Bead-Pull RF Measurement System

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Summer Internships in Science and Technology(SIST)

Internship Program, 2011

August 11, 2011

Abstract

Bead-Pull is a commonly used Radio Frequency (RF) field measurement technique. RF field measurements play an important role in qualifying any RF cavity. They are used in evaluating the field distribution inside a resonant structure and in tuning them to obtain the required field flatness [1]. The Bead-Pull system consists of a small dielectric or metallic bead being pulled through a cavity while the electric field measurement in the cavities is done. A step motor and a pulley system guide the motion of the bead through the cavity while a Network Analyzer is used to take the RF measurements. We wrote a program in National Instruments' Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) to control the hardware of a Bead-Pull system. The software will coordinate the step motor's movement, acquire data via the Network Analyzer and process the data as required. This paper describes the development and the testing of this software.

Key Words: *Bead-Pull RF Measurement System, Step Motor, LabVIEW, Network Analyzer.*

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1 Introduction

1.1 Fermilab

Fermi National Accelerator Laboratory (Fermilab) enhances the understanding of the nature of matter and energy by providing the resources for researchers to conduct research in high energy Physics and other related disciplines. I interned in the Antiproton Source (Pbar) department which is part of the Accelerator division. While here, I developed a software to be used in controlling the Bead-Pull Radio Frequency (RF) measurement system which will be used in the development and testing of cavities in the Linear Accelerator (LINAC) department of the Accelerator division.

1.2 Bead-Pull RF System

Bead-Pull Radio Frequency (RF) measurement system consists of a small dielectric or metallic bead being pulled through a cavity while electric field measurements in the cavity are taken. RF field measurements play an important role in qualifying any RF cavity. These field measurements are also used in the tuning of the cavities to obtain the required field flatness. The Bead-Pull method is based on the classical Slater perturbation theory which states that if any resonant cavity is perturbed by a small bead, its resonant frequency shifts from the original frequency. This frequency shift is proportional to the combination of the squared amplitudes of the electrical and magnetic fields at the location of the bead [1]. This relationship is given by equation 1 [2].

$$\frac{\omega^2 - {\omega_0}^2}{{\omega_0}^2} = k \int_{\Delta r} \frac{\mu H^2 - \epsilon E^2}{2U} \, dv \tag{1}$$

where ω and ω_0 are the new and the original resonant frequencies respectively, k is a constant determined by the shape of the bead, μ is the permeability constant, ϵ is the permittivity constant, U is the energy stored in the cavity while E and

H are the electric and magnetic field amplitudes respectively. From this equation, we realize that, if the magnetic field is zero (which is the case along the center of the cavity), the electric field is directly proportional to the change in resonant frequency. Therefore, if the change in resonant frequency is known, the electric field can be determined by moving the bead along a line in the cavity.

2 Tools and Methods

The hardware of Bead-Pull system consists of a Network Analyzer, a Step Motor, and miscellaneous parts such as the pulleys and the thread. The Step Motor moves a small metal or a dielectric bead linearly through a cavity. The Network Analyzer measures the change of resonant frequency which is related to the local electrical field where the bead passes. This information is useful to evaluate the field distribution or tuning of an RF resonant structure. A program is needed to coordinate the Step Motor's movement,the data acquisition of the Network Analyzer and to process the acquired data.

2.1 Network Analyzer

A Network Analyzer is an instrument that measures network parameters of electrical networks. It commonly measures the scattering parameters (S-parameters) and is mostly used at high frequencies. This is because, at high frequencies, the wavelength of signals of interest is comparable to or much smaller than the length of conductors [3] and is therefore harder to measure voltage and current. Network analyzers can measure both linear and non-linear behavior of devices. Network Analysis is concerned with the accurate measurement of the ratios of the reflected signal to the incident signal as well as the transmitted signal to the incident signal.

2.1.1 S-Parameters

S-parameters are used to characterize high frequency circuits in place of the impedance or admittance parameters that describe the low frequency circuits. S-parameters relate the transmitted or reflected waves to the incident waves while Z-parameters (impedance parameters), for example, relate port voltages and currents. An N-port device has N^2 S-parameters. Parameters such as S_{11} and S_{22} are referred to as the reflection coefficients because it is the ratio of the wave coming out of a given port to the wave incident at that port. The other S-parameters such as S_{12}, S_{21} are referred to as the transmission parameters because they refer to the ratio of the wave coming out of a different port than was incident into.

2.2 Step Motor

(a) HT23-601 Step Motor (b) Step Motor Driver (c) Power Supply

Figure 1: *Applied Motion Instruments*

We used a Step Motor to move the bead across the cavity. A Step Motor consists of a permanent magnet rotating shaft called a rotor. The Step Motor converts digital pulses into mechanical shaft rotation. Every rotation is divided into many discrete steps and it can stop at any step making it suitable for small movements. It has an excellent response to starting, stopping and reversing. However, it is hard to operate at high speeds and resonance can occur if not properly controlled. We used the Applied Motions' HT23-601 Step Motor shown in Figure 1a which is suitable for a wide range of motion control applications. It was set to 20,000 steps per rotation and we observed that for our pulley system setup, approximately 255 steps were required to move the bead by 1mm using this Step Motor. The Step Motor was run using the Applied Motions ST5-Plus Step Motor Driver shown in Figure 1b. We also used Applied Motions 24V PS150A24 Power Supply (shown in Figure 1c) to power the Step Motor and the Step Motor Driver.

2.3 LabVIEW Program

The entire program was written in National Instruments Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) software, a graphical programming environment that contains comprehensive set of tools for acquiring, displaying, analyzing and storing data. A LabVIEW program is called a virtual instrument (VI) and each VI has both a front panel and a block diagram. A front panel displays the controls and indicators while a block diagram shows how all the controls and the indicators are connected together to achieve the desired purpose. In order to develop the Bead-Pull software, we started with learning the commands necessary for performing the required operations for both the Step Motor and the Network Analyzer by reading their programming manuals and then integrating the commands to form VIs that control each individually. We then finally combined all the VIs to form an overall LabVIEW measurement program that moves the bead via the Step Motor and takes the measurements via the Network Analyzer.

2.3.1 Network Analyzer VI

The Network Analyzer VI provides an option of selecting the Network Analyzer model that is being used to take the measurements, does a single sweep and takes specified measurements (error corrected data or resonant frequency). For the resonant frequency measurements it takes the data at a given point a number of times specified by the user and averages them for better measurements. This VI also displays the measurements on the screen and converts them into the desired format.

Table 1: Network Analyzer Commands

Command	HP 4396A	Agilent 8720ES	HP 8751
Single Sweep	SING	SING	SING
In hold mode?	HOLD?	HOLD?	HOLD?
Output error corrected data	OUTPDATA?	OUTPDATA	OUTPDATA?
Wait for clean sweep	NE[1]	WAIT	NE[1]
Number of data points/sweep	POIN?	POIN?	POIN?
Returns the start frequency	STAR?	STAR?	STAR?
Returns the stop frequency	STOP?	STOP?	STOP?
Outputs active marker values	OUTPMKR?	OUTPMARK	OUTPMARK?
Previous operations complete?	NE[1]	OPC?	NE[1]

[1] No Equivalent

The program can be used with any of these three Network Analyzers: Agilent 8720, HP 4396A and HP 8751. Table 1 outlines the similarities and differences between the commands for the three Network Analyzers. To perform a single sweep, we issue the command SING which is similar for all the analyzer models. The program needs to wait until the Network Analyzer is done sweeping and is in the hold mode before the data is read from the Network Analyzer. To ensure this, the program issues another command, HOLD? which returns 1 when the analyzer is in the hold mode. Once the response is 1, the program starts taking measurements by issuing the output data command (to get the error corrected data) or the output marker value command to get the resonant frequency.

2.3.2 Step Motor VI

The Step Motor VI controls the motion of the bead via the rotation of the Step Motor. This VI calculates the number of steps required for one step size and moves the motor by that number of steps using the Feed to Length (FL) command. Table 2 shows a list of the commands used in this VI.

Table 2: Step Motor Commands

Command	Function	Explanation
AC	Acceleration Rate	Sets the Acceleration Rate. AC5 will set the acceleration rate to 5 Rev/s^2
AR	Clear Alarm	Clears Alarms and drive faults and leaves the motor in the disabled state.
CC	Change Current	Also known as the running current.
DE	Deceleration Rate	DE5 sets the Deceleration Rate to 5 Rev/s^2
FL	Feed to Length	FL20,000 will move the motor 20,000 steps in the clockwise direction
ME	Motor Enable	Restores drive current to motor.
PM	Power up Mode	It sets or requests the power up mode of the drive.
RE	Restart or Reset	This restarts the drive by resetting default conditions and reinitializing the drive with the startup parameters. It leaves the drive in a disabled state.
SM	Stop Move	Stops motion, but does not stop any WAIT commands
ST	Stop	Stops the motion immediately using the deceleration rate set by the maximum acceleration
VE	Velocity	VE5 would set the velocity to 5 Rev/s

2.3.3 Overall Bead-Pull System VI

The overall Bead-Pull software sets the parameters of the Step Motor, such as the velocity, the acceleration rate and the deceleration rate. It begins taking the measurements starting with the original position of the bead. This VI then calls the Step Motor VI to step the bead by the amount specified by the user in the step size input box and calls the Network Analyzer VI to take the measurements. This procedure is repeated while the data collected is appended to the previous data until the bead reaches the stop distance set by the user. Once it reaches the stop position, it writes all the data collected into a spreadsheet file whose location and name has to be specified by the user. It also displays a graph of the resonance frequencies against the data points on the front panel if it is in the resonant frequency measurement mode. Finally, it moves the bead back to the start position. Figure 2 shows the front panel of this VI.

3 Data and Conclusion

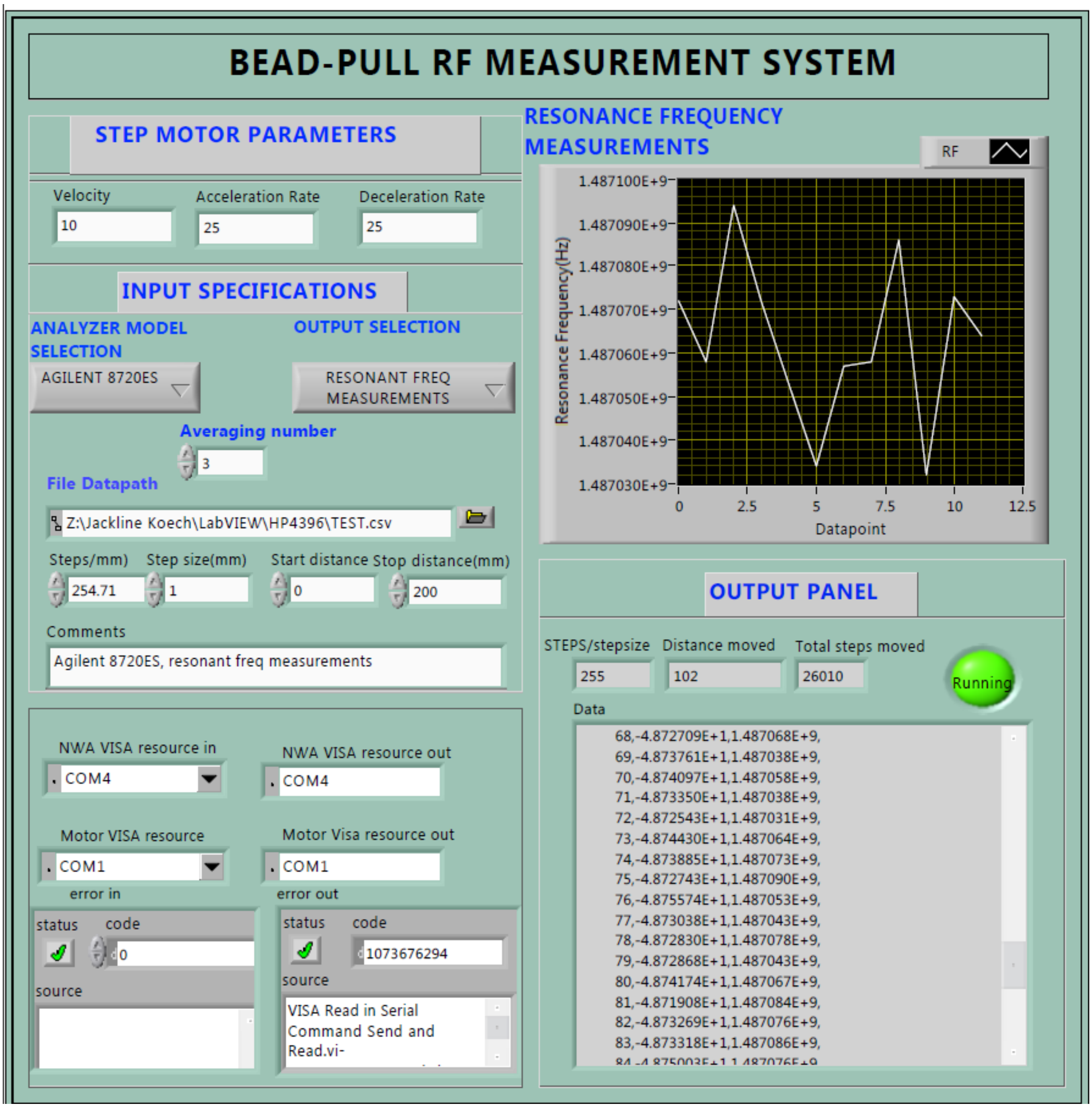

Figure 2: *Front Panel of the Bead-Pull Measurement System*

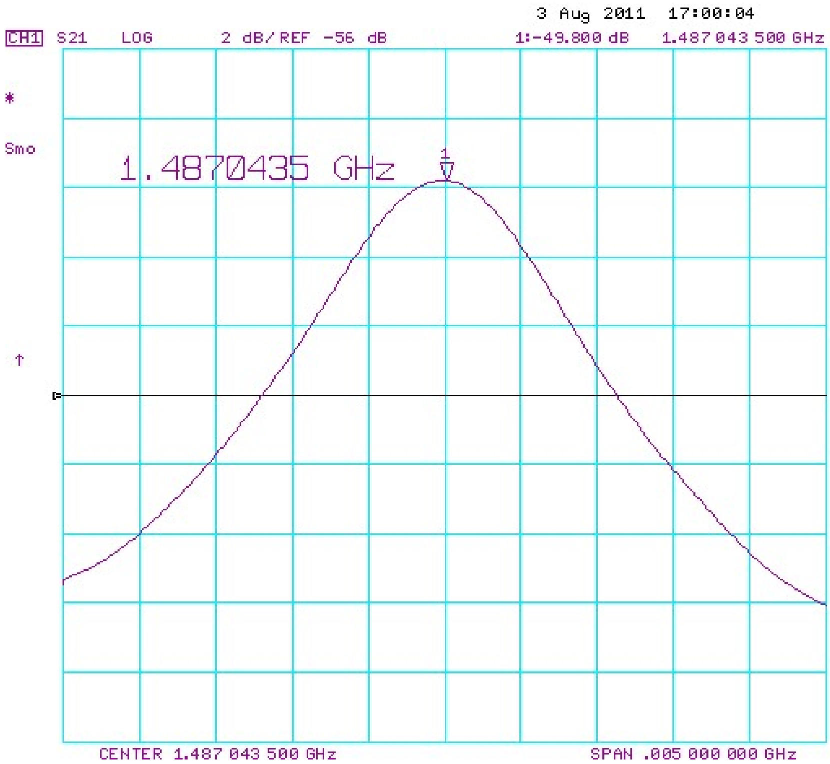

Figure 3: *Resonance Frequency Measurement*

We tested the program using a pill box test cavity (shown in Figure 4) which has a radius of 12.057cm and a length of 1.575cm with beam pipes attached on both sides. First, we were able to confirm that our software moved the bead as expected and that the steps could be repeated accurately. By taking the measurements while watching the measurements displayed on the Network Analyzer, we were also able to confirm that the program read the measurements correctly from the Network Analyzer. Figure 5 shows the graph of the resonant frequency measurements that we acquired using this test cavity. To get the resonant frequency at each datapoint, we measured the S_{21} parameter as shown in Figure 3. with the resonant frequency being the frequency at which the peak of the S_{21} occurs. As anticipated, when the bead enters the cavity the resonance frequency shifts from the original frequency (measured when the bead is outside the cavity) and reaches maximum at center of the cavity as shown in Figure 5. However, the noise level was very high in our first set of data. This was contributed to by the vibration of the thread, attached to the bead, as the bead was moved by the Step Motor. We reduced these vibrations by tightening the thread. We also included an option in the program that allows the user to input the number of times to the average data at each datapoint for more consistency. We ran the program with different values for averaging and we found that three was the optimum value that improved the data to a great extent without slowing down the program too much.

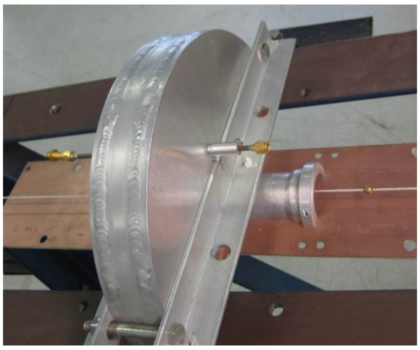

Figure 4: *Pill Box Test Cavity*

In conclusion, we have successfully developed a software that controls the Bead-Pull RF Measurement System by moving the bead and taking the measurements accurately.

4 Acknowledgments

I would like to thank Fermilab and the SIST committee for the opportunity to participate in the SIST program again this summer. Many thanks to my supervisor, David Peterson for the great mentorship throughout the summer and Ding Sun and his group for setting up the project and making sure that it was working. I would

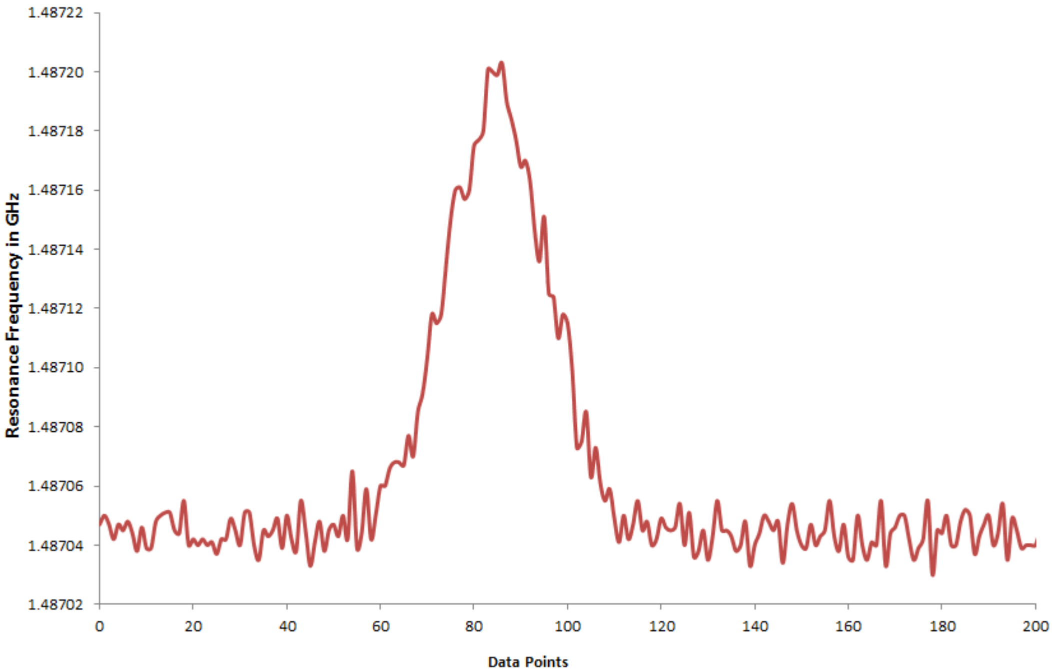

Figure 5: *Graph of Resonance Frequency Measurements of the Pill Box Test Cavity*

also like to extend my gratitude to my mentors, Cosmore Sylvester and Mayling Wong for making sure everything was running smoothly and Dr. James Davenport for the important information on paper writing and presentation. Finally, I would like to thank all the employees at the Antiproton Source Department for all their support and all those who made my experience at Fermilab a memorable one.

References

[1] S.V. Kokil D.S. Rajpoot S.K. Chauhan, S. Raghavendra and S.C. Joshi. *Development of Automated Test Bench for Measurement of the Field Distribution in Single Cell Elliptical Superconducting Cavity*. Raja Ramana Center for Advanced Technology, Indore (MP), INDIA.

[2] Edward Ginzton. *Microwave Measurements*. 1957. p 448.

[3] Agilent Technologies. Agilent network analyzer basics. Website, August, 2004. `http://cp.literature.agilent.com/litweb/pdf/5965-7917E.pdf`.