A tuning method for nonuniform traveling-wave accelerating structures

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Abstract: The tuning method of uniform traveling-wave structures based on non-resonant perturbation field distribution measurement has been widely used in tuning both constant-impedance and constant-gradient structures. In this paper, the method of tuning nonuniform structures is proposed on the basis of the above theory. The internal reflection coefficient of each cell is obtained from analyzing the normalized voltage distribution. A numerical simulation of tuning process according to the coupled cavity chain theory has been done and the result shows each cell is in right phase advance after tuning. The method will be used in the tuning of a disk-loaded traveling-wave structure being developed at the Accelerator Laboratory, Tsinghua University.

Key words: field tuning, nonuniform traveling-wave structure, reflection coefficient

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1 Introduction

A high power traveling-wave accelerator used for electron radiation is being built at Tsinghua University. The accelerator is operated in $2/3\pi$ mode with a frequency of 2856 MHz. Electrons are accelerated to a final energy of 10 MeV in a disk-loaded waveguide about 1900 mm long including a 300 mm bunching segment. Both the amplitude and phase velocity of the microwave are optimized to improve the capture efficiency. After machining, the resonant frequencies of the cells deviate from the designed value by about 2–3 MHz，resulting in cell-to-cell phase advance aberrations from the operating mode. Thus, tuning is necessary to avoid the above errors and minimize the reflections in the structure by changing the geometry profile of each cell.

The early way of tuning accelerating structures was the so-called SLAC-type method, which is difficult to use in tuning constant-gradient and nonuniform structures [1]. Refs. [1, 2] presented a new tuning method using the electric field distribution along the axis of an accelerating tube obtained from a bead-pull measurement. In this method, the field distribution was considered to be a linear superposition of forward and backward waves. The internal reflection of each cell was obtained by calculating the difference of the backward waves seen before and after that cell. After minimizing that reflection in real time by monitoring the global reflection coefficient variations from a network analyzer with some corrections, the corresponding cell was well tuned. Shi Jiaru clarified this method further and explained the tuning process of coupler cells. A related procedure was successfully used in tuning the CLIC accelerating structure prototypes at CERN [3]. However, applying the method to nonuniform structures was not discussed in these papers, which will be presented here.

2 The tuning method

For variable impedance systems like nonuniform structures, the microwave is usually represented by the normalized voltage. In this paper, the tuning method is based on the analysis of the normalized voltage instead of the field distribution. The method is suitable for tuning both uniform and nonuniform structures.

For a traveling wave propagating along an accelerator tube, the amplitude of the normalized voltage u is proportional to the square root of the transmitted power P, that is $u=\sqrt{2P}$. The phase of the normalized voltage is the same as that of the electric field. The transmitted power P and the electric field amplitude of the fundamental harmonic E are correlated by the shunt impedance per unit length Z, which can be described as $E^2=2\alpha ZP$ and α means the field attenuation per unit length. There is a proportionality factor between the fundamental harmonic and the total field (measured by the bead-pull method), and their phases are very close

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to each other in the center of the cavities. The factor can be obtained by way of numerical calculation. In the following text, when the electric field is mentioned, it means the field of the fundamental harmonic.

It is easy to see the relationship between the normalized voltage and the electric field:

$$u\mathrm{e}^{\mathrm{j}\varphi}=\frac{E\mathrm{e}^{\mathrm{j}\varphi}}{\sqrt{\alpha Z}}. \quad (1)$$

In the cases of uniform (or quasi-uniform) structures, like the constant-impedance and constant-gradient ones, the change of the product αZ between two adjacent cells is negligible. The forward and backward waves can be calculated by a linear decomposition of the electric field distribution rather than the normalized voltage, because they are approximately in proportion with each other according to Eq. (1). The complication caused by α and Z is avoided. However, when the cells are far away from each other, the attenuation factor of the field must be taken into consideration, which can be represented by the ratio of the forward waves of the two cells. This is useful for calculating the corrections between the internal reflection and the global reflection coefficient variations, as done in Refs. [1–3].

However, for nonuniform structures, the product of α and Z between two adjacent cells changes obviously, so the normalized voltage is not in proportion to the electric field. Take the traveling-wave accelerator at Tsinghua University as an example. The designed value of the electric field amplitude and the normalized voltage from the input coupler cell to the output one are shown in Fig. 1. The electric field along the bunching segment (first 11 cells) grows rapidly, while the normalized voltage decreases gradually. In this case, the tuning method should be based on the analysis of the normalized voltage, and the cell parameters α and Z also need to be taken into account. The reflection coefficient of each cell is derived as follows.

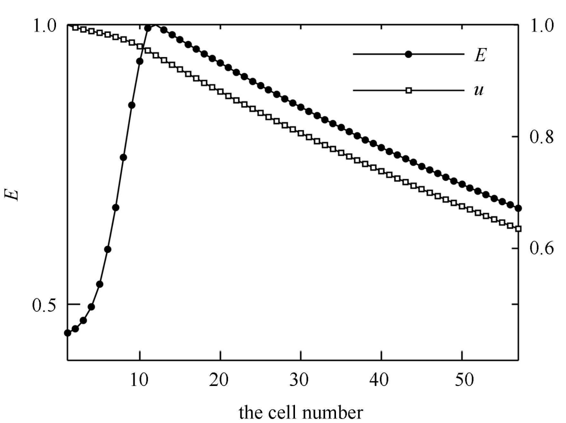

Fig. 1. The designed value of E and u (both normalized by the maximum).

The amplitude and phase of the field in the center of cell n from the bead-pull measurement are denoted as E_n and φ_n, respectively. The normalized voltage of cell n can be derived from Eq. (1). According to the linear model, the microwave is decomposed into a forward wave $a_n\mathrm{e}^{\mathrm{j}\psi_n}$ and a backward wave $b_n\mathrm{e}^{\mathrm{j}\phi_n}$ passing through disk n oppositely in the structure, as shown in Fig. 2. The phase advances of both forward and backward waves per cell are equal to the operating mode θ. The field attenuation between two adjacent cells is also considered, although it can be neglected.

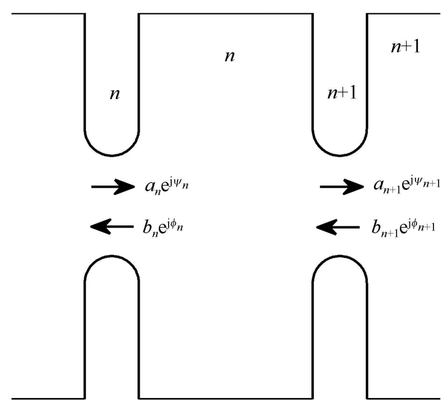

Fig. 2. The forward wave and backward wave.

For cell $n-1$ and n, $1<n<N$, we have

$$u_n\mathrm{e}^{\mathrm{j}\varphi_n} = a_n\mathrm{e}^{\mathrm{j}\psi_n}+b_n\mathrm{e}^{\mathrm{j}\phi_n}, \quad (2)$$

$$u_{n-1}\mathrm{e}^{\mathrm{j}\varphi_{n-1}} = C_n a_n\mathrm{e}^{\mathrm{j}\psi_n}+b_n\mathrm{e}^{\mathrm{j}\phi_n}/C_n, \quad (3)$$

where $C_n=\mathrm{e}^{\alpha_n D_n+\mathrm{j}\theta}$ and D_n is the length of cell n.

The solutions are obtained simply as follows:

$$a_n\mathrm{e}^{\mathrm{j}\psi_n} = \frac{u_n\mathrm{e}^{\mathrm{j}\varphi_n}-C_n u_{n-1}\mathrm{e}^{\mathrm{j}\varphi_{n-1}}}{1-C_n^2}, \quad (4)$$

$$b_n\mathrm{e}^{\mathrm{j}\phi_n} = \frac{C_n^2 u_n\mathrm{e}^{\mathrm{j}\varphi_n}-C_n u_{n-1}\mathrm{e}^{\mathrm{j}\varphi_{n-1}}}{C_n^2-1}. \quad (5)$$

For cell n and n+1, the forward wave $a_{n+1}\mathrm{e}^{\mathrm{j}\psi_{n+1}}$ and the backward wave $b_{n+1}\mathrm{e}^{\mathrm{j}\phi_{n+1}}$ can be obtained by changing the cell number in Eqs. (4) and (5).

All the incident waves and reflected waves of the n-th cell have been acquired. As an approximation, the cell is considered to be a symmetric two-port network. Thus the scattering parameters meet $s_{11}^{(n)}=s_{22}^{(n)}$, $s_{12}^{(n)}=s_{21}^{(n)}$, and there is

$$\begin{bmatrix} b_n\mathrm{e}^{\mathrm{j}\phi_n} \\ a_{n+1}\mathrm{e}^{\mathrm{j}\psi_{n+1}} \end{bmatrix}=\begin{bmatrix} s_{11}^{(n)} & s_{12}^{(n)} \\ s_{12}^{(n)} & s_{11}^{(n)} \end{bmatrix}\begin{bmatrix} a_n\mathrm{e}^{\mathrm{j}\psi_n} \\ b_{n+1}\mathrm{e}^{\mathrm{j}\phi_{n+1}} \end{bmatrix}. \quad (6)$$

Solving Eq. (6), we have

$$\begin{bmatrix} s_{11}^{(n)} \\ s_{12}^{(n)} \end{bmatrix}=\begin{bmatrix} a_n\mathrm{e}^{\mathrm{j}\psi_n} & b_{n+1}\mathrm{e}^{\mathrm{j}\phi_{n+1}} \\ b_{n+1}\mathrm{e}^{\mathrm{j}\phi_{n+1}} & a_n\mathrm{e}^{\mathrm{j}\psi_n} \end{bmatrix}^{-1}\begin{bmatrix} b_n\mathrm{e}^{\mathrm{j}\phi_n} \\ a_{n+1}\mathrm{e}^{\mathrm{j}\psi_{n+1}} \end{bmatrix}. \quad (7)$$

The $s_{11}^{(n)}$ in Eq. (7) is just the internal reflection coefficient of the n-th cell.

For the output coupler cell, which is connected to a matching load, the internal reflection coefficient is $s_{11}^{(N)}=b_N e^{j\phi_N}/a_N e^{j\psi_N}$.

For the input coupler cell, the forward wave can be approximated as $a_1 e^{j\psi_1}=a_2 e^{j(\psi_2+\theta)}$. In order to get the backward wave, let us consider the input port of the structure, where the incident and reflected waves are denoted as $a_0 e^{j\psi_0}$ and $b_0 e^{j\phi_0}$, respectively. According to the non-resonant perturbation theory [4], the incident wave has a phase angle of zero, namely, $\psi_0=0$. Thus the phase shift factor from the input port to the input coupler cell is $e^{j\psi_1}$. Assuming the matching waveguide is lossless, we have $a_0=a_1$ and $b_0=b_1$. If the reflection coefficient Γ at the input port is given by a network analyzer, we can get $b_0 e^{j\phi_0}=\Gamma a_0$ and $b_1 e^{j\phi_1}=\Gamma a_1 e^{-j\psi_1}$. So the internal reflection coefficient $s_{11}^{(1)}$ can be obtained from

$$\begin{bmatrix} s_{11}^{(1)} \\ s_{12}^{(1)} \end{bmatrix}=\begin{bmatrix} a_1 e^{j\psi_1} & b_2 e^{j\phi_2} \\ b_2 e^{j\phi_2} & a_1 e^{j\psi_1} \end{bmatrix}^{-1}\begin{bmatrix} b_1 e^{j\phi_1} \\ a_2 e^{j\psi_2} \end{bmatrix}. \tag{8}$$

When a cell is being tuned via the tuning studs, the cell frequency changes and the internal reflection decreases. Meanwhile, the global reflection at the input port is also changing. The process of tuning is to monitor the global reflection coefficient variation in real time by using a network analyzer until the cell internal reflection coefficient is minimized. The right value of global reflection coefficient variation is derived as follows.

The structure is considered as a two-port network consisting of N cascade-connected networks. Before tuning cell n, for example, the scattering matrix (s_n) is obtained by the above analysis, and the transmission matrix (T_n) can be easily derived [5]. Then the transmission matrix of the whole structure is $(T)=(T_1)(T_2)\cdots(T_N)$. The global reflection coefficient can be obtained as:

$$\Gamma_{\rm before}^{(n)}=\frac{T_{21}+T_{22}s_{11}^{(N)}}{T_{11}+T_{12}s_{11}^{(N)}}, \text{with } (T)=\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}. \tag{9}$$

After tuning, the scattering matrix of cell n is

$$(s_n)=\begin{bmatrix} 0 & 1/C_{n+1} \\ 1/C_{n+1} & 0 \end{bmatrix}. \tag{10}$$

Redoing the above calculations, we can get the global reflection coefficient after tuning $\Gamma_{\rm after}^{(n)}$. Thus we have $\Delta\Gamma_n=\Gamma_{\rm after}^{(n)}-\Gamma_{\rm before}^{(n)}$. If the plate of the input port during tuning is the same as the one during measurement, the n-th cell is well tuned until the global reflection variation reaches $\Delta\Gamma_n$. If not, the direction of the frequency deviation is determined by the method in Ref. [3] and the amplitude of the reflection variation equals to $|\Delta\Gamma_n|$ after tuning. The calculations can be done easily by using a computer.

3 Numerical simulation

A computer program is written to test the effectiveness of the tuning method with designed parameters of the traveling-wave accelerator at Tsinghua University. The structure is composed of 57 cells, including an input coupler followed by 10 bunching cells, 45 regular cells and an output coupler. The geometric parameters and microwave quantities of each cell, such as the length, resonant frequency, Q value, shunt impedance per length, group velocity, and the intercell coupling constant, are computed by using the SUPERFISH code.

Before tuning, a set of random perturbations to the resonant frequencies is added manually. The coupling factors and frequencies of the coupler cells are roughly tuned by the method presented in Ref. [6]. According to the coupled cavity chain theory, the field distribution is generated by solving the equivalent circuit equations directly after setting the input power. The global reflection coefficient at the input port of the structure is also calculated by the equivalent circuit equations [7].

The program computes the internal reflection coefficient of each cell and gives the relative variation of global reflection coefficient according to the tuning method mentioned in the above section. When a cell is being tuned, the program searches a wide band of frequencies, and finds the best one to meet the global reflection coefficient variation as the right resonant frequency of that cell. After tuning all the cells, the field distribution, phase advance errors and the internal reflection coefficients are plotted.

The random perturbations of resonant frequencies are set at 2 MHz and the results after tuning twice are shown in Fig. 3. The electric field distribution is nearly the same as the designed value in Fig. 1. The standard deviation of phase advance $\sigma_{\rm ph}$ is corrected to less than $0.1°$. The internal reflection coefficients of all the cells after tuning are smaller than 0.01, which demonstrates a good tuning effect for both bunching cavities and regular ones. By way of contrast, the tuning method based on the analysis of the electric field without considering α and Z has also been tested. The result gives no improvement of phase distribution at the buncher.

The tuning method can be used in optimizing the designed value of the resonant frequencies and intercell coupling constants of bunching cavities to achieve an excellent traveling wave in the structure. When designing a bunching cavity, one always uses a uniform structure as an approximation to do numerical calculations. As a result, reflection occurs in the cavity because it is actually nonuniform. The reflection can be obtained from the above tuning method and minimized to zero by tuning the coupling constant and resonant frequency respecti-

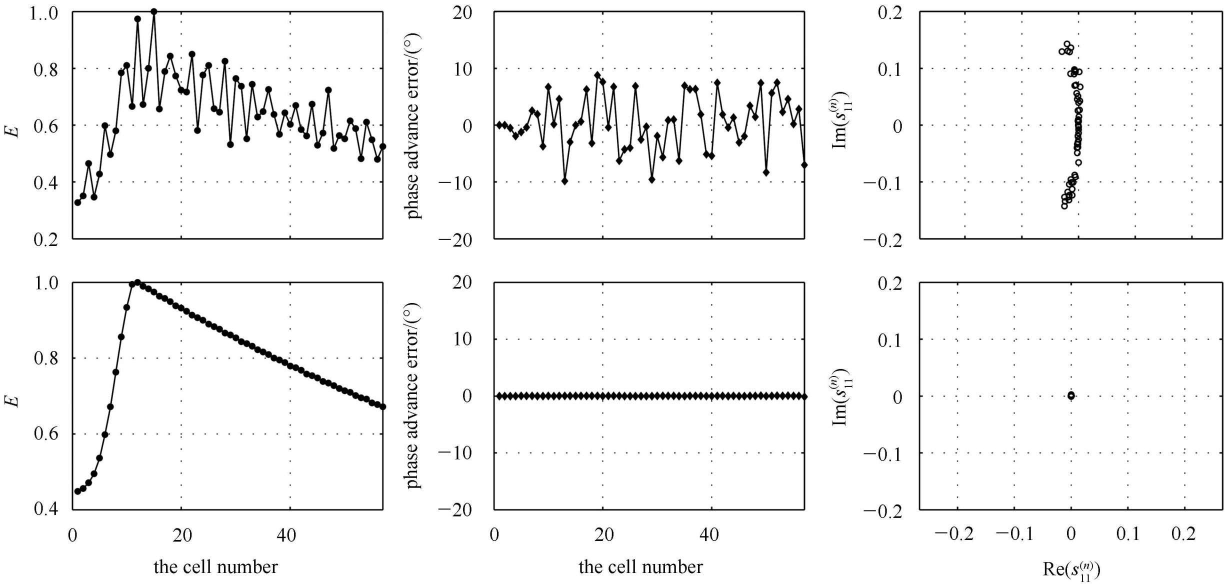

Fig. 3. The results before (up) and after (down) tuning (left: normalized amplitudes of electric field distribution; middle: cell-to-cell phase advance errors; right: the calculated cell internal reflection coefficients).

vely. Thus the optimum values of these quantities are found. This work has been done in optimizing the structural parameters of the accelerator at Tsinghua University.

4 Conclusions

The method of tuning nonuniform structures based on the non-resonant perturbation field distribution measurement is presented, which can also be applied to tuning uniform structures. A numerical test of tuning is carried out and the result shows the method is effective ($\sigma_{\rm ph}$ is less than 0.1° for phase advance at random frequency errors of 2 MHz). A computer program is being developed, aiming to be used in tuning the traveling-wave accelerator at Tsinghua University.

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