. The geo-centrifuge state estimation could be conducted by the scheme in figure 2.

Recently, there are many data fusion methods, but for different kinds of data, weighted summation is a useful and effective way. All the geo-centrifuge monitoring data could be processed by weighted summation[6]. There are three steps for weighted data fusing.

![Figure2. Geo-centrifuge running state estimation scheme](image)

Firstly, the signals from the sensors will be preprocessed. The short time sliding window could be used to process the structure stress and the arm unbalance signals; the wavelet transformation is used to process the vibration signal, then the amplitude of the vibration, frequency and phase will be extracted fully. For the running state signal, image processing will be conducted to find the main profile change of the centrifuge and container system.

Secondly, all the signals will be threshold normalized, which means that each signal is divided by its threshold, as for the input date for the fusion. Formula (1) is the threshold normalization method.

\[
S_i(t) = \frac{S_i(t)}{S_{0i}}, \quad i = 1, \ldots, n
\]  

In which, \(S(t)i\) is the signal detected by sensor, \(S0i\) is the signal threshold for a safe state. The material yield strength is recommended for the threshold value of stress monitoring; the unbalance threshold which came from other geotechnical centrifuge and its structure is used for threshold; and structure maximum displacement allowed is threshold of running state signals; and the vibration speed and displacement in common operating is the threshold for vibration.

Thirdly, summarizing all the normalized state parameters to get a geo-technical centrifuge operating state parameter by formula (2).

\[
\bar{S}(t) = \sum_{i=1}^{n} w_i \times \frac{S_i(t)}{S_{0i}}
\]  

In which, \(w_i\) is the weight factor, which is subjected to formula (3).

\[
\text{if } \bar{S}(t)_i < 1 \text{ then } \begin{cases} \sum_{i=1}^{n} w_i < 1 \quad \text{or else } \bar{S}(t)_i \geq 1 \text{ then } w_i = 1 \end{cases} \quad (i = 1, \ldots, n)
\]  

By formula(1) ~ (3), if \(0 < \bar{S}(t) < 1\), it indicates the geo-centrifuge is running normally, and the value is feed forward to the central control system, the running equipment will not be paused or interrupted. However, if \(\bar{S}(t) \geq 1\), it indicates an abnormal of the running state, the central control system will stop the running geo-centrifuge as soon as it gets the value immediately, to keep things all right.

In addition, for \(0 < \bar{S}(t) < 1\) condition, if \(0.8 < \bar{S}(t)_i < 1\) (\(i = 1, \ldots, 5\)), it means some parameters will meet their thresholds and a narrow safety margin, the state of the geo-centrifuge will be under close watch. In this condition, maybe a yellow alarm flash is a good idea.
4. Analysis of the geo-centrifuge running state monitoring

4.1. Layout of the geo-centrifuge sensors

The structure of the geo-centrifuge under testing is in figure 3. The testing sample is on the swing bucket hinged in the end of the revolving arm, the main spindle drives the arm revolving to produce the acceleration. In the process, the inertial load of the sample exerted on the bucket then by the arm to the foundation. So the structure stress detection is often carried out by strain gauge on the high stress parts (like arm and buckets) or on a inspection easy structure then interpolated to the concerned location, the real time strain reflects the stress indirectly.

Running state monitoring of the geo-centrifuge is done by high speed filming cameras fixed in the container wall, which film the system of the centrifuge and the container, the output is the running state signal, i.e. running video.

The unbalance force is crucial for a long time running safety, which could be calculated by the difference of the radial force detected between the main spindle and the arm.

Many things could make geo-centrifuge vibrate, in order to know its reason vibration detecting is used and vibration sensors are fixed near the bearings within the base, which outputs the vibration velocity, and then deduced vibration position and vibration acceleration.

4.2. State monitoring model of geo-centrifuge

Geo-centrifuge running state estimation model is showed in figure 4. As mentioned above, the arm stress, bucket stress, running state signal, base vibration and unbalance signals are vital and chosen for geotechnical centrifuge safety estimation.
Figure 4. Geo-centrifuge running state estimation model

Table 1. Signal weight factors and running threshold values

| No. | Weight factors $w$ | Threshold values $S_0$ |
|-----|-------------------|------------------------|
| 1   | 0.3               | 600MPa (34Cr2Ni2Mo) $^{[7][8]}$ |
| 2   | 0.3               | 690MPa (Q690) $^{[9]}$ |
| 3   | 0.0851            | 15mm                   |
| 4   | 0.15              | 2.5mm/s $^{[10]}$      |
| 5   | 0.165             | 10 ton                 |

The stress threshold is the material yield stress, for a certain centrifuge, the materials of arm and swing bucket could be 34Cr2Ni2Mo and Q690 respectively, then their yield stresses are 600MPa and 690MPa according heat treatment status by the standard. The threshold value of running state is the profile change which is chosen 15mm. And the base vibration is the vibration speed which is 2.5mm/s from the standard. For the unbalance it is from experience and the value is 10 ton. The weight factors reflect the importance of the parameters, then its contribution to the running safety is considered. The weight factors and threshold values showed in table 1.

Running the geo-centrifuge in 4 different conditions we acquired four groups of data from different sensors which reflects the running state of the equipment, showed in table 2.

Using formula (1) ~ (3) to processing the data, the results listed in table 3.

The last column in table 3. listed the state parameters of each running condition. We can see that case 1,2,3 are the safe running, but with base vibration velocity reaches 2.2mm/s which near the threshold value 2.5mm/s, case 4 is a unsafe condition. Moreover, the fused state parameter of case 3 is 0.826(dimentionless) exceeded 0.8 means that the running condition should be taken care. If we go back to analyze the sensors data, we could find that the detected five parameters are all close to the threshold. As we said the equipment is safe but you’d better keep one eye on it.

Table 2. State parameter of the running geo-centrifuge

| No. | Arm Stress(MPa) | Bucket Stress(MPa) | Running State(mm) | Base Vibration(mm·s$^{-1}$) | Arm Unbalance(ton) |
|-----|----------------|-------------------|-------------------|-----------------------------|-------------------|
| 1   | 320            | 400               | 1.5               | 1.8                         | 6                 |
| 2   | 200            | 300               | 3.2               | 1.3                         | 2                 |
| 3   | 500            | 560               | 12                | 2.2                         | 8                 |
| 4   | 160            | 200               | 6                 | 3                           | 8                 |
5. Conclusion

This paper put forward the requirement for the geo-centrifuge running state monitoring, then developed the strategy of the state estimation and parameter data fusion model; after this, sensors layout of the detection is provided with its structure. At last, the method is verified by analyzing the date with an example. All the work shows that the data fusion model is effective and the automatic state monitoring is feasible.

Acknowledgments

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