CONTROL SYSTEM DESIGN FOR AUTOMATIC CAVITY TUNING MACHINES *

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Abstract

A series of four automatic tuning machines for 9-cell TESLA-type cavities are being developed and fabricated in a collaborative effort among DESY, FNAL, and KEK. These machines are intended to support high-throughput cavity fabrication for construction of large SRF-based accelerator projects. Two of these machines will be delivered to cavity vendors for the tuning of XFEL cavities. The control system for these machines must support a high level of automation adequate for industrial use by non-experts operators. This paper describes the control system hardware and software design for these machines.

INTRODUCTION

For a β=1 multicell SRF cavity, the fields in neighboring cells must be close to equal in amplitude and π radians out of phase with each other and the particle must cross a cell in one-half an rf period. This flat field profile is achieved when the cells are properly tuned relative to each other and cavity frequency is equal to the design frequency (e.g., 1.3 GHz for an ILC cavity at 2K in vacuum) [1]. In addition, the tuned cavity must meet dimensional tolerances such as length, straightness and eccentricity.

Cell-to-cell tuning is usually accomplished by slightly deforming each cell until the desired cell frequency is obtained. This procedure is generally needed only after initial fabrication and after significant etching or deformation due to heat treatment.

Typical tuning methods are based on special tooling to perform mechanical deformation of each cell manually by an expert operator. This is a very time-consuming activity, not suitable for production of hundreds of cavities required for new SRF-based accelerators such as the XFEL.

An alternative method is illustrated by an automated tuning machine that has been in operation at DESY for some time. This machine is based on three independent motorized “jaws” that can squeeze or stretch a cell while keeping the cavity straight. This machine is the basis for a new series of four automated tuning machines being developed in a multi-laboratory collaboration (DESY-FNAL-KEK). These new machines are expected to significantly reduce the time it takes to characterize and tune a cavity to approximately four hours or less using less expert operators.

Based on their experience with the existing machine, DESY is fabricating improved mechanical assemblies for all four machines, including all necessary motors and sensors. Fermilab is developing an improved control system (hardware and software) for all four machines. This paper will focus on the control system design aspects of this project.

CONTROL FUNCTIONS

The following functions must be supported by the cavity tuning machine control system:

- Cavity transport along the base frame
- Eccentricity measurements of each cell and perpendicularity measurement of end plates
- Field distribution measurements for all nine monopole modes using a standard “Bead-Pulling” technique [1]
- Frequency correction prediction for each cell using a first-order perturbation method [1], [2]
- Mechanical deformation of each cell using three independent motorized “jaws” to achieve the calculated frequency correction while keeping the cavity straight
- Different tuning procedures for end cells

The control system must support two operating modes: normal mode and maintenance mode. In normal operating mode, equipment interlocks are used extensively to prevent damage to a cavity or the machine equipment. In maintenance mode, equipment interlocks can be bypassed by an expert operator.

The operation of the tuning machine can expose personnel to hazards associated with mechanical motion driven by powerful motors. The control system must support the following personnel safety functions:

- Emergency Stop: immediately remove power from moving devices when an Emergency Stop pushbutton is pressed
- Motion Inhibit: immediately stop or prevent motion when machine guarding sensors trip, indicating proximity of personnel to moving parts

These functions must be in compliance with the new European Union machine safety standard EN ISO 13849-1 because two of these machines will be delivered to European industry to support XFEL cavity fabrication.

CONTROL DEVICES

Figure 1 shows a view of the tuning machine under fabrication.

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Figure 1: Tuning Machine Mechanical Assembly in Progress.

Motion is provided by six Phytron stepper motors and three Elero linear actuators. The linear actuators move each tuning arm in or out. Stepper motors close or open each tuning jaw, pull the bead, rotate eccentricity measurement potentiometers along the equator of each cell, and transport the cavity along the base frame.

There are nearly 60 devices installed on the tuning machine for various measurements and interlocks. To measure changes in cavity axial curvature while tuning, a laser is mounted on an end flange pointing to a mirror mounted on the opposite end flange and reflecting back to a target in the laser flange. Deviations are compensated by differentially actuating the three tuning jaws. Laser-based sensors are also used to differentiate between a normal cell and an end cell under the tuning frame, and to measure the perpendicularity of end plates.

Table 1 shows a summary of input/output channels.

Table 1: Input/Output Channels Count

Analog Inputs	Digital Inputs	Motor Outputs	Digital Outputs	TOTAL I/O
21	35	9	19	84

CONTROL SYSTEM HARDWARE

The control system hardware consists of one control rack and one control station. The control rack contains the following components: a crate with a Pythron IXEa-A Controller and several I/O modules; two crates each with three Phytron SYNCRO bipolar stepper motor power stages; a custom-made Data Acquisition Box; a custom-made Linear Actuator Drive Box; a custom-made Motion Inhibit Box; a custom-made Emergency Trip System Box; an Uninterruptible Power Supply; Serial and USB bus extenders; and a rack temperature monitor. Figure 2 shows the control rack layout.

The control station consists of a PC computer running the control system software with two operator displays and a network analyzer (Agilent E5062A). In addition, there is a custom-made Linear Actuator Manual Control Box mounted on the tuning machine frame to move tuning arms in or out independent of the control system.

A key in the Motion Inhibit Box is used to switch between normal and maintenance mode. Machine guarding sensors such as door switches and safety mats are used by the Motion Inhibit Box to inhibit motor motion. Emergency Stop pushbuttons located in the control rack, the operator station, and the machine frame are used by the Emergency Trip System box to interrupt AC power to motor amplifiers.

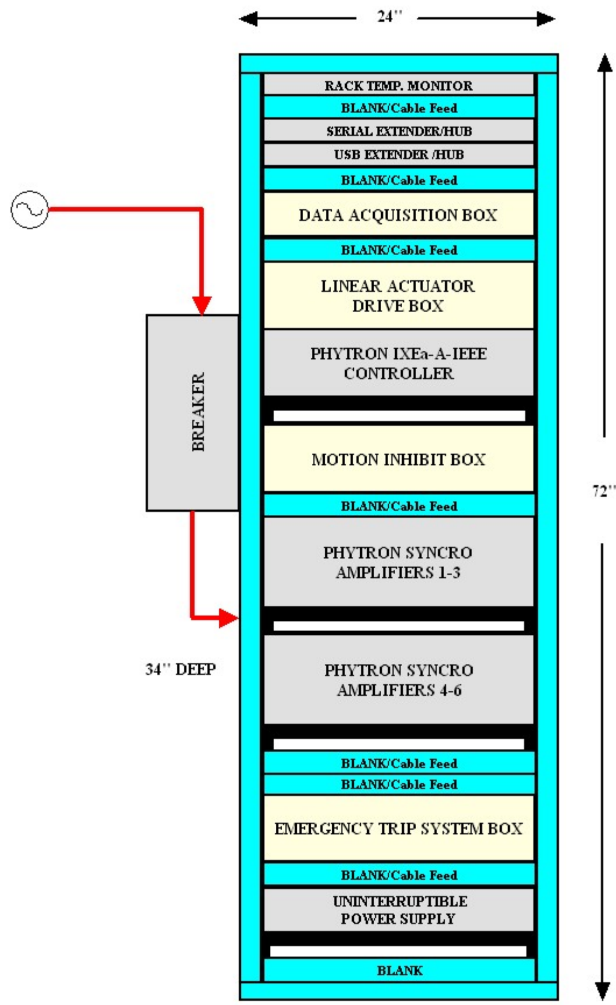

Figure 2: Control Rack Layout.

CONTROL SYSTEM SOFTWARE

The cavity tuning machine control software has been implemented in LabVIEW, and it runs in both Windows and Linux operating systems. The architecture of this software is built on the notion of plug-ins, a solution based on the ability to dynamically load LabVIEW modules. The system consists of a shell module and a set of plug-ins. The shell provides the overall system logic, control over plug-ins, and user interface integration. It also controls the state and behavior of the whole system.

Moreover, the shell will make sure that the required sequence of measurements is maintained.

Each plug-in module implements a separate measurement (e.g., eccentricity) or functionality (e.g., cavity transport). A plug-in is a complete module with a user interface and logic, and it is capable of executing outside the shell, which facilitates independent development and testing. A plug-in's front panel is integrated into the overall user interface. Figure 3 shows an example of a prototype plug-in integrated with the control program shell.

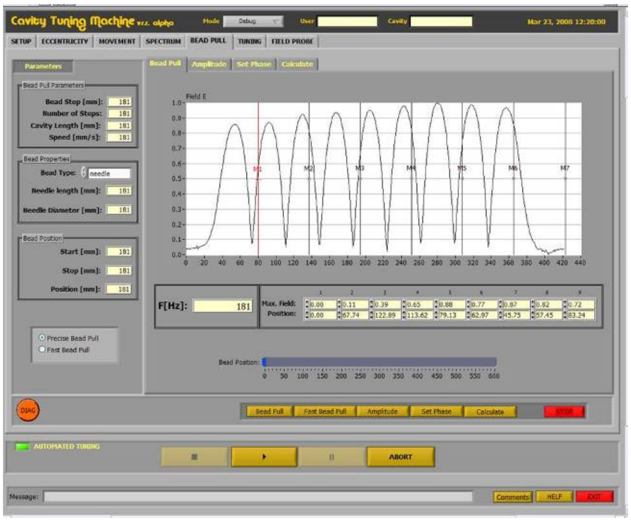

Figure 3: Example of a prototype plug-in integrated with the control program shell.

Plug-ins take advantage of a set of framework modules in order to uniformly implement common aspects such as logging, error handling, configuration and calibration data access, and data saving. They also share a common set of modules, which implement logical devices or subsystems. These modules separate plug-ins from the real DAQ hardware accessible via driver modules.

Motor stop control logic requiring fast and reliable response is programmed in Phytron controller firmware. A Phytron controller driver was developed in LabVIEW to allow software control of stepper motors and monitoring the motion and positioning switches. The driver also permits loading and executing Phytron firmware programs inside the controller. The integrity of the system is ensured by heartbeat signals. In the event that the Phytron controller firmware heartbeat signal is lost, all motion is inhibited by hardware action in the Motion Inhibit Box.

The first-order perturbation method to predict frequency correction for each cell is programmed with a MATLAB script integrated into the LabVIEW program using MathScript.

The system has two levels of automation in the normal operating mode: Manual and Automatic. In the Manual level, the user will use the controls available from the plug-in's front panel. In the Automatic level the plug-in's front panel will be disabled and the shell will control the execution of the sequence of plug-ins. The shell sends requests to plug-ins which perform operations and inform the shell about their progress and encountered exceptions. The message types used by the shell and plug-ins are standardized for all plug-ins.

The system uses XML for storing calibrations and data from all stages of the tuning process. This allows for using a hierarchical structure of the output data and promotes self-describing data, where one can identify the values, names, and types of the data from the tags that describe them.

The proposed design is mostly driven by the ability to concurrently design, test and update functional elements of the system and therefore facilitate concurrent development. It also encapsulates individual functionalities very well. Since new plug-ins can be added to the system the design is also extensible and scalable.

SUMMARY

The control system for a series of four new automated cavity tuning machine for 9-cell TESLA type cavities has been designed. It is based on LabVIEW software, Phytron controllers, and an Agilent Network Analyzer. The control system interfaces to six stepper motors, three linear actuators, and nearly 60 devices installed in the machine mechanical assembly for a total input/output count of 84 channels. The control hardware includes five custom-made electronic boxes to support various control functions. All control hardware components have been prototyped and tested, and production fabrication for all four machines has started. The control software architecture has been developed and tested; it is designed to facilitate automation and concurrent development by a team of LabVIEW programmers. Prototyping of various plug-ins is in progress. Delivery of the mechanical assembly for the first machine is expected in June 2009, and controls integration for this first machine is expected to be completed by end of December 2009. Once fully automated, these machines are expected to reduce the cavity tuning time to less than four hours by a non-expert operator.

REFERENCES

[1] H. Padamsee, J. Knobloch, T. Hays, “RF Superconductivity for Accelerators”, John Wiley and Sons, New York, 1998

[2] C. Yinghua, J. Sekutowicz, W. Yixiang, “A Different Tuning Method for Accelerating Cavities”, Proc. Of the 4th Workshop on RF Superconductivity, Tsukuba, Japan, 1990