Perturbation Measurements on RF Cavities at Daresbury.

P A McINTOSH
SERC Daresbury Laboratory
Daresbury
Warrington WA4 4AD, UK.

Abstract

Perturbation techniques are employed at Daresbury to evaluate higher order mode and shunt impedance characteristics of accelerating cavities. A small object is suspended on a kevlar thread down the central beam pipe of the cavity and is drawn along its entire length, perturbing the electromagnetic fields. The longitudinal and transverse mode impedances are then evaluated from the resultant shift in resonant frequency. The measurement process has been fully automated from a computer via a GPIB interface, controlling five high precision linear drives which enable the perturbing object to be accurately positioned in the cavity beam pipe. As the object is drawn through the cavity resonant frequency measurements are made and are stored on the computer. The data acquisition software LabVIEW® has been incorporated and converts these frequency measurements into transverse and longitudinal impedances.

1. INTRODUCTION

Perturbation measurements are performed on RF cavities to evaluate Ro/Qo, which is the *relative effectiveness* of an accelerating structure, and consequently Shunt Impedance (Ro), which is a figure for the efficiency of an RF cavity in transferring power into an accelerating voltage for particle accelerators [1]. Perturbation measurements involve drawing a perturbing object through the central beam pipe of the cavity whilst monitoring the cavity's resonant frequency as the object travels its entire length. The perturbing object, or more commonly referred to as bead, perturbs the stored energy of the resonant system by a very small amount, which results in a small shift in the resonant frequency. This frequency shift is related to the relative E-field and H-field strengths in the area of the bead.

When E and H fields are present simultaneously in accelerating cavities, the measurement process requires the identification of the individual contributions, in the vaccinity of the perturbing object. Choice of perturbing object is varied and also critical in providing accurate evaluations of the field strengths and hence determining logitudinal and transverse impedances. A restriction that is imposed by the electromagnetic fields, on the object used is that the dimensions of the object must be small enough such that the strength of the e-m field is constant over its volume. [2]

Metallic needles or disks can be specifically shaped to excite either E or H fields, not only providing an indication of the field strength but also its direction. Metallic spheres (or beads) excite both E and H fields and hence to provide a qualitative result, requires an additional measurement using a dielectric bead which excites E field only. Spheres have a number advantages over needles or disks, one of which being that spheres can be more accurately manufactured and hence provide a more accurate figure for object volume.

2. Relevant Theory

The model used to evaluate Ro/Qo can be deduced from elementary tuned circuit theory and applied measurement techniques. Fig. 1 shows the equivalent tuned circuit representation of a RF Accelerating cavity.

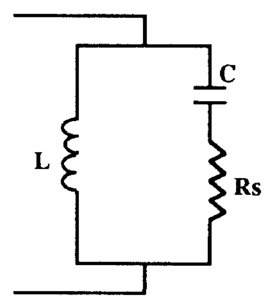

Figure 1. Accelerating cavity equivalent circuit.

It can be shown for the circuit of Fig. 1, from conventional tuned circuit theory that;

$$wo^2 = \frac{1}{LC} \quad (1)$$

$$Qo = \frac{woL}{Rs} \quad (2)$$

$$Ro = woLQo = \frac{(woL)^2}{Rs} \quad (3)$$

where;

Ro = Shunt Resistance (or Impedance at Resonance)[1]
Qo = Unloaded Q factor of the cavity

From (1), (2) and (3) we can establish;

$$\frac{Ro}{Qo} = \sqrt{\frac{L}{C}} \quad (4)$$

[1] Ro is related to the corrected Shunt Impedance ZT^2 by means of the Transit Time factor T, therefore Ro is the *uncorrected* shunt impedance (normally expressed in MΩ).

The value for Ro

$$Ro = \frac{\left(\int_{length} E.dl\right)^2}{2W} \quad (M\Omega) \qquad (5)$$

where;

W = power dissipated in the cavity (Watts)

$\int_{length} E.dl$ = Integral of E field on axis over cavity length

Standard theory also states;

$$Q_o = 2\pi \times \frac{\text{energy stored}}{\text{energy lost per cycle}}$$

$$= \frac{woU}{W} \qquad (6)$$

sub eqtn (6) into (5) gives;

$$\frac{Ro}{Qo} = \frac{\left(\int E.dl\right)^2}{2woU} \qquad (7)$$

For the case under investigation, it is assumed that the bead is on axis, and the mode under scrutiny is the fundamental accelerating mode (or TM_{010}). Hence it can be assumed that the Magnetic field H integrates to zero over the length of the cavity.

From Ginzton ;

$$\delta = \frac{w - wo}{wo} = \frac{\Delta f}{fo} = k \frac{\left(\int \varepsilon E^2 . dl\right)^2}{4U} V \qquad (8)$$

Which for a perturbing bead, k = 1 and
V = volume of bead (m^3)

then;

$$\left(\int E.dl\right) = \sqrt{\frac{\Delta f}{fo}} . \sqrt{\frac{4U}{V\varepsilon}} \qquad (9)$$

sub for ∫E.dl in eqtn (8);

$$\frac{Ro}{Qo} = \frac{1}{2\pi r^3 wo\varepsilon} \left[\int_0^L \sqrt{\frac{\Delta f(l)}{fo}} . dl \right]^2 \qquad (10)$$

where:

if using a metallic bead; $\varepsilon = \varepsilon_o = 8.854187187 x 10^{-12}$

if using a dielectric bead; $\varepsilon = \frac{(\varepsilon_1 - \varepsilon_2)\varepsilon_o}{(\varepsilon_1 - 2\varepsilon_2)}$

ε_1 = dielectric constant of medium filling cavity (F/m)
ε_2 = dielectric constant of bead (F/m)
w_o = angular unperturbed resonant frequency (rad/s)
r = radius of bead (m)
L = length of cavity (m)
$\Delta f(l)$ = perturbation change in frequency (Hz)
fo = unperturbed resonant frequency (Hz)

3. The Measurement System

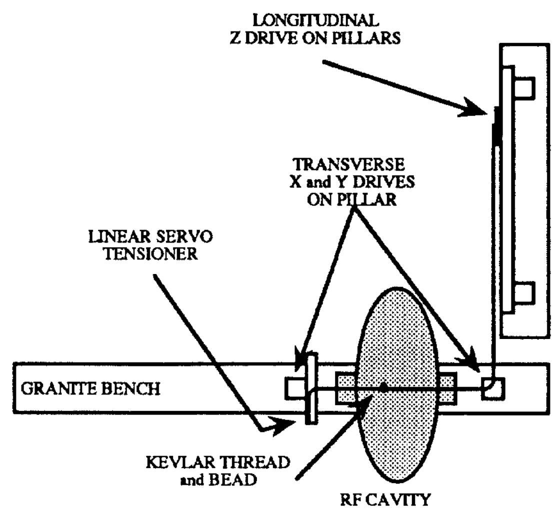

Figure 2. System Arrangement

The bead is attached to a kevlar thread, which is inserted down the central beam pipe of the cavity. Kevlar is used because of its inelasticity and strength under tension. A Mclennan servoed tensioned drive is incorporated which provides a near constant tension to the wire as it is drawn through the cavity. Two pairs of high precision INA linear drives are mounted either side of the RF cavity, which operate in parallel with each other giving X and Y (transverse) positional accuracy of the wire of <100μm. Each pair of drives house an arrangement of multidirectional roller bearings providing stable and accurate positioning of the wire as it travels through the drives. Each drive assembly are mounted via kinematic mounts, on pillars of X95 Micro Controle profile sections on a 4m long Micro-Controle granite experimental bench, which allows for longitudinal adjustment of the pillars and their drive assemblies as close to the cavity as possible. Another INA linear drive is used in the Z (longitudinal) plane which pulls the bead, via the kevlar wire, through the cavity, again positional accuracy is <100μm. Maximum length of travel of the bead is limited at present by the length of the longitudinal drive which is 1.5m.

At the moment, the system measures frequency shifts directly however it is intended that the system software be adapted to take measurements indirectly, by measurement of the phase shift of the mode under investigation, using a HP8753C Network Analyser. By measurement of the phase rather than frequency, means that relatively high averaging values may be used in the measurement process (typically >400), without introducing considerable time delays in data acquisition [3]. The Network Analyser is controlled through a GPIB (IEEE-488.2) interface via a Macintosh 11 computer utilising the data acquisition software LabVIEW® [4]. The McLennan PM341 stepper motor controller cards are RS-232 interfaced, and are also controlled via the computer through a GPIB to RS-232 PSI Brain Box bi-directional converter. The system is also contained in an air conditioned room which minimises thermal drifts over the measurement process.

As the bead travels the cavity's entire length, the linear drive arrangement allows it to be swept transversely to give an azimuthal electro-magnetic field strength *slice* of any section of the cavity's central beam pipe. This proves particularly useful when electro-magnetic field plots are produced using computer simulation, and compared with the *slice* information at the same longitudinal position. Frequency values with corresponding X, Y and Z bead position values as well as computed Qo values for each HOM, are stored on the computer in spreadsheet format. LabVIEW® is then used to provide a solution to equation (10) and from which variations in frequency of all the significant HOM's found by the system can be displayed.

4. Results

To evaluate the new measurement system, a previously unmeasured 500MHz, conventional "nose-cone" cavity was measured. The particular cavity in question being a spare Booster cavity for use on the SRS. A 5mm radius, spherical dielectric bead was drawn through the cavity on axis, perturbing only the accelerating E fields.

URMEL-T Predictions			Perturbation Results		
Freq (MHz)	Qo	Ro/Qo	Freq (MHz)	Qo	Ro/Qo
500.24	29546	107.265	499.6	26394	105.3
1245.18	41034	3.135	1263.0	53310	2.85
1444.60	52905	0.776	1442	7646	0.222
1905.81	35069	0.001	1912	65792	no shift
1935.29	44046	16.34	1924	66200	13.5
2106.05	47900	1.52	none		
2275.07	65061	5.12	2300	4120	3.48
2336.31	50615	1.27	2318	16270	0.76
2482.70	56526	6.194	2577	32480	0.35
2695.53	45210	2.61	2721	14376	1.2

Figure 3. Comparison of URMEL-T predicted and perturbation derived Ro/Qo for Daresbury 500MHz Booster Cavity (Longitudinal HOM only).

For the bead to traverse the length of the cavity, acquiring frequency information and performing the calculations required to find the solution to Ro/Qo for eqtn (10), takes the measurement system approximately 5 minutes for a 580mm longitudinal travel. The time taken depends on the length of cavity being measured and also the number of measurements per length of cavity.

The probe used for the measurements was a simple loop coupling probe which was critically coupled (B=1) with 50dB return loss at resonance. The error is mainly due to the frequency measurement, for the fundamental frequency with a 40KHz sweep using 801 points, the error in frequency is;

$$\text{Frequency Error} = \pm \frac{40 x 10^3}{2 x 801} = \pm 24.96\,Hz$$

The error in the unperturbed frequency shift will therefore be 49.92Hz. The unperturbed frequency must not drift over the measurement cycle, as small variations cause a large contribution to the overall impedance figure. [5]

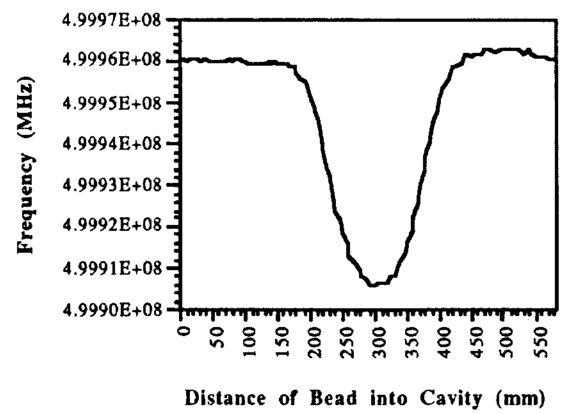

Figure 4. SRS Booster cavity 500MHz frequency shift.

5. Conclusions

The results from the new system are excellent providing very good agreement with computer simulations. It is obvious that the efforts made in design stage of eliminating possible errors in the system, be they positional or thermal, have proved invaluable in providing such results. The sytem is however, not yet fully complete, improvements to the system have been identified and it is hoped thay can be implemented relatively quickly.

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5. References

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