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A rail vibration test and analysis method for the electromagnetic launching process ☆

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ABSTRACT

During the electromagnetic launching (EML) process, rail vibrations occur due to the electromagnetic force generated by an acute current. These vibrations result in a reduced launch velocity and decreased launch efficiency. To measure the vibration amplitude of a rail accurately and to analyze the internal relationships between current strength, rail material and vibrations, a small transient vibration in a strong electromagnetic field was studied in this paper. Related experiments were also performed on the test system. Fiber-optic displacement sensors were used to collect vibration data at key locations along the rail. Using virtual instrument technology, a software platform was designed that displayed the vibration waveform and analyzed the time, frequency domain and other parameters. We collected data on the vibration response and the modal parameters of the rail and determined the natural frequencies of the electromagnetic launch system by performing a modal analysis of its vibrations and dynamic responses that combined experimental and theoretical methods. Methods of optimizing the structure's vibration and dynamic response and of assessing the damage to it could be studied further on the basis of the results described in this paper.

1. Introduction

An electromagnetic railgun is subject to extremely complex dynamic loading conditions during the launch process. The load includes an electromagnetic field, heating effects caused by the high currents and friction, and the effect of these high temperatures on the stress and strain of the armature and the rail, which affect the weight of railgun, its firing precision and its service life [1–3]. In the design of an electromagnetic railgun, it is very important to ensure that the rails will not produce violent oscillations during the launch process because these oscillations will reduce the firing accuracy. Therefore, it is necessary to test and analyze the vibrations of the electromagnetic rail launcher's rails.

There has been a great deal of theoretical research into the dynamic response of an electromagnetic railgun. Tzeng and Sun [4] used an elastic foundation beam as an orbital mechanics-based model of an electromagnetic launcher with the assumption that the armature was uniform along the rail to study the effect of the rail length on the resonance speed; Tzeng [5] analyzed the effect of varying the orbit parameters on the critical velocity of the electromagnetic launcher and offered guidance on the railgun's

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design; Daneshjoo et al. [6] calculated the orbital displacement and static stress using the finite element method and concluded that orbit design and projectile velocity were related. At launch speed, the frequency of the force applied by the electromagnetic railgun and the railgun's natural frequency are nearly the same. The amplitude of the vibrations of the rails, especially the transverse vibrations, is quite large, affecting the railgun's its firing accuracy. Cornette et al. [7] analyzed the results of the past few years' research on electromagnetic launching, paying particular attention to the influence of continuous emission firing on the accuracy of the orbit and the strain of the rails; Schuppler et al. [8] and Ghassemi et al. [9] used displacement and acceleration sensors to study the effect of the charging voltage on the vibration amplitude.

A fiber-optic displacement sensor was used in the numerous experiments described in this paper. The influence of various parameters on the rail vibration amplitude was studied during the electromagnetic emission process with the goal of providing a basis for developing an electromagnetic railgun and analyzing its material composition.

2. Measurement program

To measure vibration data effectively in the harsh electromagnetic interference (EMI) environment, fiber-optic sensors were used because they were immune to electromagnetic interference.

In this experiment, a simulation test machine was used to simulate the electromagnetic environment. Three fiber-optic displacement sensors were installed in the testing machine, as shown in Fig. 1. To eliminate the influence of external vibrations on the railgun, a pressure device was used to set the pressure and a separate stent was designed to hold the sensor in place because the railgun's vibrations would reduce the accuracy of the sensor's measurements. High-speed equipment was used for data acquisition and storage. To intuitively reflect measurement results, a control interface was configured using LabVIEW on the host computer. This real-time interface could remove high frequency noise, display the vibration signal and analyze the spectrum. The interface is shown in Fig. 2 below.

Remark 1: According to the Ref. [7], we can see that there are less literature about vibration real-time monitoring method of electromagnetic launching process, In order to acquire the small transient vibration in the process of emission, a real-time vibration monitoring system has been proposed in this paper.

3. Modal analysis method

(1) In the electromagnetic launcher's structural design, it is important to ensure that the frequency of the dynamic load and the natural frequency of the system are different so that there is no resonance. Therefore, it is necessary to carry out a modal analysis of the electromagnetic launcher and determine its inherent frequency [10–14]. Taking the electromagnetic emission testing machine as a vibrating body, the test machine can be modeled as a vibrating body using the standard equations for free vibrations.

The basic differential equation for free vibration is as follows:

$$[M]\{\ddot{x}\} + [K]\{x\} = 0 \quad (1)$$

In this equation, $[M]$ and $[K]$ represent the mass and stiffness matrices, respectively, of the structure, $\{\ddot{x}\}$ is the acceleration vector, and $\{x\}$ is the displacement vector.

A solution to Eq. (1) is the following simple harmonic equation

$$\{x\} = \{\varphi\}\sin\omega t \quad (2)$$

In this equation, $\{\varphi\}$ represents the modal shape and ω represents the circular frequency.

Substituting (2) into (1) results in the following characteristic equation:

$$([K] - \omega^2[M])\{\varphi\} = 0 \quad (3)$$

In Eq. (1), $\{\varphi\}$ should have a non-zero solution that makes the determinant of the coefficient matrix zero, namely:

$$\det([K] - \omega^2[M]) = 0 \quad (4)$$

$$\text{Or}\ \det([K] - \lambda[M]) = 0 \quad (5)$$

In these equations, $\lambda = \omega^2$.

The left side of Eq. (5) is a polynomial in λ. Solving this polynomial results in a set of characteristic values, $\lambda_\imath$. Eq. (5) can be rewritten as:

$$\det([K] - \lambda_\imath[M])\{\varphi_\imath\} = 0 \quad (\imath = 1, 2, 3, \ldots N) \quad (6)$$

where N is the dimension of the stiffness matrix $[K]$ and the number of degrees of freedom in the system, λ_i is the i th characteristic value, and $\{\varphi_i\}$ corresponds with the i th modal vector.

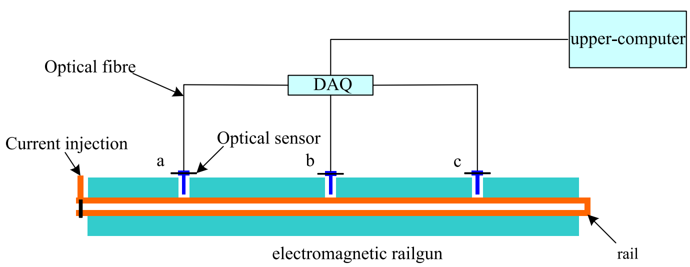

Fig. 1. The test system.