Numerical Simulation Research on Inter-electrode Capacitance of High-power Electronic Tetrode

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Abstract. High-power electronic tetrode is the RF wave transmitting component in the ion cyclotron range of frequency (ICRF) heating system in EAST. In high-frequency use, its inter-electrode capacitance is an important factor that cannot be ignored, which will have a significant impact on the operating frequency and output power. Based on the theory of electrostatics and considering the influence of each electrode, this paper established a three-dimensional solid model of the electronic tetrode, and the numerical simulation about the inter-electrode capacitance is calculated by the finite element software COMSOL. The obtained inter-electrode capacitance simulation calculation values are all within the actual test value range. On this basis, the relationship between the inter-electrode capacitance and the inter-electrode distance is studied, and the adjustable range of the electrode diameter is calculated. The finite element numerical simulation method calculated the inter-electrode capacitance of high-power tetrodes and the quantitative relationship between the inter-electrode capacitance and inter-electrode distance more accurately, which can provide a reference for the simulation and design of megawatt-level electronic tetrodes in the future.

1. Introduction
High-power electronic tetrode is the core component of the ion cyclotron range of frequency (ICRF) heating system in EAST. It is often employed as the final RF power amplifier to provide megawatt-level RF output power [1-3]. In actual high-frequency applications, the inter-electrode capacitance will become a non-negligible part of the oscillation circuit. It will have an impact on the operating frequency, which limits the operating frequency of the electronic tetrode. At the same time, the parasitic coupling generated by it will cause the instability of the amplification, which will have an adverse effect on the normal operation of the electronic tetrode. Therefore, in order to reduce some empirical experiments in the development process, it is of practical significance to use computer software to numerical simulate the inter-electrode capacitance of high-power electronic tetrodes for high-frequency applications.

This paper will discuss the high-frequency response of the electronic tetrode, analyze the relationship between the inter-electrode capacitance, the operating frequency and output power. According to the structure and parameters of a certain type of electronic tetrode produced by Chengdu Xuguang Electronics Co. Ltd, based on the concept of mutual capacitance in classical electrostatics, the electronic tetrode is considered as a multi-conductor system, and the finite element analysis software COMSOL is...
used to simulate and calculate the inter-electrode capacitance of the electronic tetrode.

2. High frequency response of electronic tetrode

When the electronic tube is used as an oscillator or amplifier, its output power will decrease continuously as the operating frequency increase, and even eventually it will unable to obtain effective oscillation or amplified output power [4], that is, the output power of the electronic tube tends to decrease with the increase of frequency. As shown in Figure 1, $f_{lim}$ is the limit frequency of the electron tube, at which the tube has stopped working. One of the main reasons for this phenomenon is the oscillation system of the electron tube [4-5].

\[
\text{Figure 1. Relationship between output power and frequency at high frequency}
\]

The electrodes of electronic tetrode and its leads have certain capacitance and inductance, which can be represented by the equivalent circuit shown in Figure 2. The capacitances and inductances of $C_{g2a}$, $C_{g1a}$, $C_{g2g1}$, $C_{g2k}$, $C_{ak}$, $L_a$, $L_{g1}$, $L_{g2}$, $L_k$ are all small, and their influence can be ignored during low-frequency operation. However, in high-frequency applications, the inter-electrode capacitance and lead inductance become the main factors that determine the frequency.

\[
\text{Figure 2. Equivalent circuit of tetrode at high frequency}
\]

If the electrodes work in case of a short circuit at the tube base, the highest operating frequency is given by

\[
f = \frac{1}{2\pi \sqrt{LC}}
\]

where $L$ is the equivalent inductance in the tube, and $C$ is the equivalent capacitance in the tube. When working at the highest operating frequency, the output power and efficiency of the tube is actually zero. It can be seen that the inter-electrode capacitance and lead inductance of the tube have certain restrictions on the high-frequency use of the tube. The existence of the inter-electrode capacitance will have an impact on the fundamental equivalent load impedance $R_{oe}$, which mainly depends on the characteristic impedance $\rho$ and the quality factor $Q$ of the loop [4], as expressed in equation (2).

\[
R_{oe} = \rho \cdot Q
\]

where $\rho = \sqrt{\frac{L}{C}}$, $Q = \frac{\rho}{\gamma}$. For the amplifier, if the $R_{oe}$ is too low, the output will drop, causing the amplifier to fail.

At the same time, the existence of the inter-electrode capacitance will also affect the gain [4]. When
the common cathode circuit is used, the gain expression is given by

\[ G = \frac{S}{4\pi C_{g1k} C_{g2a} \Delta f} \] (3)

In the formula, \( G \) is the gain (dB), \( S \) is the mutual conductance (mA/V), \( C_{g1k} \) is the capacitance between the cathode and the control grid (F), \( C_{g2a} \) is the capacitance between the anode and the screen grid (F) and \( \Delta f \) is the frequency bandwidth (Hz). Under the premise of ensuring bandwidth, according to Eq. (3), we know the effective way to increase the gain is to increase the mutual conductance and reduce the inter-electrode capacitance of the tube [4-5].

Therefore, the inter-electrode capacitance is an important factor that affects the normal operation of the electronic tetrode. Improving the structure of the electronic tube to reduce the influence of distributed capacitance is an important way to improve the working performance of tetrode [5].

3. Simulation analysis of inter-electrode capacitance of tetrode

3.1 Introduction and testing of tetrode

The electronic tetrode studied in this paper is a coaxial electrode structure, ceramic-metal tetrode with a directly heated thoriated tungsten cathode, a pyrolytic graphite grid and a hypervapotron cooling anode. The actual product is shown in Figure 3.

![Figure 3. Electronic tetrode](image)

The electronic tetrode is a mature product of Chengdu Xuguang Electronics Co. Ltd. The company has a complete electronic tube static parameter test room. The inter-electrode capacitance test is carried out in accordance with the national standard electronic tube inter-electrode capacitance test method. Through the actual test and inspection of a large number of this type tetrode, we have obtained the reference range of the inter-electrode capacitance, as shown in Table 1.

| Inter-electrode capacitance | Reference range (pF) |
|----------------------------|----------------------|
| \( C_{g1k} \)             | 73-85                |
| \( C_{g1g2} \)            | 110-130              |
| \( C_{g2a} \)             | 20-23                |

3.2 Calculation method of inter-electrode capacitance

In the simulation, the electronic tetrode is analyzed as a multi-conductor system [6], and the system satisfies the conservation of charge equation (4).

\[ \frac{\partial P}{\partial t} + \nabla \cdot J = 0 \] (4)

The potential of each electrode is not only related to the charge of the electrode itself, but also related to the charges of other electrodes. The relationship between charge, capacitance and potential [6-7] is given by
where $C_{ii}$ is the self-capacitance of the $i^{th}$ conductor, and $C_{ij}$ is the mutual capacitance between the $i^{th}$ conductor and the $j^{th}$ conductor. The simulation in this paper will lead to the concept of mutual capacitance to solve the inter-electrode capacitance of the electronic tetrode. When calculating $C_{ij}$, the potential $\varphi_{i+1}$, and the potential of all other electrodes is equal to zero, as expressed in equation (6) [6-8]. That is, during the solution process, the $i^{th}$ electrode is applied 1V and the other electrodes are grounded.

$$C_{ij} = \frac{Q_{ij}}{\varphi_{i+1} \varphi_{i} \varphi_{i-1} \cdots \varphi_{n}}$$

3.3 Simulation calculation of inter-electrode capacitance

According to the design drawings of the electronic tetrode provided by Chengdu Xuguang Company, the electrode components are drawn by computer 3D drawing software, and combined to establish a simulation model. The simulation model of tetrode diagram is shown in Figure 4. The simulation model consists of cathode, control grid, screen grid and anode. The simulation uses the electrostatic interface of the AC/DC module in the finite element analysis software COMSOL to calculate the inter-electrode capacitance of the electronic tetrode, import the built model into COMSOL, set the materials for each component, and then add four terminals of cathode, control grid, screen grid and anode in the electrostatic interface to set the boundary conditions and various physical parameters. The meshing is then completed, the meshing diagram is shown in Figure 5, and finally the steady-state solution is performed.

Taking the calculation of the capacitance $C_{g1k}$ between the control grid and the cathode as an example, according to the foregoing analysis, we set the control grid terminal voltage to 1V and other electrodes to 0V. After dividing mesh, steady-state solution is carried out to obtain the electric field distribution and the cathode terminal charge [8], as shown in Figure 6. According to Eq.(6), the value of $C_{g1k}$ can be obtained. The simulation calculation methods of $C_{g1g2}$ and $C_{g2a}$ are the same. The results are shown in Table 2, and compared with Table 1, it can be seen that the simulation calculation results are all within the reference range.
4. Analysis of the inter-electrode distance of tetrode

The cathode of the electron tube is responsible for emitting electrons, whose structure is the most complicated. The anode of the electron tube involves collecting electrons, and a reasonable anode cooling system has been designed, so the positions of the cathode and anode are not changed [5]. Firstly, adjust the distance between the cathode and the control electrode to obtain the distance range corresponding to the lower limit value 73pF and the upper limit value 85pF of $C_{g1k}$. Secondly, adjust the distance between the screen grid and the anode on the basis of the lower limit interval and the upper limit interval of $C_{g1k}$ respectively. Finally, the distance between the screen grid and the anode corresponding to the lower limit of 110pF and the upper limit of 130pF of $C_{g1g2}$ can be obtained. Through the simulation calculation, the simulation results are shown in Figure 7 and Figure 8. It can be seen that the inter-electrode capacitance shows a decreasing trend with the increase of the inter-electrode distance. Figure 7 shows that the adjustable range of the distance between the control grid and the cathode is 0.77-0.92mm, that is, the diameter of the control grid has an adjustable range of about 0.28mm. When the distance between the control grid and the cathode is 0.77mm and 0.92mm, the adjustable distance between the screen grid and the anode is 8.02-8.20mm and 7.85-8.03mm respectively, and the diameter of the screen grid has an adjustable range of about 0.36mm(Figure 8).
5. Conclusion

This paper has carried out a numerical simulation study on the inter-electrode capacitance of high-power electronic tetrode, and the simulation results are good. These studies provide a good reference for the next step of the nationalization of megawatt tetrode. The paper discusses that the operating frequency and output power of the tube are limited by the influence of the distribution parameters, and other factors such as the height of the cathode and the emission capability are not considered. Meanwhile, the electronic tetrode has complex structure with many parts. There is a slight deviation in the establishment of the three-dimensional solid model in the simulation experiments. In the following research, the three-dimensional solid model will be optimized, and considering the influence of multiple factors, the correlation between inter-electrode capacitance, operating frequency and output power will be further studied.

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