Durability Evaluation of Superconducting Magnets

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Abstract. It is one of the most essential things to verify the durability of devices and components of JR-Maglev system to realize the system into the future inauguration. Since the load requirements were insufficient in terms of the durability under vibrations under mere running tests carried out on Yamanashi Maglev Test Line hereinafter referred to YMTL, we have developed supplemental method with bench tests. Superconducting magnets hereinafter referred to SCM as used in the experimental running for the last seven years on the YMTL were brought to Kunitachi Technical Research Institute; we conducted tests to evaluate the durability of SCM up to a period of the service life in commercial use. The test results have indicated that no irregularity in each part of SCM proving that SCM are sufficiently durable for the practical application.

1. Introduction
A number of running tests have been conducted on YMTL for the last eight years to evaluate the durability of vehicles and pertinent facilities and components. With respect to SCM, the load requirements were insufficient in terms of the durability under vibrations with only tests results achieved from the running test carried out on YMTL. We hence attempted to carry out bench tests, which simulated vibrations with 60-degree pitch levitation coils and 120-degree pitch single-layer propulsion coils. The bench tests were successive to a period equivalent to fifteen years after the Maglev system would have been incorporated into commercial service. This paper reports a method to evaluate the durability of SCM and the bench test results.

2. Positioning of Evaluation
Vibrations caused by vehicle running, load movement, excitation and demagnetization, heat cycles adversely affect SCM. On YMTL, compared to conventional trains running on existing lines, Maglev test vehicles have run back and forth on a segment in a limited length very frequently under the aforesaid conditions repeatedly, applied by abrupt acceleration/deceleration. The bench test results regarding excitation, demagnetization and heat cycles proved sufficient durability of SCM compatible to fifteen years under commercial service. In addition, the durability of major components of SCM i.e. inner vessels and heat-insulated supporter has also been verified.

Concerning the durability under vibrations on the contrary, the frequency for the load requirements under YMTL running tests is less than those under commercial operations.
3. Selection of Test Conditions

3.1. Load Requirements
Based on the conditions under vibrations generated by the vehicle running tests on YMTL, we selected test conditions considering running conditions assumed in the future commercial operations. A force susceptible to SCM is more intense under a speed of 450-480 km/h during the acceleration/deceleration in a resonance area to compare with a constant speed of 500 km/h; therefore, a method to reproduce vibrations in a resonance area is reasonable in the evaluation of durability under vibrations, as shown in Fig. 1.

The time continued on vibrations was decided as $2 \times 10^6$ seconds (556 hours) based upon the prerequisite that acceleration and deceleration are 1 m/s$^2$; an effected area of resonance vibrations is ±5 km/h and considering an operational pattern in commercial service for fifteen years.

3.2. Excitation Requirements
Although there are some test methods for SCM vibration impressions, in order to generate vibrations for a long period under a large load, an electromagnetic vibration test has a technical problem in terms of consumption of liquid helium and heat-generation in vibration coils.

Contrarily, from the previous results of analyses of vibration data on running tests under electromagnetic vibration and mechanical vibration, there was no big difference in between regarding the reproduction of SCM resonance vibration mode and a relative movement between outer vessel and inner vessel. Therefore, we selected mechanical vibration without excitation as a test.

3.3. Temperature Requirements
In terms of material strength, fatigue strength increases in a low temperature than a room temperature [1][2]. Therefore, the test conditions in room temperature are severe than the temperatures under SCM are substantially applied. However, considering the effects of heat contractions, it is conceivable that the tests in low temperature simulated a substantial condition. The heat contraction under a room temperature less than the nitrogen temperature is very limited; heat contractions from room temperature to helium temperature is very similar to the nitrogen temperature, mechanical load added to SCM by heat stress is the same as helium temperature and nitrogen temperature. We therefore selected tests in nitrogen temperature as the test can be readily performed constantly for a long time, and the amount of freezing mixtures can be saved.

3.4. Test Facilities
SCM test specimens and mechanical vibration units are arranged in a soundproof laboratory as shown in Fig. 2, which enable supplying/discharging of liquid nitrogen and gas nitrogen. Under the test condition of 60-degree pitch levitation coil, SCM are vibrated out of phase at both upper ends and the center bottom of the outer vessel as shown in (1) of Fig. 3, which seems a vertical twist mode that adjoining Superconducting coils hereinafter referred to SC-coils are out of phase as shown in Fig. 4.

(a) Under the test condition of 120-degree pitch single-layer propulsion coil, SCM are vibrated in a
phase with three points at the center level of SC-coils as shown in (2) of Fig. 3, which resembles to a tertiary horizontal bending mode as shown in Fig. 4. (b).

Control and measurement systems are organized at a control PC, two monitoring PCs and a controller for automatic nitrogen supply. Watching items are vibration acceleration, the degree of vacuum, tank pressure, departmental temperatures, force and phase of vibrating points. Vibration acceleration, the degree of vacuum and tank pressure have each threshold, where exceeding the threshold, vibrations are automatically stopped to maintain the safety.

**Fig. 3. SCM and vibration unit’s arrangements**

| [Test Conditions] | (1) Levitation simulation | (2) Propulsion simulation |
|-------------------|---------------------------|--------------------------|
| SCM vibration mode: Vertical twist | SCM vibration mode: Tertiary horizontal bending |
| Phase difference during vibration units: 180-degree | Phase difference during vibration units: 0-degree |

**Fig. 4. Vibration mode of outer vessel**

4. Test Results

4.1. Levitation Simulation

4.1.1. Selection of test conditions

Based on vibrations of SCM under the running tests at sections where 60-degree-pitch levitation coils provided on YMTL, we selected vibration points, frequency, phase, and vibration forces.

- Vibrating points and frequency: As shown in Fig. 3. (1), 283 Hz equivalent to 458 km/h
- Vibrating force and phase: 1,080N-360N-1,080N, 180-degree

A vibratory condition was selected assuming that vibration acceleration at each part is equivalent to the running tests as shown in Fig. 4 (a), and the vibration force was increased to 1.2 times, which considered the payload of bogie. The reason is that the payload under the running test is 181 kN, and the limit of payload is 216 kN, which is decided on the design of bogies.

4.1.2. Test results of durability evaluation

We carried out tests to evaluate the durability on a levitation simulation, with a total time of 556 hours within a period of 48 days. There was no time series change observed at vibration waves of respective parts as shown in Fig. 5, which proved no defect in the inner structures of SCM.

**Fig. 5. Time series change of vibration waves on levitation simulation**
4.2. Propulsion Simulation

4.2.1. Selection of test conditions
Based on vibrations of SCM under the running tests at sections where 120-degree-pitch propulsion coils provided on YMTL, we selected vibration points, frequency, phase, and vibration forces.

- Vibrating points and frequency: As shown in Fig. 3. (2), 149 Hz equivalent to 483 km/h
- Vibrating force and phase: 6,000N-6,000N-6,000N, 0-degree

The maximum current of propulsion is assumed approximately 1,000A in commercial lines. We hence selected a vibratory condition such that vibration accelerations at various parts are equivalent to the running tests as shown in Fig. 4. (b), which accelerated with 1,010A of propulsive current.

![Fig. 6. Time series change of vibration waves on propulsion simulation](image)

4.2.2. Test results of durability evaluation
We performed durability evaluation test on the propulsion simulation, within a total of 556 hours within a period of 59 days. There was no time series change observed in vibration waves at various parts as shown in Fig. 6, which proved no defect in the inner structures of SCM.

4.3. Verification of Integrity of SCM
We carried out excitation tests under the identical conditions as those for newly manufactured SCM as shown in Table 1. Following the vibration tests, which equivalent to fifteen years under commercial service, there was no defect in prime structures of SCM, i.e. power leads, permanent current switch and wires; the test results verified the integrity of SCM. An increment of heat load is equivalent to that of the newly manufactured SCM; there was no recognizable time series change.

| Table 1. Excitation Tests Requirements |
|--------------------------------------|
| Requirements | Magnet motive force | Condition |
|--------------|---------------------|-----------|
| Rated excitation | 700 kA | Maintain 2 minutes on PC-mode |
| Over excitation | 750 kA | Maintain 2 minutes on PC-mode |

5. Conclusions
- The vibration tests verified the entire durability of SCM, which is equivalent to fifteen years service life in commercial operations.
- There was no recognizable time series change at each part of vibration waves and the degree of vacuum, which verified no defect in the inner structures of SCM.
- Performing a rated-excitation test with 700 kA and an over-excitation test with 750 kA followed by the vibration tests, we could verify the integrity of SCM.
- It was possible to establish a method to verify the durability of SCM in the resonance area of vibrations by the mechanical vibration tests.

We could verify the sufficient durability of SCM equivalent to the service life in commercial lines with the comprehensive results of vehicle running tests and element tests. This technical development was partly subsidized by the Ministry of Land, Infrastructure and Transport, Japan.

References
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