On vibration characteristics of thermal field emission electron gun filament

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Abstract. Thermal field emission electron gun is used as electron source in scanning electron microscope. Its filament made by tungsten wire is bended like a hairpin and is prone to vibration disturbance, therefore deteriorating outcome images. To model filament’s mechanical performance under vibrating conditions, finite element modal analysis was carried out, and frequency response was calculated. It was shown that the filament was more sensitive to lateral excitation, and due to its unique structure, vibration characteristics were different in two lateral directions. Stiffness of the two lateral directions was compared through static calculation to verify the calculated mode order. Besides, characteristics between room temperature and working temperature were compared. If allowed, electron gun should be mounted in the way that its sensitive direction be kept away from the most intensive excitation’s direction.

1. Introduction
Scanning electron microscope (SEM) replaces light wave with electron wave, taking advantage of the latter’s shorter wavelength, to overcome resolution limit and increase magnification [1]. To image an area being observed, electron beam released by electron gun must follow specific path when it’s focused on the sample’s surface [1-2]. However, due to disturbances cause by many factors, including mechanical vibration, imaging process will be interfered and outcome image could deteriorate. When it comes to mechanical vibration, distorted edges were observed [3-4]. Fortunately, this effect has already been noticed and methods were taken to drive it away. Post-processing the outcome image using digital approaches is very straightforward [4-5]. And direct involvement in imaging process by canceling beam pointing error with image-shifting coil is also a selection [6-7]. Some seem to rely more on mechanical ways through isolating excitation from microscopes passively [8] or actively [9] to eliminate the problem from the very beginning. However, new problem that aforementioned methods tend to lose their functionality in specific frequency range is noticed, and efforts need to be taken to figure out what happens to imaging process when these specific excitations present. A preliminary step is to model electron gun’s filament and reconstruct its vibration characteristics.

Thermal field emission (TFE) electron gun plays the role of generating electron beam in SEM [10], and its filament with cathode is cantilevered in the gun, which means they are prone to vibration. Figure 1 shows the structure of filament in the electron gun. It is bended like a hairpin and fixed to two thick poles providing current for heating cathode to working temperature at about 1500°C. The cathode releasing electrons is fixed to the tip. Be aware that figure 1 doesn’t show the rest parts of the gun for simplicity, and a complete electron gun should also have an anode and a control grid to function normally.
2. Modal analysis using finite element method

The filament is connected to the gun through the base as shown in Figure 1, and excitation comes from base as well, which means this is a base excitation problem. So outer cylinder surface of the base should be fixed in finite element model. Figure 2 gives the mesh and the distribution of element quality. As shown, element quality is good on the filament, while coarse elements appear at the base, but overall the mesh is acceptable.

Table 1 lists the first 6 calculated natural frequencies of the filament with description on relevant mode shape. To make it clear, figure 3 shows the filament’s mode shapes. As shown, these mode shapes
contains mainly lateral and torsional mode. And the natural frequencies range from 1183.9Hz at 1st order to 27424Hz at 6th order. The 1st order mode is lateral in y direction, and excitation frequency won't exceed 1st order natural frequency, so filament should vibrate laterally in y direction when excited. Although lateral modes is present in x direction, their natural frequencies are relatively high, and mechanical excitation's frequency might not reach. That’s to say, the filament is more sensitive in y direction than in x direction.

| Order | Natural frequency (Hz) | Mode description |
|-------|------------------------|------------------|
| 1     | 1183.9                 | 1st order lateral, y direction |
| 2     | 8389                   | torsion, z axis    |
| 3     | 8474                   | 1st order lateral, x direction |
| 4     | 10125                  | 2nd order lateral, y direction |
| 5     | 13517                  | lateral x direction |
| 6     | 27424                  | torsion, z axis    |

But it’s too early to reach this conclusion for lacking evidence from other perspective of view. It’s known that natural frequency corresponds with mass and stiffness of structure. Since aforementioned natural frequencies come from the same structure, the difference in stiffness shall result in the different lateral natural frequencies. To verify this, lateral stiffness in the x and the y direction is compared through static calculation.

3. Stiffness comparison by static calculation
Stiffness is defined by following equation.
To compare stiffness between different directions, according to equation (1), simply apply force to specific direction and calculate the displacement in that direction. To simplify calculation, taking modal results in section 1 into consideration. As shown in figure 3, in first 6 modes, displacement, or precisely, relative amplitude mainly distribute along filament, not poles supporting and heating the filament and cathode, so calculation in this section only use filament. Figure 4 shows the schematic used for calculating lateral stiffness in x and y direction, calculation is performed independently in each direction.

![Figure 4. Schematic for static stiffness calculation.](image)

As shown, the filament is modeled by two cantilever beam with circular cross section, joined at free end to form the tip. Force is applied at the tip so displacement should also been taken from the tip. Stiffness in the x and the y direction are given below.

\[ k_x = \frac{2EA}{l} \]  
\[ k_y = \frac{24EI}{l^3} \]

\( E \) is elastic modulus, \( A \) is cross section area and \( I \) is cross section inertia. In the x direction, although presence of internal moment is assumed, substitution wipes out the term related to internal moment and therefore its stiffness only relates to axial internal force. In the y direction, applied force is perpendicular to both halves of the filament and won’t induce axial internal force, so term related to axial internal force vanishes naturally, displacement is only caused by bending. To show stiffness difference between the x and y direction, stiffness ratio is defined by following equation.

\[ kr = \frac{k_x}{k_y} \]

Combine equation (2) to equation (4), and recall that filament has circular cross section, final form of stiffness ratio appears.

\[ kr = \left( \frac{l}{3d} \right)^2 \]

As shown, stiffness ratio is relevant to length-to-diameter ratio, while material properties and tip angle don’t appear in the equation. Since filament is made of long, thin tungsten wire, length-to-diameter ratio largely exceeds 1, then stiffness ratio exceeds 1 as well, so stiffness in the y direction is evidently lower than that in the x direction, which coincides with the frequency order calculated by finite element method in section 1, for lower stiffness causes lower natural frequency.

4. TFE electron gun’s frequency response

Finally, filament’s frequency response to base’s displacement excitation in frequency range 0 to 2000Hz is calculated through mode superposition. Frequency interval is set to 50Hz away from natural frequencies and decreases to 0.5Hz near natural frequencies to balance performance and accuracy. The outcome is defined through dividing calculated tip’s displacement amplitude by excitation amplitude to
produce a dimensionless quantity.

$$P_s = \frac{X_{tip}}{X_{excitation}}$$ (6)

Bond graph depicted using the quantity defined above is shown in figure 5. Damping ratio is set to 0.01 to avoid infinite peak value near natural frequency. A more reliable damping ratio needs to be measured through testing. Since excitation frequency considered won’t exceed 1st natural frequency, response is reliable under this condition.

Figure 5. Calculated frequency response of filament tip (damping ratio=0.01).

In both the x and the y direction, one peak is observed at 1st natural frequency, while peak value of the x direction is lower than that of the y direction. In frequency range 0 to 2000Hz considered in this problem, only the 1st mode is present, so one peak fulfills expectation. Referring to figure 3(a), the 1st mode is a lateral mode in the y direction, resulting in higher peak value in the y direction.

As shown in figure 5, response between room temperature and working temperature is also compared. Temperature higher than room temperature causes elastic modulus to decrease, therefore lowering structure stiffness. The lower the stiffness, the lower the natural frequency, that’s why response spectrum under working temperature shifted left compared to that under room temperature in figure 5. Then, the lower the natural frequency, the closer it will be to excitation frequency and consequently the higher the response amplitude when excitation frequency is lower than 1st natural frequency. However, stiffness difference between the x and the y direction still exists and sensitive direction remains unchanged which coincides with equation (5).

5. Conclusion
By means of modal analysis, mode superposition and static calculation, the filament’s vibration characteristics are obtained, including natural frequencies, directional displacement frequency response and frequency order is verified. The filament has only 1 mode with natural frequency of 1183.9Hz in frequency range of interest, which is a lateral mode in the y direction. Lateral mode in the x direction has a higher natural frequency due to higher stiffness, which is verified by stiffness comparison through static calculation. Thanks to this stiffness difference, frequency response differs in the x and y direction, making y direction the filament’s sensitive direction. Under working temperature higher than room temperature, filament’s stiffness lowers and enlarges response amplitude under 1st order natural frequency as well as lowering the frequency itself, but sensitive direction remains unchanged. To reduce mechanical vibration’s disturbance to filament, its sensitive direction must be kept away from those directions with the most intensive excitation.

6. Future work
The vibration characteristics aforementioned are all calculated, not measured, they are prediction to the filament’s real behavior under vibration. And damping ratio used for calculating frequency response is
arbitrarily set to avoid infinite value, not for precisely simulation. To eliminate unreliability, tests are needed to measure the filament’s real performance as comparison and supports for refining calculation model and results.

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