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MECHANICAL AND THERMAL ANALYSIS OF BERYLLIUM WINDOWS FOR RF CAVITIES IN A MUON COOLING CHANNEL *

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Abstract

Thin beryllium windows (foils) may be utilized to increase shunt impedance of closed-cell RF cavities. These windows are subject to ohmic heating from RF currents. The resulting temperature gradients in the windows can produce out of plane displacements that detune the cavity frequency. The window displacement can be reduced or eliminated by pre-stressing the foils in tension. Because of possible variations during manufacture, it is important to quantify the actual pre-stress of a Be window before it is put into service. We present the thermal and mechanical analyses of such windows under typical operating conditions and describe a simple non-destructive means to quantify the pre-stress using the acoustic signature of a window. Using finite element analysis, thin plate theory and physical measurements of the vibration modes of a window we attempted to characterize the actual Be window pre-stress in a small number of commercially sourced windows (30% of yield strength is typical). This method can be used for any window material and size, but this study focused on 16 cm diameter Be Windows ranging in thickness from 125 microns to 508 microns and with varying pre-stresses. The method can be used to non-destructively test future Be windows for the desired pre-stress.

1 INTRODUCTION

It was postulated that pre-stress (in-plane, or membrane stress) could be derived from the foil natural frequencies. Similar in concept to tuning a guitar by varying the string tension, the resonant frequency of a window varies with tension, or pre-stress. This pre-stress is an artefact of material properties and manufacturing processes.

Experiments were conducted to determine the pre-stress of several Be windows by measuring the frequency response. In order to quantify the relationship between frequency response and pre-stress, the measured frequency spectrum was compared to the theoretical frequency response extracted from ANSYS [1] 2D models and Pro/Mechanica [2] 3D models. FEA models have been used previously for Be windows to simulate the relationship between pre-stress, thermal load and out-of-plane displacement [3].

The frequency response measurements were performed using three different methods. The results were consistent between the methods giving reasonable confidence that the desired fundamental frequency was identified. It was found that the higher order mode shapes were more difficult to discriminate, but may not be necessary to measure pre-stress.

2 DESCRIPTION OF BE WINDOW

Each window is comprised of a foil of 99% pure beryllium. It is brazed between two annular rings of lower purity (98.5%) PS200 beryllium [4], with annuli of 160 mm for the 805 MHz windows; the rings are each approximately 1.6 mm thick (See Figure 1).

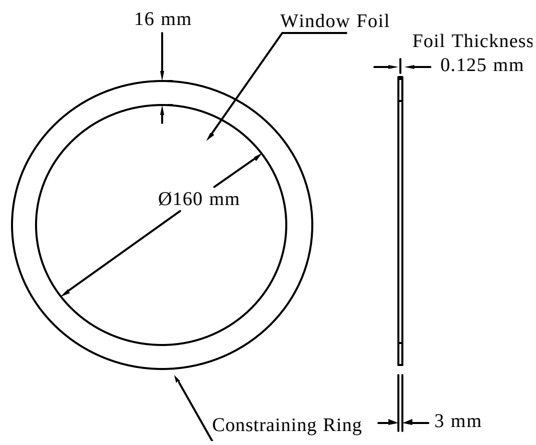

Figure 1: Layout of Beryllium test window [units: mm]

The single thickness windows tested are a commercial product acquired from Brush Wellman. The windows available for testing were 16 cm Be window at 5 mil (0.127 mm), 10 mil (0.254 mm) and 20 mil (0.508 mm) thick. It is important to understand pre-stress because the resulting temperature gradients in a cavity window while under RF load can produce out of plane displacements that detune the cavity frequency. [3,5] It can be shown that two parameters affect the magnitude of pre-stress developed in a window assembly. The first is a difference in the coefficient of thermal expansion (CTE) between the ring and foil. The second is the braze temperature. Figure 2 shows how pre-stress can vary considerably with small changes in braze temperature and, or material thermal expansion properties. The tested windows are estimated to have a nominal CTE of 11.5 ppm / °K for the 99% pure Be windows with a 5% delta CTE for the 98.5% pure Be.

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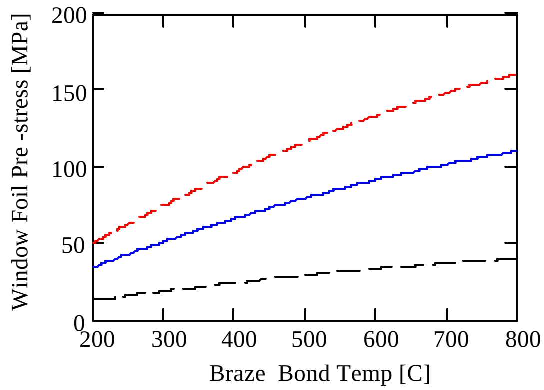

Figure 2: Theoretical pre-stress in a 16 cm window as a function of braze temperature. Cases shown for a Delta CTE of 8% (top), baseline 5% (middle) and 2% (bottom).

3 THERMAL STRESS DEFLECTION

The thermal out-of plane displacement of the window was measured under simulated RF loading conditions. The temperature profile and displacement data was taken for several windows and plotted in Figure 3. The windows provided a limited sampling of pre-stress conditions, so an ANSYS 2D axisymmetric FEA model was developed to generate out-of-plane displacements throughout a full range of pre-stresses from 0 MPa to 220MPa. The ANSYS simulation results were plotted against the measured data. The graph shows that the best agreement for a 5 mil window is at a pre-stress of 120 MPa.

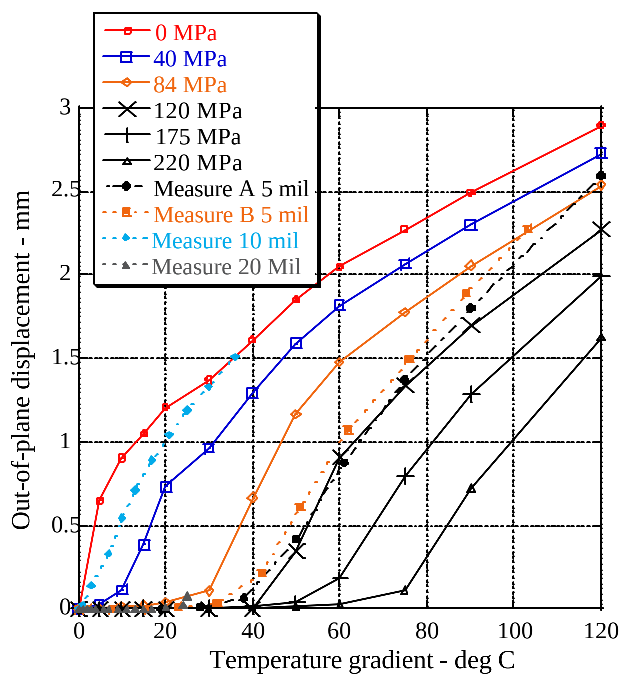

Figure 3: Thermal gradient and out-of-plane displacement. Experimental and ANSYS data.

4 MODAL ANALYSIS OF WINDOWS

Several experimental and analytical methods were used to extract spectral response data from the windows.

4.1 Frequency Response Measurements

Two methods were devised for directly measuring the window frequency response. The first method used a low mass accelerometer directly mounted to the window. The second method measured the acoustic signature of the window using a microphone (See Fig. 4). To measure the frequency response a window was excited with either an acoustic, or impulse method (in an attempt to isolate specific modes). The acoustic method of excitation used a small speaker and function generator to sweep over a frequency range to excite modes independently. The impulse method struck the window directly with either a pendulum (to isolate only the fundamental), or a tuned modal hammer (excites all the modes simultaneously) (See figure 5). The microphone pickup provided good spectral signatures but it was difficult to determine which of the higher order modes was being excited.

Figure 4. Pendulum and Be window in 805 MHz cavity (Left). Microphone measures acoustic response. (Right).

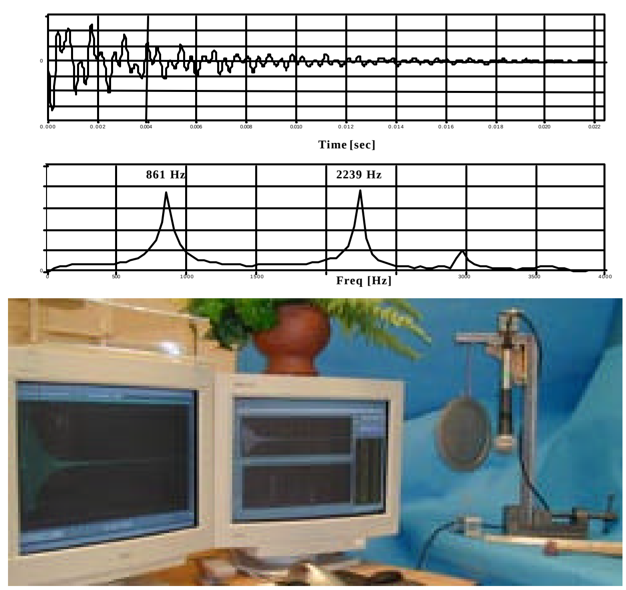

Figure 5. Acoustic time history (Top).
FFT with modes at 861 Hz , 2239 Hz (Middle).
Data acquisition and Tuned hammer (Bottom).

4.2 Finite Element Modal Analysis

There were two FEA models developed for identifying the frequency profile for a given pre-stress. The first model was an ANSYS 2D axisymmetric model, which gave a direct output of natural frequency for the first four mode shapes as a function of pre-stress (See Figure 5). To explore asymmetry issues and validate the ANSYS model, a second 3D model was built with ProMechanica (See Figure 6). Both models correlated well with each other and also with the vibration theory of circular membranes (See Equation 1). For comparison, equation 1 is also plotted against the ANSYS model in Figure 5.

$$f_1 = \frac{0.765}{D}\sqrt{\frac{1}{\sigma}} \qquad (1)$$

T – membrane tension in Newtons/meter
σ = density in kg per square meter
D – diameter of membrane in meters

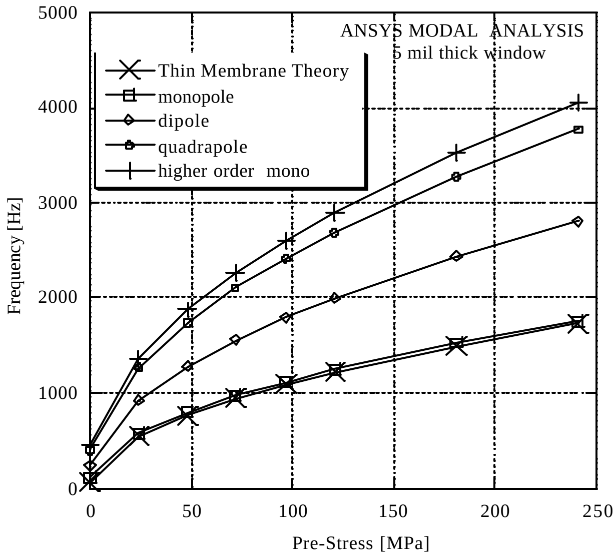

Figure 5: Theoretical and ANSYS FEA predicted frequency response versus Pre-Stress for 5 mil foil

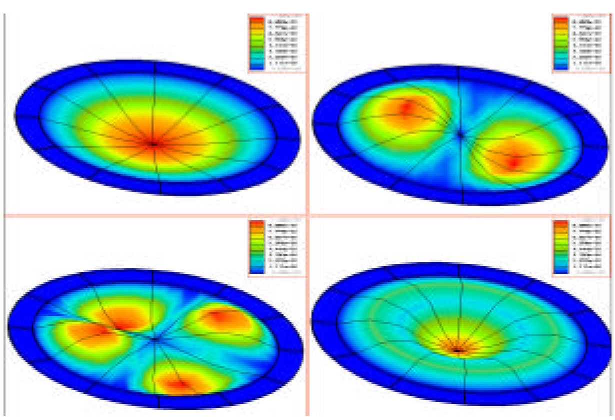

Figure 6: Pro/Mechanica 3D FEA modal analysis. Mode shapes for a 16 cm diameter, 0.127 mm thick window. Prestress: 50 MPa, (left to right, starting top) 822Hz, 1319 Hz, 1781 Hz, 1918 Hz.

5 CORRELATION OF FREQUENCY AND PRE-STRESS

The pre-stress predicted by the original thermal displacement models were compared to the pre-stress extracted from window frequency measurements and the modal analysis models (See Table 1). Although the frequencies were measured with a high degree of confidence the table shows that pre-stress predicted by the thermal stress model does not correlate with the modal analysis models.

Table 1. Pre-stress determined from frequency measurement of windows.

		PRE-STRESS		
Window Description	**Meas. Freq.** Hz	**Accel. Modal** MPa	**Acoustic Modal** MPa	**Temp. Disp.** MPa
5 mil uncoated	732	40	45	110
5 mil 125Å TiNi	775	NM	48	110
5 mil 125Å TiNi	796	NM	50	NM
10 mil uncoated	334	5	5	0
10 mil 200Å TiNi	796	NM	44	NM
20 mil uncoated	991	45	42	ID
20 mil 200Å TiNi	ID	NM	ID	NM

Notes: NM = No Measurement taken.,
ID = Insufficient, or Inconclusive Data.

6 CONCLUSION

It was shown using vibration theory and finite element modal analysis that a unique frequency spectra and mode shape can be correlated with the pre-stress condition of a Be window. The models in concert with the physical measurement of the frequency response of a window can be used to predict the pre-stress. Although the thermal stress FEA model and modal frequency models did not uniquely identify a pre-stress, these models will be useful as a prediction and design tool for windows in a variety of thickness, sizes and materials.

7 REFERENCES

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