Case Study of the Excessive Vibration of the Medium and High Speed Motors in Circulating Water Filtration System

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Abstract. In one Chinese nuclear power plant, the problem of excessive vibration of medium and high-speed motors (MHMs) in the Circulating Water Filtration System (CFI) frequently occurred during the reactor power operation level. Excessive motor vibration caused the motors to trip, further causing the CFI to shut down automatically. Through a series of theoretical studies and experimental demonstrations, this paper finds out the root cause of excessive vibration of MHMs. The reason is that there are defects in the design and installation of motors, and the motors' installation methods do not meet the operating requirements. To solve the problem, we designed a support frame with adjustable supporting forces and determined its optimal supporting force through a large number of experiments. Compare the motors' vibration data before and after the installation of the support frame, and it can see that the support frame fundamentally solves the problem of high vibration of MHMs, and improves the reliability and safety of the units. The support frame designed in this paper also provides a good demonstration of solving similar problems.

1. Introduction

The function of the Circulating Water Filtration System (CFI) is to filter all the seawater the nuclear power plants requiring and to prevent the system equipment of seawater-using system from blockage and biological corrosion[1]. The CFI of each unit has two seawater inlet circuits, each of which has a cylindrical rotating filter, which called a drum-type filter with three speeds. Seawater flows from the inside to the outside of the drum-type filter. The filtered seawater is drawn out by the pumps of other systems.

The drum-type filter is driven by two low-speed motors (one of which is spare) or one medium and high-speed motor with the same deceleration drive mechanism. The driving mechanism drives the drum-type filter through the meshing gear on the outer back of the drum-type filter to rotate[2]. Each drum-type filter is equipped with an ultrasonic water level difference gauge and two pressure-sensitive water level difference gauges. The water level difference gauge monitors the pressure difference between the inside and outside of the drum-type filter and controls its rotating speed. The higher pressure difference between inside and outside of the filter screen, the higher clogging rate of the filter screen will appear. When the pressure difference reaches the limit, the pump of the circulating water system will be shut down to prevent the pressure difference from further increasing and protect the filter from deforming under the action of the higher pressure difference [3].
The drive gearbox of the drum-type filter is composed of worm gears and worms, and the deceleration drive mechanism of CFI is composed of three gearboxes [4]. Among them, two identical primary gearboxes are installed at the upper and lower ends of the transmission shaft of the secondary gearbox. The secondary gearbox is installed on the drive shaft of the drum-type filter. The lower primary gearbox is connected to two low-speed motors (LSMs), and the upper primary gearbox is connected to the medium and high-speed motor. When any one of motors is working, the three gearboxes (two primary and one secondary gearboxes) will run. The installation form of the motors and gearboxes is shown in Figure 1[5].

![Diagram of motors and gearboxes installation](image)

**Figure 1.** The motors and gearboxes installation diagram of drum-type filter.

The equipment operation manual specifies the technical parameters of the drum-type filter motor during normal operation, as shown in Table 1. It can be seen that the motor's allowable vibration limit value is 18 mm/s. In February 2016, we discovered during the test of Unit 1 that when the drum-type filter was rotating at medium speed, the vibration of the MHM was high. Through measurement, we found that the maximum vibration value of the LSM was 8 mm/s, and the maximum vibration value of the MHM was 24 mm/s. In April 2016, the drum-type filter was in the state of medium speed operation. We once again measured the motor's vibration value. And the MHM's vibration value was 23 mm/s. Subsequently, we measured the CFI motor's vibration value of each unit. The measurement results show that the vibration value of each MHM does not meet the requirements of Table 1. In this context, when the unit 1 of the power plant was operating at full power in June 2017, the two LSMs were overloaded and tripped one after another, causing the drum-type filter to stop operating.

It can be seen that excessive vibration of MHM will increase the operational risk of nuclear power plants, which is not conducive to the safe operation of power plants. Therefore, it is very important to analyze the causes of excessive vibration of MHM and to solve the problem.

| Drum-type filter | Motors         | Vibration limit | Noise  | Starting current | Operating current |
|------------------|----------------|-----------------|--------|------------------|-------------------|
|                  | 001MO/007MO   | <18mm/s         | <66dB  | √51A             | √17A              |
| 031TF            | 003MO         | <18mm/s         | <78dB  | --               | √18.5A            |
|                  | 005MO         | <18mm/s         | <78dB  | --               | √36A              |
| 031TF            | 002MO/008MO   | <18mm/s         | <66dB  | √28.8A           | √12A              |
2. Problem analysis
To solve the problem of excessive vibration values of MHMs, this nuclear power plant has taken a series of measures to seek the cause. After dismantling the reduction gearboxes of the drum-type filter, we found that the worm's bearings of the gearboxes have been severely damaged. In this section, this paper seek the cause of the excessive vibration value of the motors by analyzing the causes and consequences of bearings damage.

2.1. Bearing damage description
We observed the disassembled gearboxes and found that the cage and the inner ring raceway of the worm bearing close to the MHM were partially broken, and a small amount of bearing balls were missing. Part of the surface of the existing bearing ball peeled off. At the same time, it was found that some metal powder adhered to the surface of the worm gears. Compared with a complete bearing, about one-third of the material in the damaged inner ring was missing. The upside of the outer ring raceway has a peeling phenomenon on the entire ring, and partial material was missing. The inner ring raceway has a peeling phenomenon on the downside of the entire ring. See Figure 2 and Figure 3 for the details of bearing damage on the upper end of the worm. According to preliminary analysis, the direct cause of excessive vibration of MHMs in CFI is caused by the damage of the gearbox bearing.

![Figure 2. Damage details of bearing cage.](image)

![Figure 3. Damage details of bearing raceway.](image)

2.2. Analysis of the bearing damage
In this section, the cause of bearing damage is found through a force analysis of the bearing. It can be seen from Figure 1 that the rear end of the MHM lacks supports, and its weight is directly borne by the primary gearbox of the reducer. We conducted a force analysis on the upper bearing of the worm gear, and the analysis schematic diagram is shown in Figure 4. After analyzing the bearing force, we also analyzed the interaction force between the bearing ball and the bearing raceway. The schematic diagram is shown in Figure 5.

The direction of connection of point A and B in Figure 4 is the radial direction of the upper bearing, which is the same as the axial direction of MHM. The installation method of MHM determines that its and the primary gearbox's gravity acts on the upper bearing, so that point B is subjected to downward force. According to the principle of leverage, point A bears upward force. Under the action of these two opposing forces, the outer ring of the upper bearing tilts. At this time, the plane of the bearing will no longer be perpendicular to the worm gear shaft.
In Figure 5, $F_2$ and $F_3$ are the forces of the bearing balls acting on the outer ring raceway, and $F_4$ and $F_5$ are the forces of the bearing balls acting on the inner ring raceway. $F_{2z}$, $F_{2r}$, $F_{3z}$, $F_{3r}$, $F_{4z}$, $F_{4r}$, $F_{5z}$, $F_{5r}$ are their axial and radial component forces, respectively. The inner ring of the bearing rotates together with the worm gear shaft. During the rotation, the inner and outer rings of the upper bearing bear alternating loads. Because the bearing force direction changes continuously, the bearing is unevenly stressed. Uneven bearing forces can cause excessive vibrations in MHM during operation. The vibration of MHM aggravates the uneven stress on the inner and outer rings of the bearing. Under the effect of this vicious circle, the worm gear bearing suffered fatigue damage. The damage of the bearing caused the motor to trip, which caused the stop of drum-type filter and other events.

![Figure 4. Bearing force analysis.](image)

![Figure 5. Bearing ball force analysis](image)

By observing the damage traces of the inner and outer ring raceways of the bearing, it can be found that the peeling traces of the inner ring raceway of the upper bearing develop upward and gradually deepen in the circumferential direction, and the traces of the outer raceway gradually develop downward in the circumferential direction, and the damage at point A is the most serious. The damage of the bearing is consistent with the results of the bearing force analysis, which shows the correctness of our analysis.

3. Solution
The previous analysis shows that the uneven force on the upper bearing during the operation of the drum-type filter causes the bearing to break under the action of alternating loads, which causes the vibration of MHM to exceed the standard. The uneven force is caused by the cantilever installation method of MHM. Therefore, we can get that the fundamental reason for the CFI's outage is that the design and installation structure of MHM is unreasonable[6].

To solve this problem, we need to change the installation form of MHMs. Our starting point is taking measures to increase the verticality of the MHM's shaft and the worm gear shaft of the gearbox as much as possible and to improve the uneven stress of the bearing[7]. To this end, this paper proposes a solution which is increasing a motor support frame to achieve the purpose of reducing motor vibration.

3.1. The form of the support frame
Considering the reason for motor vibration, the support we designed must not only support motors but also absorb the motor vibration, so as to further improve the uneven stressed bearing condition. The form of the support frame designed in this paper is shown in Figure 6.

The component 6 in Figure 6 is a Belleville spring, which is the core component of the support frame. Belleville springs can withstand great loads in a small space. Compared with other types of springs, the Belleville spring has a larger deformation energy per unit volume and has an excellent shock absorption capacity. Especially when the superimposed combination is used, the ability of the
Belleville spring on absorbing impact and dissipating energy will be more outstanding due to the effect of surface friction resistance[8]. This support frame adopts 24 Belleville springs, which are divided into four groups, and each group is installed in a superimposed combination[9].

**Figure 6.** Motor support frame plan and three-dimensional map.

This support can provide an adjustable vertical support force by adjusting the amount of compression of the Belleville spring by adjusting the nuts[10]. The difference in the installation method makes the vibration of the motors different. Therefore, the optimal supporting force required when the vibration of each motor is minimum is different. This paper will find the optimal supporting force for each motor through experiments. The experiment process will be shown in section 3.2.

3.2. Experiment process

3.2.1. Experimental principles: The weight of MHM is 151Kg, so the upper limit of the supporting force set in this experiment is 1510N. First, measure the vibration value of MHM when there is no external supporting force, and then increase the supporting force of equal magnitude in sequence. After adjusting the support force each time, record and analyze the changing trend of the vibration value of the motors and gearboxes. When the vibration value of the motors and gearboxes is the smallest, the corresponding external supporting force is the optimal supporting force.

3.2.2. Method of applying external supporting force: In the normal operation state of the drum-type filter, use the sling to lift MHM upwards. The height of the motor tail lifted corresponds to the magnitude of the supporting force applied by the sling. The tension force on the sling is indicated by a spring scale. After increasing the force by 100N each time, measure the vibration value of the motor and gearbox.

3.2.3. Experimental data: The vibration data of different devices under different supporting forces are recorded in Table 2 to Table 8. It should be noted that the unit of vibration value is mm/s.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|-------------------|----------------------------|------------------------|
|                  | Horizontal (H1) | Vertical (V1) | Horizontal (H2) | Vertical (V2) | Axial (A2) | Horizontal (H3) | Vertical (V3) | Axial (A3) | Horizontal (H4) | Vertical (V4) | Axial (A4) |
| 0 Kg             | 1.88                 | 1.17              | 1.37                   | 0.73              | 1.01       | 1.17                | 1.06        | 1.11       | 0.51                | 1.07        | 1.40        |
| 30 Kg            | 1.70                 | 0.37              | 1.62                   | 0.53              | 1.09       | 0.57                | 0.80        | 0.47       | 0.71                | 0.10        | 0.83        |
| 40 Kg            | 2.2                  | 1.25              | 1.57                   | 1.05              | 1.28       | 0.89                | 0.66        | 1.20       | 0.51                | 1.05        | 1.12        |
| 60 Kg            | 2.07                 | 0.93              | 1.44                   | 0.56              | 1.27       | 1.02                | 0.91        | 1.10       | 0.67                | 1.10        | 1.23        |

Table 2. The vibration value of 1CFI031TF.
### Table 3. The vibration value of 1CFI032TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|----------------------------|------------------------|
|                  | Horizontal (H1) Vertical (V1) | Horizontal (H2) Vertical (V2) | Horizontal (H3) Vertical (V3) | Horizontal (H4) Vertical (V4) Axial (A4) |
| 0kg              | 0.69 0.57             | 0.39 0.37          | 0.51 0.28                 | 0.37 0.24               |
| 10kg             | 0.54 0.40             | 0.27 0.58          | 0.46 0.24                 | 0.52 0.29               |
| 20kg             | 1.05 0.63             | 0.52 0.35          | 0.87 0.32                 | 0.53 0.32               |
| 30kg             | 0.65 0.71             | 0.65 0.62          | 0.32 0.37                 | 0.28 0.29               |
| 40kg             | 1.00 0.45             | 0.70 0.67          | 0.83 0.37                 | 0.20 0.29               |
| 50kg             | 0.90 0.65             | 0.65 0.55          | 0.62 0.37                 | 0.23 0.29               |

### Table 4. The vibration value of 2CFI031TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|----------------------------|------------------------|
|                  | Horizontal (H1) Vertical (V1) | Horizontal (H2) Vertical (V2) | Horizontal (H3) Vertical (V3) | Horizontal (H4) Vertical (V4) Axial (A4) |
| 0kg              | 1.49 0.42             | 0.65 0.35          | 0.59 0.27                 | 0.47 0.39               |
| 10kg             | 1.09 0.30             | 0.59 0.26          | 0.28 0.21                 | 0.47 0.35               |
| 20kg             | 1.46 0.25             | 0.71 0.26          | 0.54 0.21                 | 0.45 0.26               |
| 30kg             | 0.99 0.35             | 0.65 0.55          | 0.51 0.20                 | 0.28 0.24               |
| 40kg             | 1.90 0.45             | 0.70 0.67          | 0.47 0.30                 | 0.28 0.29               |
| 50kg             | 1.55 0.32             | 0.90 0.27          | 0.45 0.32                 | 0.27 0.23               |

### Table 5. The vibration value of 2CFI032TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|----------------------------|------------------------|
|                  | Horizontal (H1) Vertical (V1) | Horizontal (H2) Vertical (V2) | Horizontal (H3) Vertical (V3) | Horizontal (H4) Vertical (V4) Axial (A4) |
| 0kg              | 0.46 0.24             | 0.47 0.38          | 0.49 0.35                 | 0.44 0.36               |
| 10kg             | 0.65 0.36             | 0.46 0.42          | 0.58 0.35                 | 0.42 0.38               |
| 20kg             | 0.66 0.37             | 0.70 0.48          | 0.37 0.27                 | 0.46 0.38               |
| 30kg             | 0.68 0.37             | 0.59 0.59          | 0.66 0.37                 | 0.35 0.26               |
| 40kg             | 0.62 0.36             | 0.59 0.59          | 0.66 0.37                 | 0.35 0.26               |
| 50kg             | 0.58 0.51             | 0.65 0.35          | 0.42 0.51                 | 0.37 0.26               |

### Table 6. The vibration value of 3CFI031TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|----------------------------|------------------------|
|                  | Horizontal (H1) Vertical (V1) | Horizontal (H2) Vertical (V2) | Horizontal (H3) Vertical (V3) | Horizontal (H4) Vertical (V4) Axial (A4) |
| 0kg              | 1.54 0.51             | 1.30 0.48          | 0.54 0.45                 | 0.52 0.24               |
| 10kg             | 1.21 0.54             | 0.92 0.46          | 0.35 0.25                 | 0.58 0.37               |
| 20kg             | 1.09 0.54             | 0.73 0.53          | 0.70 0.35                 | 0.47 0.40               |
| 30kg             | 0.83 0.14             | 0.13 0.17          | 0.41 0.13                 | 0.46 0.31               |
| 40kg             | 1.37 0.68             | 0.78 0.50          | 0.53 0.47                 | 0.60 0.48               |
| 50kg             | 1.17 0.53             | 0.78 0.41          | 0.48 0.55                 | 0.61 0.46               |

### Table 7. The vibration value of 4CFI031TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|----------------------------|------------------------|
|                  | Horizontal (H1) Vertical (V1) | Horizontal (H2) Vertical (V2) | Horizontal (H3) Vertical (V3) | Horizontal (H4) Vertical (V4) Axial (A4) |
| 0kg              | 0.40 0.50             | 0.60 0.40          | 0.50 0.20                 | 0.20 0.20               |
| 10kg             | 0.46 0.47             | 0.58 0.45          | 0.40 0.26                 | 0.23 0.20               |
| 20kg             | 0.55 0.49             | 0.55 0.38          | 0.41 0.23                 | 0.26 0.20               |
| 30kg             | 0.50 0.41             | 0.53 0.38          | 0.29 0.22                 | 0.24 0.20               |
| 40kg             | 0.51 0.45             | 0.65 0.43          | 0.23 0.28                 | 0.26 0.21               |
| 50kg             | 0.53 0.40             | 0.41 0.43          | 0.45 0.30                 | 0.27 0.24               |
To observe the influence of the supporting forces on the motor vibration value facility, we have plotted the vibration value trend with the change of the supporting force, and shown in Figure 7 to Figure 13.

Table 8. The vibration value of 4CFI032TF.

| Supporting force | Non-driving end of MHM | Driving end of MHM | Non-driving end of gearbox | Driving end of gearbox |
|------------------|------------------------|--------------------|---------------------------|-----------------------|
|                  | Horizontal (H1) | Vertical (V1) | Horizontal (H2) | Vertical (V2) | Axial (A2) | Horizontal (H3) | Vertical (V3) | Axial (A3) | Horizontal (H4) | Vertical (V4) | Axial (A4) |
| 0kg              | 2.85                  | 1.34               | 1.75                    | 0.95                | 1.50          | 0.62           | 0.48          | 0.72          | 0.90          | 0.50          | 0.55          |
| 10kg             | 2.50                  | 1.37               | 2.00                    | 1.10                | 1.87          | 0.68           | 0.52          | 0.74          | 1.10          | 0.65          | 0.63          |
| 20kg             | 2.65                  | 1.10               | 1.97                    | 0.89                | 1.87          | 0.63           | 0.51          | 0.69          | 0.92          | 0.62          | 0.82          |
| 25kg             | 2.85                  | 1.34               | 1.75                    | 0.95                | 1.50          | 0.62           | 0.48          | 0.72          | 0.90          | 0.50          | 0.55          |
| 30kg             | 2.85                  | 1.24               | 2.40                    | 0.86                | 2.20          | 0.72           | 0.67          | 0.74          | 0.94          | 0.51          | 0.78          |
| 40kg             | 2.85                  | 1.92               | 1.99                    | 0.93                | 1.75          | 0.78           | 0.58          | 0.79          | 1.23          | 0.55          | 0.63          |
| 50kg             | 2.70                  | 1.42               | 2.58                    | 0.93                | 2.15          | 0.55           | 0.46          | 0.82          | 1.25          | 0.47          | 0.76          |

Note: 1 CFI 031 TF

Unit No. System Code Equipment No. Equipment Code

Figure 7. Vibration value of 1CFI031TF.

Figure 8. Vibration value of 1CFI032TF.

Figure 9. Vibration value of 2CFI031TF.

Figure 10. Vibration value of 2CFI032TF.

Figure 11. Vibration value of 2CFI031TF.
Through above pictures, we can record the supporting force when the vibration of the motors and gearboxes is small. Then use this value as the basis for adjusting the amount of compression of the belleville spring. The optimal supporting force adopted in this paper is listed in Table 9.

Table 9. Optimal supporting force.

| Unit No. | Supporting force of 031TF(kg) | Supporting force of 032TF(kg) |
|----------|-----------------------------|-----------------------------|
| 1        | 30                          | 30                          |
| 2        | 30                          | 30                          |
| 3        | 30                          | /                           |
| 4        | 30                          | 25                          |

3.3. Installation requirements about support frame

After determining the optimal supporting force of each MHM, we give the specific method of support frame installation in this section. The support frame in this paper provides the supporting force shown in Table 9 through the compression of the Belleville spring. Therefore, the key point for the installation of the support frame is the determination of the compression of the Belleville spring. The main points for support frame installation are given below.

- The three longer longitudinal beams are fixed on the ground by anchor bolts, and the shorter longitudinal beam is placed on the driving motor platform directly. A rubber pad is added between the longitudinal beam and the platform to prevent mutual sliding.
- Support frame installation sequence: First install the frame (component 1) in Figure 6, the angle steel that constitutes the frame is fixed by bolt connectors (component 2). Second, install the primary motor base plate (component 3). Third, put the Belleville springs (component 9) on the stud bolts (component 5), and finally install the secondary motor base plate (component 4).
- Adjust the compression of the disc spring: First set the lifting weight of the spring scale to the corresponding value in Table 9, and then use the spring scale to lift the tail of MHM. During the lifting process, the indication of the spring scale will gradually decrease. At this time, slowly tighten the Belleville springs’ adjusting nuts (component 8). When the scale of the spring scale is reduced to 0, stop tightening the adjusting nuts.
- The MHMs are in contact with the primary motor base plate through rubber pads. The rubber pad not only prevents the rigid contact between the motor and the steel plate from wearing the motor heat sink but also has the function of absorbing the vibration of the motors.

4. Conclusions

Through a series of analyses, this paper finds out the fundamental cause of excessive vibration of MHMs, which is the cantilever installation method of MHMs causes the motor to lack sufficient support during operation. In order to solve this problem, we propose to install support frames with the adjustable supporting force for the motors. In this paper, we conducted a large number of vibration measurement experiments. Experimental data shows that after installing the support frames, the
The vibration of MHMs have been improved largely, and the vibration index is qualified. The scheme dramatically improves the operation safety and reliability of nuclear power plants and provides a good demonstration for solving the similar problems of other power plants.

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