INDIVIDUAL HALF-CELLS FREQUENCY MEASUREMENTS OF A DUMBBELL CAVITY *

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Abstract

Precise dumbbell fabrication is a critical step in the manufacture of multi-cell SRF cavities. The resonant frequency of each individual half-cell can be determined by perturbing the welded dumbbell and measuring the TM_{010} 0- and π-mode. A correction to a previously derived formulae for π-mode frequency of each individual half-cell is presented and compared to SLANS simulations. The RF fixture and data acquisition hardware was designed and validated during 7-cell cavity fabrication. The system comprised of a mechanical press with RF contacts, a network analyzer, a load cell and custom LabVIEW and MATLAB scripts.

INTRODUCTION

Production of the first superconducting cavities for the Cornell University Energy Recovery Linac (ERL) is complete. In order to minimize cavity tuning, a mid-process quality control step is introduced during the cavity fabrication when the half-cells (or cups) are welded together to form "a dumbbell". Variability in the raw niobium, deep-drawing and weld shrinkage results in increased deviations in the dumbbell shape. These errors can be compensated by fabricating cups with an extended equators, determining the supplementary length using frequency measurements and, finally, machining each equator to the target length and hence frequency. We used the wealth of SC cavity experience published by DESY and JLab [1, 2, 3]. Both labs used measurement fixtures with a perturbing body to identify dumbbell asymmetry. There are no direct references in the DESY publications of how this asymmetry is used to define cup frequencies, but in the JLab publication the measured frequencies with and without perturbation were used to determine the individual π-modes of the cups.

CALCULATION OF HALF-CELLS FREQUENCIES FROM DUMBBELL MEASUREMENTS

The formula for the frequencies of two coupled oscillators used by [3] is derived in [4, 5]:

$$f_{\pi,U} = \sqrt{\frac{f_\pi^2 + f_0^2}{2} + \frac{(f_\pi^2 - f_0^2)\cdot(2+R)}{2\sqrt{R+4}}},$$
$$f_{\pi,D} = \sqrt{\frac{f_\pi^2 + f_0^2}{2} + \frac{(f_\pi^2 - f_0^2)\cdot(2-R)}{2\sqrt{R+4}}}, \tag{1}$$

with the substitution

$$R = \sqrt{\frac{f_\pi^2 - f_{\pi,P,U}^2}{f_\pi^2 - f_{\pi,P,D}^2}} - \sqrt{\frac{f_0^2 - f_{0,P,U}^2}{f_0^2 - f_{0,P,D}^2}}. \tag{2}$$

Here "0" and "π" denote the 0-mode or π-mode respectively and half-cells are distinguished by their location in the fixture with indices "U" for up and "D" for down. Frequencies measured with the perturbation are additionally marked with the index "P". One can see that both (1) and (2) are asymmetric relative to a swap of indices "U" and "D". Analysis of the derivation of the formula in [4] shows that there should be R^2 in the denominators of (1):

$$f^*_{\pi,U} = \sqrt{\frac{f_\pi^2 + f_0^2}{2} + \frac{(f_\pi^2 - f_0^2)\cdot(2+R)}{2\sqrt{R^2+4}}},$$
$$f^*_{\pi,D} = \sqrt{\frac{f_\pi^2 + f_0^2}{2} + \frac{(f_\pi^2 - f_0^2)\cdot(2-R)}{2\sqrt{R^2+4}}}. \tag{3}$$

Now, the formulae in (3) are symmetric if R in (2) changes its sign when the dumbbell is turned upside-down. However, this can happen only if both right components in (2) are close to a unity:

$$R = \sqrt{\frac{f_\pi^2 - f_{\pi,P,U}^2}{f_\pi^2 - f_{\pi,P,D}^2}} - \sqrt{\frac{f_0^2 - f_{0,P,U}^2}{f_0^2 - f_{0,P,D}^2}} \approx$$
$$\approx (1+\alpha) - (1+\beta) = \alpha - \beta,$$
$$R' = \sqrt{\frac{f_\pi^2 - f_{\pi,P,D}^2}{f_\pi^2 - f_{\pi,P,U}^2}} - \sqrt{\frac{f_0^2 - f_{0,P,D}^2}{f_0^2 - f_{0,P,U}^2}} \approx$$
$$\approx \frac{1}{1+\alpha} - \frac{1}{1+\beta} \approx \beta - \alpha \approx -R. \tag{4}$$

This, in its turn, can happen when the shift caused by the extra length of the cell is less than the shift due to perturbation.

One could transform the formula for R so that it would be symmetrical, e. g. by taking a mean arithmetic of R and $-R'$, or using an expansion by the small parameter mentioned above. But the original formula (2) is rather compact and the transformed formula would be presumably more cumbersome and hardly more accurate. A verification of (2) and (3) was done with SLANS [6] using a dumbbell with pre-defined equator lengths. We assume SLANS gives exact frequency values of a dumbbell with and without perturbations. We can also determine the relationship

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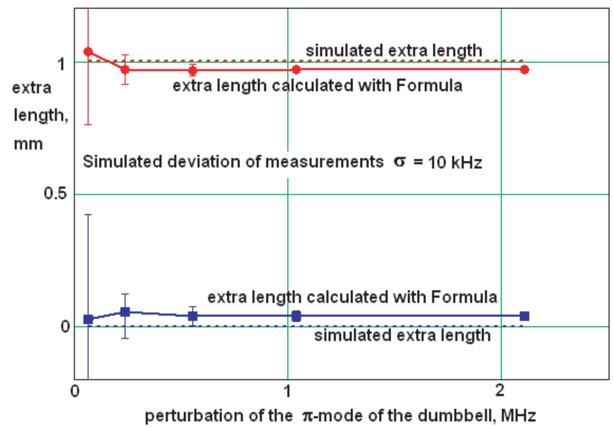

Figure 1: Simulation of a dumbbell with extra lengths 0 and 1 mm.

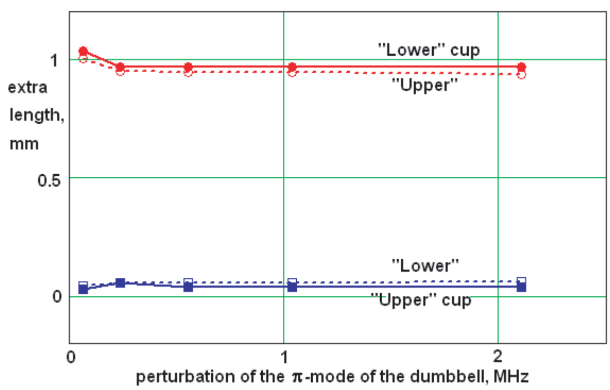

Figure 2: Extra length calculated with Formula.

between the extra equator length and frequency, commonly referred to as the trimming parameter, t. In our case, we determined that $t = 5.1$ MHz/mm. Knowing the frequency of an "ideal" cup, or the target frequency, f_{target}, we can determine the extra equator lengths

$$\Delta_U = \frac{f_{target} - f^*_{\pi,U}}{t}, \text{ and } \Delta_D = \frac{f_{target} - f^*_{\pi,D}}{t} \quad (5)$$

to be trimmed. SLANS outputs frequencies for a dumbbell of known length, thereby giving us a means of validating formulae (3). We can also analyze how measurement errors of the dumbbell frequencies influence the accuracy of the found extra length. For this purpose, we can generate random values of frequencies around the values calculated by SLANS and use again the formulae (2) and (3) but now for 6 arrays of "measured" frequencies. Repeated measurements show that the standard deviation of each resonant frequency is about $\sigma = 10$ kHz. Let the dumbbell have an extra lengths on one cup only: $\Delta_1 = 1$ mm, $\Delta_2 = 0$. The perturbation used in this calculation was such that the frequency shift of the π-mode when inserted from the "ideal" side ($\Delta_2 = 0$) is 60 kHz to 2.1 MHz, Fig. 1.

One can see that very small perturbations lead to uncertainty of extra length due to the errors of measurements. Conversely, large perturbations do not reproduce the exact extra lengths as calculated with (5).

We can treat the cup with the extra length $\Delta_1 = 1$ mm as an "Upper" or "Lower" cup. The choice of the cup location is conditional. R changes its sign when the dumbbell is turned over but also slightly changes its absolute value. The values of extra lengths calculated for these two possibilities are shown in Fig. 2.

We will have practically the same graph if $\Delta_1 = 2$ mm, $\Delta_2 = 1$ mm (the numbers on the ordinate axis will increase by 1). Therefore, we conclude that *the error is always smaller if the cup with bigger deviation of the π-mode is taken as the lower cup*. As is seen from the graph, the accuracy is improved by a factor of two.

If the cups have similar dimensions, this difference between frequencies defined with swapped upper and lower cups becomes small (no difference if $R = 0$).

A DUMBBELL MEASURING FIXTURE

To measure the resonant frequencies of a fabricated niobium dumbell, a fixture with supporting hardware and software was constructed, Fig. 3. The system was inspired by the JLab system, with the most notable difference being the operating frequency (1300 MHz instead of 1500 MHz) [3]. The fixture was designed to accommodate completed end group measurements. In the case of end groups, no perturbation was used since the cavity was comprised of a single half-cell. Two feedthroughs with antennas were placed in the upper and lower plates, and the RF measurement was done in transmission. For the end group, one antenna was replaced by a flexible conductor such that it was easily inserted into the cavity. In each case, the antenna length was trimmed such that the cavity was heavily undercoupled with a $Q_{ext} \approx 10^6$, giving $Q_l \approx Q_0$.

The measurement system consists of a HP85047A network analyzer (NA), a RF dumbbell fixture with copper contact fingers, and a Transducer Techniques load cell with analog readout. The NA and load cell were connected to a LabVIEW program which logs the frequency (f_0), quality factor (Q_0) and applied force. Q_0 and f_0 were determined by fitting the amplitude of S_{21} to the Lorentzian function while accounting for a constant direct transmission between antennas. LabVIEW was choosen to increase the measurement accuracy while simplifying the measurement and processing procedure.

The six measured frequencies comprised the 0 and π-mode, with and without perturbation in the upper and lower half-cells. These values were written to a file and then processed using MATLAB. The script calculates the individual π-mode frequencies according to the modified formulae (3). The program recognizes which half-cell has the biggest π-mode deviation and assigns this cup as 'lower,' in spite of its physical location. The program also incorporates a correction for ambient conditions: humidity, temperature and atmospheric pressure [7].

The value of the frequency perturbation should be bigger

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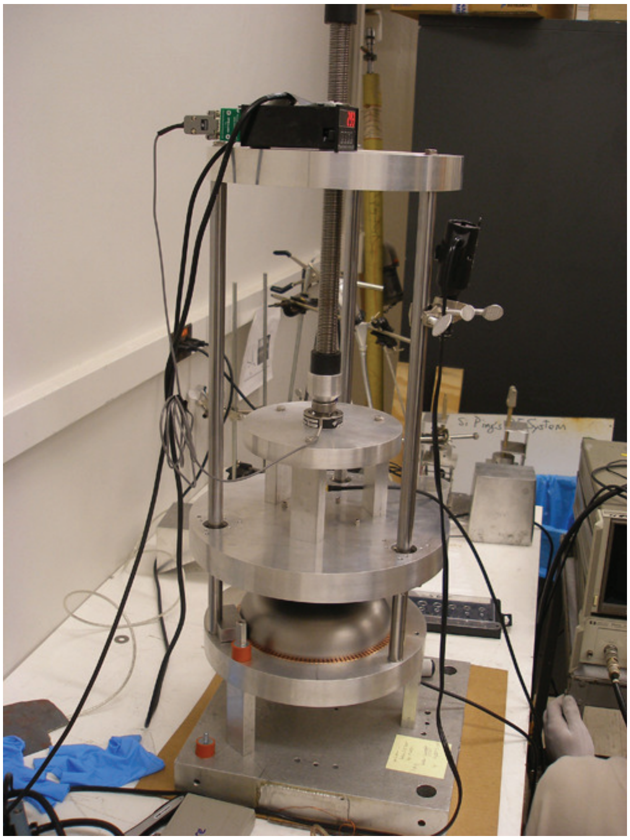

Figure 3: Dumbbell measuring fixture.

than the error in measurement (10 kHz) but less than the difference between the 0 and π-mode frequencies (about 26 MHz). We have chosen our perturbation such that $\Delta f \approx$ 0.5 MHz. The perturbing body is a cylinder 3.175 mm in diameter with a spherical top, and the total length of 6.5 mm. In order to guarantee reliability, the perturbation was fastened with a torque wrench to 10 inch·lb.

To obtain a reliable RF contact at the Nb/Cu joint, the fixture must compress the dumbbell between copper plates. The mechanical press comprised of linear bearings mounted on aluminum plates, sliding on case-hardened shafts. The press was manually driven by a 1-inch ACME screw. ANSYS simulations show that the force applied to the dumbbell should be kept below 350 lbs, in order to prevent inelastic deformation. Therefore, our operating pressure was 300 lbs. Plastic deformation will affect the resonant frequency of the cavity, but a linear extrapolation to zero pressure of the f_0 versus F curve found this deviation to be neglibible compared to our machining tolerance. To overcome the dry-contact friction between components, a small mechanical vibrator was attached to the fixture. It was also helpful to gently rub the niobium dumbbell against the copper contact using a circular motion. To exclude the copper contamination of the niobium, a 30 minute nitric acid etch of the equators was performed prior electron-beam welding.

These measures resulted in Q_0's between 5000 and 7000. The theoretical value simulated in SLANS was about 7500 for both 0- and π-modes, given our geometry and material. We assumed that a Q_0 greater than 5000 indicates a reliable RF contact. Using the methods outlined above, we demonstrated repeatable frequency measurements with σ=10kHz, regardless of cavity orientation or re-insertion.

CONCLUSION

Dumbbell cavities for the Cornell ERL multicell cavity were measured in a measuring fixture constructed for this purpose to determine equator trimming lengths. Corrections were introduced into the formulae for calculation the individual half-cell frequencies. LabVIEW and MATLAB software was written for a semi-automatic measurements with a network analyzer, load cell, and RF dumbbell fixture. Our system helped to control individual cell frequencies to within narrow limits: the first completed Cornell ERL 7-cell cavity has a frequency deviation of 360 kHz, and a field flatness of 88 %. This corresponds to an average deviation of less than 0.003 inches (75 μm) per cell.

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