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DESIGN OF A FULLY AUTOMATED TEST BENCH FOR MESURING THE FIELD DISTRIBUTION OF STANDING WAVE CAVITY*

Y. Lu, T. N. Hu, G. Y. Feng, J. Jiang, X. D. Tu, Y. Q. Xiong
School of Electrical and Electronic Engineering,
Huazhong University of Science and Technology, Wuhan, China

Abstract

The resonant cavity plays a great role in the linear accelerator. An accurate measurement of the cavity field distribution is very important to design linear accelerators. A fully computer controlled bench for the electric field distribution has been developed in this context. Based on the perturbation theory, the acquisition of the resonant frequency shift is proportional to the square of E (electric field). In order to verify the reliability of the test bench, a standard cylindrical cavity has been tested in this measurement system. The simulation by HFSS (High Frequency Structure Simulator) and the practice will be both presented in this paper. And the result demonstrates that, because of its high concentricity, the automated test bench achieves high precision in measuring the distribution of electric field.

INTRODUCTION

RF cavities can support various electromagnetic fields. When designing a cavity to accelerate electrons, the field distribution should be calculated analytically. Bead pulling method based on perturbation theory is the most common technique to measure the field distribution in the cavity. This paper describes that a fully automated test bench that has been applied to detect the electric field distribution. The test bench has a compact structure, but realizes an accurate measurement and costs a little time to complete measurement due to automated measurement system.

BASIC PERTURBATION THEORY

The perturbation theory describes that the presence of a small volume of dielectric sample in the resonant cavity can make a slight change in resonant frequency and perturb the electromagnetic field [1]. The frequency shift is related to the intensity of electric field and magnetic field where the dielectric sample exists. According to Maxwell equations, the equation between frequency shift and electromagnetic parameters can be given as

$$\frac{\omega-\omega_0}{\omega_0} \approx -\frac{\int_{\Delta V}(\Delta\varepsilon|\boldsymbol{E}_0|^2+\Delta\mu|\boldsymbol{H}_0|^2)\mathrm{d}\Delta V}{\int_V(\varepsilon|\boldsymbol{E}_0|^2+\mu|\boldsymbol{H}_0|^2)\mathrm{d}V} \quad (1)$$

The volume of resonant cavity is V. In the unperturbed state, let the relative permittivity and the magnetic permeability be ε and μ. The electric field and magnetic field are $\boldsymbol{E}_0$ and $\boldsymbol{H}_0$, and the resonant frequency is ω_0. After placing a conductor sample whose volume is ΔV in the cavity, the electric field, the magnetic field and the resonant frequency become $\boldsymbol{E}$, $\boldsymbol{H}$ and ω. Let the relative permittivity and the magnetic permeability of the bead be $(\varepsilon+\Delta\varepsilon)$ and $(\mu+\Delta\mu)$.

For cylindrical accelerating cavities work at the TM010 mode, the magnetic field on the central axis is zero, namely $\boldsymbol{H}=0$ at $r=0$, where r is the radial position in the cavities. So if the dielectric sample is placed on the central axis, in the region of the sample, the equation (1) can be simplified as

$$\frac{\omega-\omega_0}{\omega_0} \approx -\frac{\int_{\Delta V}(\Delta\varepsilon|\boldsymbol{E}_0|^2)\mathrm{d}\Delta V}{\int_V(\varepsilon|\boldsymbol{E}_0|^2+\mu|\boldsymbol{H}_0|^2)\mathrm{d}V} \quad (2)$$

Hence,

$$E_z(r=0,z) \propto \sqrt{\Delta f(z)} \quad (3)$$

Therefore, it's feasible to get the distribution of axial electric field by moving the dielectric sample along the central axis and measuring the resonant frequency point by point.

MEASUREMENT PROCEDURE OF THE TEST BENCH

According to the perturbation theory, the axial electric field is acquired by measuring the resonant frequency when a metallic conductor sample is displaced through the cavity. In the design of automated test bench, a small bead is used as a small conductor sample and it is moved by the bead displacement system which consists of a wire, a stepper motor and several pulleys. The bead gets accurate position along the central axis by a stepper motor, which is controlled by a computer over a LAN(Local Area Network). Besides the resonant frequency of cavity could be measured by the VNA(Vector Network Analyzer) with the same control method. An agilent E5061B VNA measures the S11 transmission coefficient through the cavity and find the resonant frequency [2, 3]. And it offers an excellent stability and accuracy, and an easy control via LAN.

Thus, the data collection and processing are achieved automatically. The design of automated measurement system, shown in Figure 1, could obtain the distribution of the axial electric field by perturbation method. The components of the measurement system: a computer, a VNA, a cylindrical cavity excited by a probe, a stepper motor and several pulleys.

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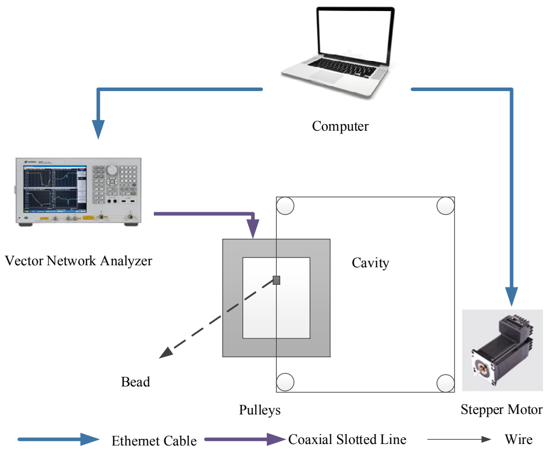

Figure 1: The scheme of automated measurement system.

Based on LabVIEW, the system program consists of program module for main control, communication module for stepper motor and VNA, data processing and online display module. Figure 2 presents the block diagram of the main program.

The automated measurement system prevents the measurement error from manual operation and avoids the measurement error which is caused by the jitter of the bead. Therefore, it's convenient and efficient to measure the axial electric field of microwave cavity with high precision.

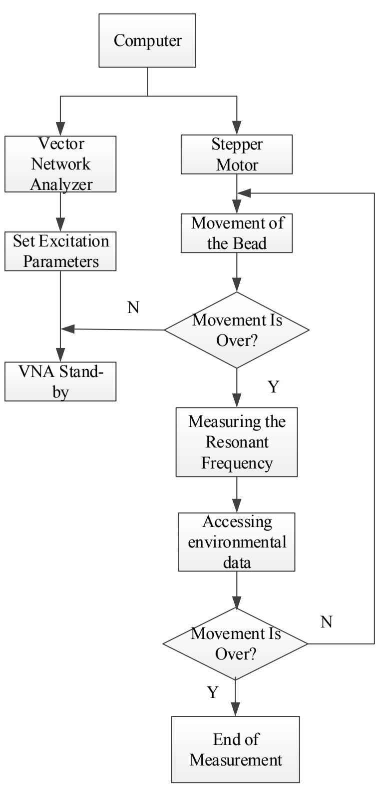

Figure 2: The block diagram of the main program.

SIMULATION AND MEASUREMENT

After establishing the test bench, in order to verify the reliability of the test bench, a standard cylindrical cavity has been used for detecting the axial electric field by this measurement system. The results of the measured electric field will be compared with the simulation results.

An S-band cavity has been designed in ANSYS HFSS software as shown in Figure 3 [4]. The radius of the cavity is 40.2mm, the length is 50.2mm, and the wall thickness is 10mm.The material of the cavity is aluminum. There are two holes on the cross section. And they will allow the bead to move through the central axis of the cavity to complete the measurement of the electric field and they are also used as beam holes in linear accelerator. The radius of the hole is 2.5mm. The cavity is excited via an external coupling probe whose material is copper. And the coupling probe is formed by extending the feeding coaxial cable.

According to probe coupling theory, the current in the probe is small, but the voltage creates an electric field between the probe and the adjacent wall of the resonator. The filed radiates energy into the resonator like a small monopole antenna. The mode in the cavity and the strength of the electromagnetic field are related to the position and the length of the probe [5]. Considering the size of the N to SMA adapter, the section radius of the coupling probe is 0.5mm.

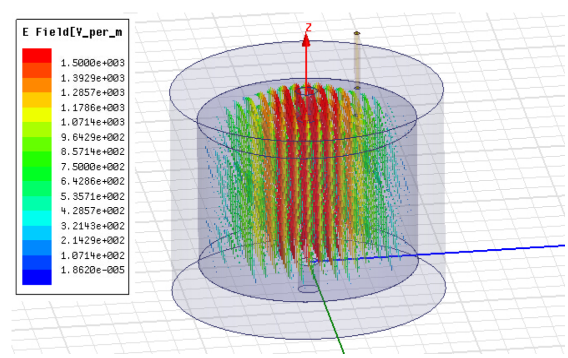

Figure 3: Design of an S-band resonant cavity and the electric field inside cavity.

Since TM010 is the mode that we need, the probe should locate at the top place of the cavity and unwanted modes can be avoided. And the electromagnetic field should be as large as possible so that the resonant frequency shift could be measured. After several simulations, the length of the coupling probe might better be 4mm. Figure 3 also shows the simulation of the electric field inside the TM010 mode resonant cavity.

The automated measurement system is shown in Figure 4. The bead displacement system consists of 6 pulleys so that the bead could realize movements on both horizontal and vertical directions. Therefore, different kinds of cavities could be measured by this system.

In the practice, the parameters of the resonant cavity are the same with parameters of simulation. The radius of the bead is 1mm and its material is stainless steel. The motor step size is 1mm.

Before operating the system, it's necessary to adjust the position of pulleys which are collinear with the bead, so that the moving trail of the bead coincides with the central

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axis of the cavity. And the basis of the coincidence between the bead and the axis is that the guiding wire is collinear with the axis. The direction of guiding wire is the horizontal tangent line of the bottom of pulleys on both sides of the bead. If the geometric center of the bead coincides with the center of the beam hole in the entrance and exit of the cavity, then it satisfies that the bead moves along the central axis of the cavity.

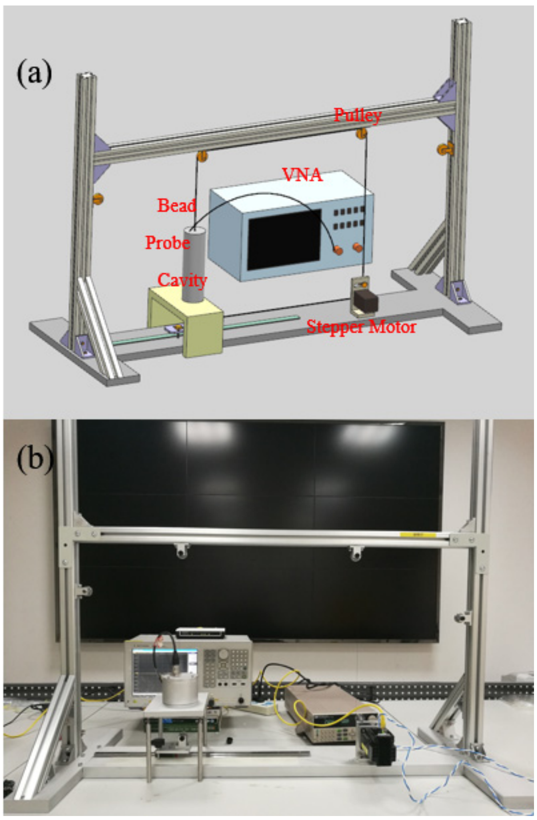

Figure 4: The automated measurement system. (a) design drawing (b) photograph of the system.

From the S11 data of VNA, the resonant frequency without perturbation is 2848.497MHz and in the perturbed state, the maximum value of frequency shift is 2MHz. The reasons why the resonant frequency is smaller than 2856MHz are machining error and the influence of air. The relationship between frequency in air and frequency in vacuum could be given as

$$f_r \approx \frac{f_0}{\sqrt{\varepsilon_r}} \tag{4}$$

f_r is the resonant frequency in the air, f_0 is resonant frequency in the vacuum and ε_r is relative permittivity of the air. ε_r could be figured out by the following equation.

$$\varepsilon_r = 1 + 210\times10^{-6}\frac{P_d}{T} + 180\times10^{-6}\left(1+\frac{3580}{T}\right)\frac{P_w}{T} \tag{5}$$

The T is the environment temperature. P_w and P_d are the water vapor pressure and the dry air pressure respectively, which could be given by the air humidity. When the temperature is 18□ and the humidity is 75%, the resonant frequency in the air is 2855MHz. It implies that the machining error has a greater impact on the resonant frequency than the environment.

After data processing, Figure 5 shows normalized electric field curves about simulation and measurement. The electric field intensity of measurement is smaller than that of simulation at the entrance and exit of the cavity. Maybe it's because that the bead makes a large perturbation at the entrance and exit and results in the distortion of measurement result [6]. But if the size of the bead is too small, the bead won't perturb the cavity so that the resonant frequency shift is impossible to be measured. In the cavity, the distribution curve of the electric field intensity is in good agreement with that of simulation. Compared with the traditional manual measurement, the automated measurement system has an excellent accuracy of position and a good repeatability of measurement. The measurement error has been reduced as much as possible. It's a highly efficient measurement and it takes no more than 5 minutes to complete the measurement after choosing a reasonable step size of the stepper motor.

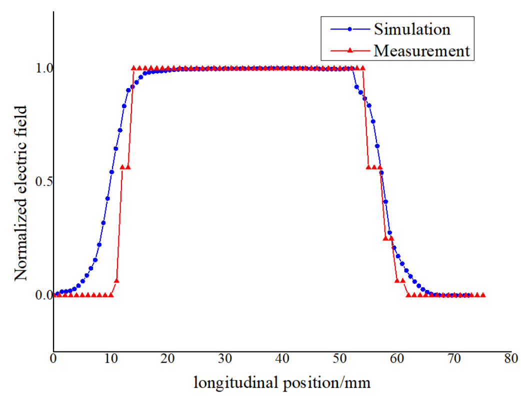

Figure 5: Electric field curves of simulation and measurement.

CONCLUSION

The fully automated test bench has turned out to be efficient by measuring the electric field distribution of an S-band cylindrical cavity. The automation and high sensitivity of the bead displacement system is very important to the measurement system.

Compared to traditional measurement, the measurement system has a high accuracy and saves time, furthermore the complete system has a compact structure and is easily transportable.

The system program is based on LabVIEW. Due to its convenient operation and easily extending function, the measurement system can be easily adapted to measure other parameters such as Q factor and R/Q. In the future, and it will be used for measurement in other normal conducting cavities.

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