A study of dynamics of marine circuit breakers based on vibration

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Abstract. Marine circuit breaker is an important equipment on board, its mechanical failure generated by the vibration can cause the power system failure. Therefore, it is necessary to evaluate the structure of the circuit breaker system. The finite element method is used to establish the dynamics model of the whole circuit breaker system under the vibration, and the dynamic response analysis of the circuit breaker is carried out with real vibration load. According to the analysis results, the overall structural strength of the circuit breaker and the occurrence of mis-operation are evaluated, then the sensitive weak position of the circuit breaker structure are identified, and finally the structural optimization design is carried out.

1. Introduction
Ships are inevitably subjected to various periodic or non-periodic disturbances from the main engine, propellers, waves or caused byreefing, bombs or fish explosions during navigation or combat, thus triggering severe vibration of the hull, and the circuit breaker, as an important electrical equipment on board, is directly related to the stability and reliability of electrical power supply [1-2]. The severe vibration of the ship hull may damage the key parts of the circuit breaker, thus affecting the performance of the breaker [3].

Many scholars at home and abroad have conducted a lot of research on various aspects of circuit breakers using various methods from different perspectives. For vibration response analysis, Breeuwer et al. [4] proposed the use of free velocity to describe the vibration characteristics of the device, free velocity measures the velocity of an elastically mounted device in the free vibration state, and it can be used to approximate the vibration intensity of the device .Gibbs et al. [5] ignored the phase difference between the excitation at each point and between the frequency response, and used the average free velocity and average frequency response at each point to calculate the power flow, which is the product of force and velocity . Steiberg et al. [6] proposed a method for vibration shock resistance of ship electronic equipment through theoretical analysis, which provides an important basis for vibration design . In terms of solid modeling, Wu et al. [7] constructed a virtual prototype of circuit breaker operation for multi-body dynamics simulation, analysed the circuit breaker breaking process and obtained its dynamics characteristics . Zhang et al. [8] used MSC.Adams software to conduct a dynamics simulation study of the virtual prototype of the operating mechanism of the circuit breaker to obtain the
force changes of the insulated tie rod during the circuit breaker breaking and closing process. Zhao et al. [9] based on the structure of the circuit breaker to model to study the different effects of each element of the circuit breaker on the characteristics of its breaking and closing process, which is important to achieve fault site identification, fault classification and diagnosis. Huang et al. [10] adopts a new method for mechanical fault diagnosis of high-voltage circuit breakers based on S-transformation and limit learning machine (ELM). Firstly, the local singular values of vibration signals generated during the action of high-voltage circuit breakers in different time periods and frequency bands are calculated based on S-transform, and the maximum singular value is selected as the feature vector for fault diagnosis, and then the limit learning machine is used to classify the faults, and finally the effectiveness of the method is verified by experimental methods.

At present, not too much work has been done to analyse the combination of the mechanical and excitation parts of the circuit breaker itself. In this paper, a finite element model of the circuit breaker is established based on the structure of the circuit breaker using the special connection between the mechanical part and the excitation part of the circuit breaker, and then the motion characteristics curve and the motion law of the key parts are obtained in the simulation. And analyse the influence of three different directions and vibration magnitudes on the characteristics of the marine circuit breaker.

2. Basic structure of circuit breaker and finite element model
Circuit breaker is a switching device capable of closing, carrying and opening the current under normal circuit conditions and closing, carrying and opening the current under abnormal circuit conditions within a specified time. This paper studies a marine circuit breaker with the model number EHV4.

2.1. Basic structure of circuit breaker
The circuit breaker is mainly divided into four parts: main frame, manipulating mechanism, connecting rod assembly and arc extinguishing system, of which the main frame adopts a U-shaped support structure with a wall thickness of 2 mm. the outer dimensions of the circuit breaker are 825 mm (left and right width) × 718 mm (height) × 716 mm (front and rear depth). The main frame is welded and fixed to the switchgear by four M20 bolts at the bottom. The overall structure of the circuit breaker is shown in Fig 1.

![Fig 1. Marine circuit breaker system](image)

2.2. Modal Analysis
Modal analysis is the basis of all dynamics analysis and is the analysis that determines the inherent frequency and the inherent mode of the structure. The distribution of structure, mass and stiffness of a circuit breaker determines its vibration characteristics. The intrinsic frequency and the modal vibration mode are the key parameters for structural design, which also serve as the basis for the vibration analysis of the circuit breaker. The obtained intrinsic frequencies of the circuit breaker are shown in Table 3. From its first 20 orders of mode, it can be seen that the intrinsic frequency of the circuit breaker system is concentrated in the low frequency part. The excitation load in the low frequency section may have a
great impact on the circuit breaker, in the high frequency section on the impact on the whole circuit breaker is small, so in the calculation of the frequency, taken to 150HZ can be, so comprehensive consideration of the calculation of efficiency and time, take the first 16 order modal involved in the calculation of vibration, the vibration pattern of each order modal as shown in the fig 4, which reflects the free state of the whole system vibration trend, and the fundamental frequency is in the excitation frequency 1 to 60HZ, the system is likely to resonate.

Table 1. Frequency of each order of circuit breaker

| Order | Natural Frequency | Order | Natural Frequency |
|-------|------------------|-------|------------------|
| 1     | 33.312           | 11    | 118.96           |
| 2     | 46.94            | 12    | 123.61           |
| 3     | 58.246           | 13    | 137.71           |
| 4     | 61.809           | 14    | 140.85           |
| 5     | 82.85            | 15    | 141.69           |
| 6     | 86.738           | 16    | 164.67           |
| 7     | 93.586           | 17    | 169.95           |
| 8     | 101.83           | 18    | 170.21           |
| 9     | 111.75           | 19    | 171.81           |
| 10    | 116.68           | 20    | 173.18           |

3. Vibration Analysis

3.1. Vibration excitation
The boundary conditions of the circuit breaker were input on the X, Y, Z 3 directions of sine vibration. The vibration magnitudes are: 1mm when the frequency is 1~16Hz; 10m/s^2 when the frequency is 16~60Hz. and analyze the vibration resistance of the circuit breaker.

\[ A = 4\pi f^2 U \]  

According to the equation (1), the vibration displacement excitation into acceleration excitation, the greater the vibration frequency, the greater the acceleration load on the circuit breaker, so the more violent the vibration, set 15 intervals between 0 and 60HZ, each interval step for 4HZ, the results are obtained as Fig 2.

![Acceleration excitation input](image)

According to the vibration requirements, the sinusoidal acceleration in three directions is recorded under the damping ratio of 2%. The interrupting system is the key part of the circuit breaker, and the circuit breaker cannot perform normally if the moving contact is deformed or has large displacement, so the moving contact is selected as the test observation point. Through the post-processing of harmonic response analysis, the curves of frequency vs. stress, strain vs. acceleration in X, Y and Z directions can be obtained as shown from Fig.5 to Fig.7.
(1) In the X, Y and Z directions, the deformation and stress all reach their maximum values at the first-order natural frequency when excited by sinusoidal loads.

(2) Due to the connection between the moving contact and other components, and the first-order restrained mode vibration pattern of the circuit breaker moving contact is along the vertical direction, the strain in the Z direction is greater than that in the X and Y directions.

(3) The maximum stress of the dynamic contact is 30.115 MPa, which is much smaller than the allowable stress of the dynamic contact material, so no structural damage occurs in the dynamic contact. The movable and static contacts are separated by 11mm, and the maximum deformation of the X, Y and Z directions is given as the displacement value corresponding to 33HZ along the Z direction, which is 1.669mm in size, much smaller than the distance between the movable and static contacts.

**Fig 3.** X-direction Displacement-frequency relationship

| Frequency (HZ) | Displacement (mm) |
|---------------|-------------------|
| 0             | 0.00              |
| 5             | 0.05              |
| 10            | 0.10              |
| 15            | 0.15              |
| 20            | 0.20              |
| 25            | 0.25              |
| 30            | 0.30              |
| 35            | 0.35              |
| 40            | 0.40              |
| 45            | 0.45              |
| 50            | 0.50              |
| 55            | 0.55              |
| 60            | 0.60              |
| 65            | 0.65              |

**Fig 4.** stress diagram in X direction

a) Stress diagram of left dynamic contact  
b) Stress diagram of right dynamic contact

**Fig 5.** Y-direction Displacement-frequency relationship
4. Conclusion
In this paper, a finite element model for marine use is developed and the frequency domain analysis from 1HZ to 60HZ is simulated to determine the steady state response of the circuit breaker under a sinusoidal load of known frequency and amplitude.

(1) From the modal calculation results of the whole cabinet model, it can be seen that its self-oscillation frequency is low, and the first 16 orders of the intrinsic frequency is relatively concentrated, and the whole cabinet has a large amplitude of each order of the amplitude of the location of most of the performance in the lower part of the front cabinet wall.

(2) The results of the modal analysis of the circuit breaker can be seen, the first-order inherent frequency of the circuit breaker is 33.312HZ, so the possibility of resonance of the circuit breaker in the vicinity of 33HZ.
(3) Under each condition, the deformation of the circuit breaker in the z-direction (i.e., the front and rear direction of the circuit breaker) is the largest, in the y-direction (i.e., the upper and lower direction of the circuit breaker) is the second largest, and the most stable in the x-direction.

In this paper, the vibration characteristics of the contact system of a marine circuit breaker are studied when it is subjected to linear vibration, while the contact will generate nonlinear vibration when it is divided and closed, and the linear vibration of its contact system can be subsequently coupled with nonlinear vibration for study.

References

[1] GJB 4.1-83. Environmental Testing General Ship Electronic Equipment[S].
[2] Li, Qiannian, Tang, Xuezhi. Design of impact vibration resistance of naval instrument structure[J]. Ship Defense and Chemical, 2008(4):40-43.
[3] GJB 150.16A-2009, Laboratory Environmental Test Methods for Military Equipment, Part 16: Vibration Test [S]. Beijing: General Armament Department of the Chinese People's Liberation Army, 200.
[4] Roizman. V, Petyak. V. The dynamic effects and impacts in electronics. IEE Power Electronics and Variable Speed Drives. 1998:393-398.
[5] Petersson B A T, Gibbs B M. Towards a structure borne sound source characterization[J]. Applied Acoustics, 2000, 61:325-343.
[6] Steinberg, Dave. S. Vibration Analysis for Electronic Equipment 2nd Ed. John Wiley and Sons: New York, 1988, 414-420.
[7] Wu Yang, Mingzhe Rong, Xiaohua Wang, et al. Dynamic simulation of high-voltage circuit breaker concerning electrodynamic force[J]. Proceedings of the CSEE, 2003, 23
[8] Hongjun Zhang, Wenwen Wang, Qiang. Dynamics simulation analysis and experimental study of circuit - breaker’s insulation pull rod [J]. High Voltage Apparatus, 2012, 48(10): 83-87.
[9] Zhao H.S., Zhao Y., Song W., Yu Y.. Modeling and simulation analysis of circuit breaker operating mechanism based on structural analysis [J]. High Voltage Electrical, 2021
[10] Huang Nantian, Chen Huaijin, LIN Lin, et al. Mechanical fault diagnosis of high voltage circuit breakers based on S - transform and extreme learning machine[J]. High Voltage Apparatus, 2018, 54(6): 74-80.