Research and Improvement on Characteristics of Emergency Diesel Generating Set Mechanical Support System in Nuclear Power Plant

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Abstract. There are often mechanical problems of emergency power generation units in nuclear power plant, which bring a great threat to nuclear safety. Through analyzing the influence factors caused by mechanical failure, the existing defects of the design of mechanical support system are determined, and the design idea has caused the direction misleading in the field of maintenance and transformation. In this paper, research analysis is made on basic support design of diesel generator set, main pipe support design and important components of supercharger support design. And this paper points out the specific design flaws and shortcomings, and proposes targeted improvement program. Through the implementation of improvement programs, vibration level of unit and mechanical failure rate are reduced effectively. At the same time, it also provides guidance for design, maintenance and renovation of diesel generator mechanical support system of nuclear power plants in the future.

1. Introduction
Nuclear power plant has a high reliability of power system and each unit is equipped with two emergency diesel alternating current power supply as the backup. When the plant unit bus line causes a power failure due to the main power supply outside power plant or failure of bus line, the emergency diesel generator set will provide power supply for safety system and equipment of power plant within 10 seconds so that the power can be provided to safety system and equipment of power plant in time and guarantee emergency safety shutdown of reactor to prevent the damages of important components caused by the power failure of power system, especially it can prevent the core melting accident from occurring.

Nuclear power plant emergency diesel generator set often has mechanical failures, which seriously affects safety and reliability of emergency power supply in power plant; and as reciprocating power machinery, the complexity, diversity and non-linearity of this system determines the fault diagnosis and processing difficulties. The power plant hopes to further study the vibration performance of diesel engine and reduce the mechanical failure rate of unit, so that the relevant important equipment and accessories generally achieve a good running state to eliminate the adverse factors caused by failure factors.
2. Analysis of Main Mechanical Faults of Diesel Engine and Overview of Support System

After various mechanical faults of diesels in nuclear plant are sorted and analyzed, it is found that a large number of mechanical faults are related to the severe vibration of its components. And the factors that cause severe vibration include two factors, unit body and design of support system.

Through the overall dynamic test of unit, according to GB/T10397-1989 Small and Medium-power Diesel Vibration Rating Standards and GB/T6075.6-2002 (or ISO10816-6: 1995) mechanical vibration —evaluating of machine vibration by measurements on non-rotating parts —part 6: reciprocating machines with power ratings above 100kW "standard. Through the analysis of the data, the final conclusion shows that the vibration level of the diesel engine body should be in the A / B area specified by national standard, which belong a good level, thus the diesel engine would have the capacity to run for a long time.

Considering the nuclear safety design, nuclear power plant emergency diesel generator set must be isolated from the outside world, to avoid external factors as much as possible such as earthquake. Therefore, it is required that there should be isolation design which is independent of surrounding environment for main support systems including foundation support, pipe support, equipment accessories support. The support system design and installation failure are the main factors in causing mechanical failures.

Study is made on the design and performance of the support system of the emergency diesel generator set in a nuclear power plant of China General Nuclear Power Group with analysis on three factors including base, typical equipment support and the pipeline support.

3. Research on Base Characteristics of Diesel

The vibration isolation should be taken into consideration of the base design of heavy duty diesel generator. On the one hand, it should be avoided transmitting dynamic loads to external surroundings during the operation, which could cause the base sink:On the other, decoupling from the external interference should be designed to protect the unit from the damage caused by the earthquake and so on. The simple mechanical model of the diesel generator set is shown as Figure 1.

![Figure 1. Diesel generator mechanics model](image_url)

Assuming that the exciting force is a sine function, its absolute transfer rate (or transfer coefficient) is expressed as follows:

\[ \eta_A = \frac{U}{A} = \frac{F_T}{F_0} = \frac{1 + 4\xi^2(\lambda^2)}{(1 - \lambda^2)^2 + 4\xi^2}\lambda^2 } \]

(1)

\(A\) is the amplitude of the device \(m\); \(U\) is the base amplitude; \(F_T\) is the dynamic load transmitted to the foundation base after vibration isolation; \(F_0\) is the exciting force of the device; \(K\) and \(C\) represent the
elastic and damping elements respectively: $\xi$ is damping factor of system; $\lambda$ is the frequency ratio, that is, the avoidance degree of equipment operating speed $\omega$ and the critical speed and other natural frequencies (frequency ratio).

The mechanical support design of diesel engine unit in nuclear power plant is based on the above mechanical model. The support system made of springs and dampers has functions such as filtering the vibration of the equipment and isolating the safe shutdown earthquake (SSE).

**Table 1. Parameters Comparison of Nuclear Power Plant Diesel Generating Set Base Support System**

|                | Diesel generator weight / kN | Base weight / kN | Spring box performance / kN·mm$^{-1}$ | Damper performance / kN·m$^{-1}$ |
|----------------|-----------------------------|-----------------|--------------------------------------|----------------------------------|
|                | Old unit                    |                 |                                      |                                  |
|                | 502                         | 1 465           | $K_v=5.8$                            | $C_v=250$                        |
|                |                             |                 | $K_h=6.8$                            | $C_h=250$                        |
|                |                             |                 | Spring box number:16 pieces          | Damper number:4 pieces          |
|                | New unit                    |                 |                                      |                                  |
|                |                             |                 | $K_v=5.8$                            | $C_v=62.5$                       |
|                |                             |                 | $K_h=6.8$                            | $C_h=62.5$                       |
|                |                             |                 | Spring box number:16 pieces          | Damper number:16 pieces         |

Although the base mechanical support design of different sets are slightly different, their performances are basically the same with specific parameters shown in table 1. First, both of them meet the design criteria under the earthquake SSE and reduce the impact of external vibration such as earthquakes; secondly, it can effectively isolate the vibration and reduce the impact of equipment operation on the foundation and surrounding equipment. According to the calculation based on design parameters, the efficiency of vibration isolation can reach 98%, which means that during the process of the diesel generating set operation, the support system almost filters all dynamic loads, then the basic column only bear static load basically. Therefore, through low-frequency damping suppression and high-frequency dynamic decoupling, the base design satisfies requirements of SSE anti-seismic performance and has a high vibration isolation efficiency, which could meet the needs of long-term operation.

Compared with the vibration change before and after the foundation transformation, the vibration value kept below 2.0 mm/s. It can be seen that the changes of the anti-seismic support system have little effect on the vibration of diesel engine.

**4. Research on Supporting Characteristics of Typical Equipment Accessories**

The analysis is made on the case of the influence of turbo charger.

**4.1 Overview of problems on Turbo Charger**

The horizontal connection bolt between the old diesel engine supercharger and intercooler fractured frequently. In order to solve this problem, the support mode of supercharger bracket has been improved by using the U-shaped bracket and cancelling horizontal connection with the intercooler to avoid the interaction between the intercooler and the supercharger. Comparison of supercharger support before and after the transformation is shown in Figure 2.

In the re-identification of function, it was found that the vibration amplitude exceeded the control standard 65 mm / s, and there were still a number of partial weld crack leakage and other failures in the subsequent operation. In order to further find out vibration reasons and completely solve the problem of supercharger vibration, as well as, eliminate the risk of vibration deterioration, a series of investigation, measurement and analysis have been carried out.
After making comparison of old and new diesel supercharger-related connection structure, it is found that there are different supporting forms for exit of supercharger. The exit of old diesel supercharger is connected with cooling water pipe through the H-shape angle steel support, which can provide assistant support to cooling water pipeline. However, there are no supports between exit of new supercharger and cooling pipe, which is separated from each other, as shown in Figure 3 and Figure 4.

![Figure 2. Form of U support](image1)

![Figure 3. Platform Comparison of the top structure of the supercharger between new and old diesel](image2)

![Figure 4. Platform of the H-support between of old supercharger and cooling water pipe](image3)
4.2 Characteristics Analysis of Turbocharger Support

4.2.1 Analysis on Structural stress
Source of structural stress:

① The structural stress generates during the process of U-shaped support field installation and ribbed slab welding for reinforcement. The Survey shows that the way to install U-shape support and weld ribbed slab for reinforcement both in old and new unit cannot meet standard fully. There is no torque requirement for the bolt fastening between supercharger and U-shape support, but there are also two types of welding, one is full welding and the other is partial welding. The main differences between the two types welding of ribbed slab are the effects on deformation and structural stresses of supports. As the supercharger bracket material is made of 16Mn steel, its strength is high. If the ribbed slab is adopted with full welding, the welding heat is higher than partial welding, resulting in different deformation and structural stress of the support’s side plate and floor plate. If U-shaped bracket and supercharger which had large deformation or structural stress could not install correctly, there would be larger possibility to produce vibration in the course of the operation.

② The structural stress generates during the process of H-shape support on-site installation. There is no torque requirement for the H shape support fastening slot which connects the supercharger with cooling water pipes. In the experiment of adjusting H shape bracket fastening bolts, it is found that the degree of tightening bolts is not the same, so the vibration and stress between supercharger and cooling water pipe are not the same.

③ The stress generated by thermal deformation of equipment. During the operation, the equipment has the tendency of expansion and deformation, and the expansion will be obstructed when the bolts are completely fastened, and the stress doesn’t release well, which presents as vibration level rise. After releasing the connecting bolts, the vibration level significantly reduces due to the release of the structural stress.

4.2.2 Analysis on support characteristics
(1) The impact of two type’s brackets. The change of the natural frequency before releasing the U-shaped brackets and the H-brackets is compared with that after releasing the U-shaped brackets and H-shaped brackets respectively, and the natural frequency of the supercharger changes within 1Hz. The H-shaped bracket has a significant effect on the natural frequency of the structure. Compare to the U-shaped bracket, H-shaped bracket acts on the force and torque from the top of the supercharger at the same time. It is not difficult to understand the structural characteristics and the impact of vibration.

(2) Support factor analysis. The support of supercharger of old unit include the support and fastening of the U-bracket and the bottom of the connecting bolts, the confinement on both sides of the U-bracket and the fastening of the bolts, and the fixing of the top of the H-bracket. U-brackets and bottom bolts are essential for support and fastening. After releasing all the U-shaped bracket and the H-shaped bracket, the vibration of the supercharger body is close to the vibration level of the U-shaped bracket and equivalent with the vibration level of the diesel engine body, which indicates that there is no obvious mechanical looseness; and from the perspective of the elimination of structural stress, the degree of tightening the supercharger of the two brakes should not be too high.

In summary, although the vibration source of the supercharger vibration is the vibration of the diesel engine body, the reason for causing the high level vibration is the comprehensive influence of the local factors.

By loosening the U-shaped bracket horizontally connecting bolts and H-brackets, and sacrificing some mechanical looseness, it avoids structural resonance and eliminates the effect of structural stress to a certain extent, so as to achieve the effect of effectively reducing the vibration level.

4.2.3 Improvement scheme and effects. By eliminating the H-shaped bracket of the diesel engine turbocharger of old unit and transforming the bottom U-shaped bracket, it effectively reduces the diesel engine supercharger vibration level, which makes it close to the diesel engine body vibration
level. At the same time, based on the stress evaluation, removing the H-shaped bracket does not affect
the fatigue life and seismic requirements of connected cooling water pipe. The mechanical failure and
high vibration problems of diesel engine supercharger of old unit can be solved.

5. Researches on Characteristics of Main Pipeline Support System

5.1 Analysis of Main Problems of Main Pipeline
Different from the design concept of modern diesel engine which need compact structure, decreasing
vibration and noise reduction, supercharger and cooler and connected pipe locating at both ends of the
unit, is a typical cantilever structure (as shown in Figure 5), and it forms an absolute rigid connection
between the body and surrounding space. Some of the hoses used for vibration reduction are far away
from the diesel engine body, and the effect of vibration reduction is rather limited. The main pipe span
is too long, and has too many elbows. The piping itself, pipe fittings and stents constitute piping
system is regarded as a vibration system of mechanical structure. When the pressure pulsation acts on
the bend of pipeline or pipe cross-section whose size changes, it will produce unbalanced force. This
force will cause mechanical vibration of the pipe. In particular, when the frequency of the interference
force is proportional to the natural frequency of the structural system, the vibration will increase
significantly. As the diesel engine’s vibration is 12.5 Hz and harmonic-based broadband vibration, it is
easy to be similar to the frequency of attachment structure, which forms resonance phenomenon.

Because the seismic design of the diesel engine requires it must be isolated from the outside
surroundings, with the large span of the pipeline floating direction, the original design of the pipe
support was limited by spatial structure that the cooling water inlet pipe and the backwater pipe and
the body are fixed mutually by bundled, as Figure 6 shows. This type of support design will lead the
previous pipeline vibration and bracket fracture problem into misunderstanding, which could improve
the strength of the bracket by inertia as a control mean. In fact, the rigid support plays a role of
vibration transmission between the vibrating source and the pipe, which can increase the mutual
interference between the pipes. Increasing the bracket to a sufficient strength can prevent it from
breaking, but the maximum stress position of the pipe is transferred, which often causes failure on
other stress sensitive locations on the pipe.

In addition, there is no strict specification of the bracket on-site installation, such as the difference
between the bolts tightening torque, welding process and quality differences, which often determines
the difference between the pipeline vibration and the probability of failure. A large number of test
results show that improper bracket fastening is likely to cause the phenomenon of pipeline resonance.

![Figure 5. Typical partial cantilever beam structure](image1)

![Figure 6. Typical Bundled Fixed Form](image2)

5.2 Diesel engine pipeline vibration reduction test
In order to test the effect of the fixed bracket between the inlet pipe and the return pipe in the main
pipeline system of the diesel engine, the pipe support adjustment test was carried out. By adjusting the
support rigidity of each bracket in the main pipeline system, the overall level of pipeline vibration
shows a decreasing trend of consistency, and the vibration phenomenon is improved comprehensively.
The maximum vibration of the pipe of one of the units drops from 122 mm / s to 28 mm / s, and the
frequency of vibration (RMS) decrease by 77%. The peak frequency is 37.5 Hz before that decrease
by 87%, which significantly eliminates the influence of pipeline resonance.
5.3 Improvement test of main pipeline support system

According to the overall seismic design requirements of the diesel engine and the characteristics of the pipeline space structure, combining with the modeling analysis, and introducing the damping support produced by professional agencies, a set of pipeline support program is finally designed, as shown in Figure 7:

1. Installing soft pad in the pipe clamp between No. 1 support and No. 3 support.
2. The No. 2 support is changed from \(\nabla\) shaped to V-shaped and rubber resistors are added to each support.
3. Adding No.4 support (which is between cylinder A5 and A6 cylinder head). The rubber vibration isolator is assembled in the middle of the No.4 support.

![Figure 7. Finite element calculation model for cooling water pipes](image)

5.4 Renovation and Effect of Main Pipeline Support System

5.4.1 The purpose of pipeline support system transformation

1. Improve the design defects of the pipe bracket: Due to the severe vibration and mechanical failure caused by the unreasonable design of the support, the design of the support is improved. Reducing the transmission rate of the interference force between the pipes, this can effectively eliminate the resonance effect and reduce the stress and other time-related potential effect, and unify the formation of contradictory pipes and brackets.
2. Improve installing defects of the pipe bracket: Weakening impacts of human factors produced by the torque-free tightening bracket, in order to make the pipeline vibration stay in a more stable state.

5.4.2 The effect of pipeline support system transformation. According to the test plan, all the main pipeline support systems of the diesel engine unit have been transformed. The vibration, stress and seismic capacity of the pipeline after the improvement are compared with that before the improvement. The effect is as follows: ① overall vibration level of the pipeline is improved on the basis of the adjustment of the bracket, and several points with high vibration level were improved obviously. ② meeting the seismic requirements; ③ the stress range of components with poor fatigue resistance is improved to varying degrees.

Through years of running practice, the parameters are stable and mechanical failure rate is greatly reduced.
5.4.3 Evaluation of modified bracket effect. The improving effect of the pipeline support determines the availability of the elastic support. The rigid support which is designed originally is compared with the elastic bracket after transformed, as shown in Table 2.

| Considerations          | Original design rigid support                                                                 | Modified elastic support                                                                 |
|-------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|
| Vibration               | Easily leading to pipeline resonance. In fact, it transfers the diesel engine body vibration source to the pipeline, with an increase of the transmission rate of interference | Adjusting the natural frequency of the pipeline, which could effectively suppress the resonance amplitude and significantly reduce the resonance effect; Effectively isolating the vibration source and reducing the transmission rate of interference, in order to offset and consume vibration energy |
| Stress                  | Improper bracket fastening will make the pipeline accumulate stress in thermal expansion, resulting in deterioration of vibration or weld fatigue fracture and other phenomena; under the reaction force, the fracture of bracket is easy to occurred at the weld position | After the installing the vibration damping brackets, the alternating stress of the components with poor fatigue resistance of the pipe is improved to varying degrees; releasing stress, which can decrease the interaction force between the pipeline and the support and have a potential effect on the long-term safe operation of the unit |
| Anti-seismic requirements| Meeting the anti-seismic requirements                                                        | The impact on the seismic capacity is not obvious; meeting the anti-seismic requirements |
| Maintenance             | Installing the bracket without the torque requirements that leads more human factors which could cause high vibration; obtaining raw material locally and low maintenance cost | The damping block requires a certain amount of compression; installation should be standardized; spare parts need to be prepared; higher maintenance costs |

6. Conclusion
(1) A large number of mechanical faults in the emergency power generation unit of the nuclear power plant are related to the design defect of the supporting system. Due to the isolation requirements of the diesel engine from the outside world, there is a need to design an independent support system. While with the mistakes of manufacturers design ideas, the daily maintenance of power plant diesel engine and the transformation work is led to errors.
(2) It is necessary to carry out a comprehensive analysis and evaluation of the overall status and causes of the diesel engine unit. The blind work should be avoided. The diesel engine foundation design is ideal and there is no need for reformation.
(3) For the main pipe support system and supercharger and other important equipment components support design, it needs to effectively reduce the transmission rate of interference between each other. In practices, it proves that the use of flexible support is a practical support improving measure.

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