Nondestructive Evaluation of Ceramic Candle Filters Using Vibration Response[1]

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Introduction

This paper presents an on-going research study of nondestructive evaluation of ceramic candle filters using a dynamic characterization method. These ceramic filters were tested at different sets of exposure times at the Power Systems Development Facility (PSDF). More than seventy-five specimens, which include 12 new Coors alumina/mullite, 24 new Schumacher SiC TF20, 10 used (1-483 hrs, 5-500 hrs, and 4-982 hrs) Schumacher SiC TF20, 1 used (600 hrs) Schumacher SiC F40, 23 new Pall Vitropore 326, and 5 used (2-203 hrs and 3-400 hrs) Pall Vitropore 326 have been nondestructively inspected.

Objectives

The present research is focused on the application of an effective non-destructive evaluation technique based on dynamic characterization to evaluate the relationship between changes in the vibration frequencies of ceramic candle filters and different levels of damage. This study aim at enhances inspection process during power plant annual maintenance shutdowns. The objectives of the present on-going study are to establish the vibration signatures of ceramic candle filters at varying degradation levels due to different operating hours and to develop an effective non-destructive evaluation technique to predict the remaining useful life of ceramic candle filters.

Experiments and FEM Analysis

The modal testing experimental setup for the ceramic candle consists of excitation, sensing, and analysis mechanism. Each one of the filter specimens was suspended freely by its open end by using elastic tubes. The excitation was applied at 10 different locations on the filter. The structural response was detected by an accelerometer. Vibration parameters such as natural frequencies, mode shapes and frequency response functions (FRF) are used as the basis for the nondestructive evaluation (Chen and Parthasarathy, 1996). The first eight flexural vibration modes, covering a frequency range up to 4000 Hz, were studied. The FRF obtained were averaged to minimize experimental errors arising from improper excitations.

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Analysis using a dynamic Finite Element Method (FEM) was conducted to compare with the experimental results. An FEM model was built for the filter specimens by using the nominal weight and dimensions (Chen and Kiriakidis, 1997). Linear elastic modal analysis was performed. Eight nodes, three-dimensional isotropic solid elements, were used.

Results

Table 1 shows first eight flexural vibration modes (averaged frequency) and standard deviation for the vibration mode of the new Refractron, new Schumacher TF-20 and new Coors alumina/mullite filters obtained. The comparison of Coefficient of Variation's (COV's) for the averaged frequencies of Coors, Schumacher, and Refractron filters are shown in Table 1. The COV shows that the Refractron has higher values than Schumacher, which in turn is higher than Coors filters. Same conclusions can be said about the standard deviation of the three groups of filters. This comparison shows that Refractron filters have the highest average stiffness, however, the stiffness variation among the Refractron filters is also the largest.

Table 1. Average Experimental Vibration Frequencies of New Filters

	23 REFRACTRON Pall 326		24 SCHUMACHER TF-20		12 COORS P-100A-1	
MODE #	AVE	COV	AVE	COV	AVE	COV
1	137.47	4.33	120.04	2.71	112.10	1.68
2	374.51	12.05	328.45	7.16	305.43	4.32
3	728.43	22.62	639.19	13.95	589.38	9.11
4	1176.04	35.27	1039.12	22.14	952.61	13.83
5	1710.60	51.67	1515.32	31.67	1383.35	19.76
6	2320.27	72.48	2056.07	41.62	1866.48	26.32
7	2994.92	93.48	2664.17	55.19	2407.11	37.34
8	3709.65	113.02	3300.27	63.59	2970.16	43.08

Figure 1 shows the calculated Young's Modulus distribution for ten Schumacher TF-20 specimens. Specimen 324H21 was tested when it was new and after used for 483 hrs. Specimens 324H04, 324H05, 324H06, 324H07, and 344E232 were tested before and after they were used for 500 hrs and specimens 324H01, 324H03, 324H08, and 324H10 were tested before and after they were used for 982 hrs. All the filter specimens, but the 344E232, present a clear reduction of stiffness after being used as shown in this figure. The stiffness reduction for the 324H21-filter specimen after 483 hrs of exposure time is about 16.02%. The percentage shifts between new and 500 hrs used filters are about 5.57%, 7.81%, 5.93%, 3.2% for 324H04, 324H05, 324H06, and 324H07, respectively, while the stiffness for the 344E232 filter increased about 3.52%. The percentage shifts between new and 982 hrs used filters are about 10.54%, 13.90%, 11.44%, and 14.27% for 324H01, 324H03, 324H08, and 324H10, respectively.

The Young's Modulus distributions for all the new Refractron 326 filters are compared with the 400 hrs used ones and are shown in Figure 2. Because the used filters have not been tested when they were virgin, they are compared with averaged results of the new filters. One can notice that the used filters 1-51A, and 3-79A have lower stiffness than the averaged stiffness of the new ones. The percentage of stiffness shift is about 7.36% and 5.64%. Although the 2-69A has higher stiffness than the averaged value, there are four new Refractron filters with higher stiffness values (4-31A, 4-87A, 1-35A, and 3-35A) than the 2-69A.

A damage detection procedure developed in this paper is based on the modal strain energy. The numerical calculation of the strain energy involves the modal curvature (second derivative of the mode shape). A comparative plot of the new 2-49A Pall 326 (undamaged) and the 2-24A Pall 326 (damaged, survived from April '97 fire at PSDF) strain energy distribution for the first mode is shown in Figure 3. One can clearly see in this figure the sudden increase in the energy at the damaged location (midspan), for the 2-24A damaged filter. Figure 4 shows the comparative plot of mode 3 for the 4-981 damaged filter (survived from April '97 fire at PSDF). The energy levels around the damaged location increased. From the strain energy analysis, both 2-24A and 4-981 candles indicate a damage location at around mid-span.

Theoretical Analysis

The theoretical calculation in this study used both the Bernoulli-Euler beam theory and the Timoshenko beam theory. Chen and Parthasarathy (1996) used the Bernoulli-Euler beam equation to compare with the experimental results. This equation was found to be suitable in the lower modes, while in the higher modes a large deviation in the frequency results were noted. The Timoshenko beam vibration equation was used to consider the shear effect. The frequency equation with free-free boundary conditions was derived to obtain the vibration frequency of each bending mode.

Figure 5 summarizes the comparison of the experimental result with the theoretical results from both the Bernoulli-Euler and the Timoshenko beam equations. The modal frequencies obtained with both theoretical calculations are compared to study the influence of the shear deformation in the vibration frequencies for the filter specimens. The theoretical results are also compared accurately with the modal frequencies obtained from the FEM. The results show that the Timoshenko beam equation perform better than the Bernoulli-Euler beam equation. However, the difference between the experimental measured frequencies and the calculated frequencies at higher modes remains noticeable. Further study is needed to develop a frequency equation to simulate the candle filter vibration.

Summary

Results from this study indicate that the vibration signatures of the filters can be used as an index to quantify the mechanical properties of the ceramic candle filters. The modal frequencies are independent from the locations that were obtained on the ceramic filter. Used filters have lower natural vibration frequencies, which also indicate lower stiffness, than new filters. The modal strain energy based procedure presented seems to have the potential to detect damage locations. Further study is needed to develop a frequency equation to simulate the candle filter vibration, which should consider the shear effects and the boundary condition effects. The application of this study can be implemented to develop a future in-situ inspection of the ceramic candle filters.

Acknowledgments

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References

Alvin, M.A., R.E. Tressler, T.E. Lippert, E.S. Diaz, and E.E. Smeltzer. June 1994. "Durability of Ceramic Filters," Paper Presented at Coal-Fired Power System 94 – Advances in IGCC and PFBC Review Meeting, 545-571. DOE/METC-94/1008. NTIS/DE94012253. Morgantown, WV.

Chen, H.L., Kiriakidis, A.C. "Nondestructive Evaluation of Ceramic Candle Using Vibration Response," Proceedings, Advanced Coal-Fired Power System '97 Conference, July 1997, Pittsburgh, PA.

Chen, H.L., Parthasarathy, B., "Nondestructive Degradation Evaluation of Ceramic Candle Filters Using Vibration Signatures," Proceeding of Advanced Coal-Fired Power System '96 Review Meeting, July 1996, Pittsburgh, PA.

Chen, H.L., Parthasarathy, B., "Nondestructive Evaluation of Ceramic Candle Filters at Varying Degradation," Published in the First US-Japan Symposium on Advances in NDT, June 1996, Hawaii.

Chen, H.L., Spyrakos, C.C., Venkatesh, G. 1995. "Evaluating Structural Deterioration by Dynamic Response," Journal of Structural Engineering, ASCE, Vol. 121, No. 8, 1197-1204, August 1995.

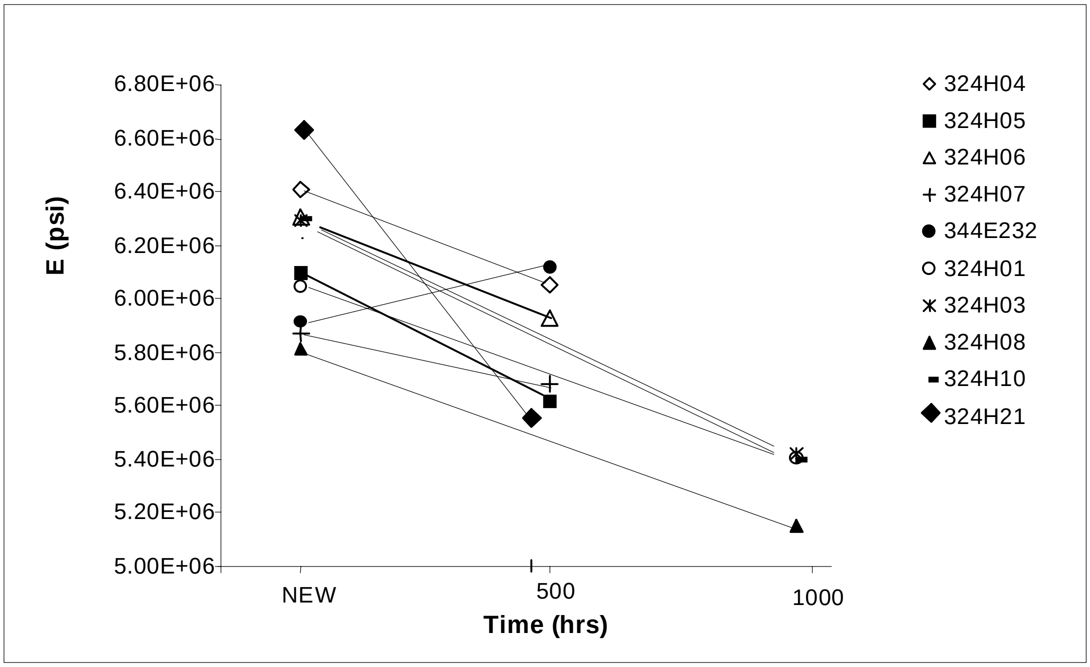

Figure 1. Stiffness Comparison of Schumacher TF-20 Filters

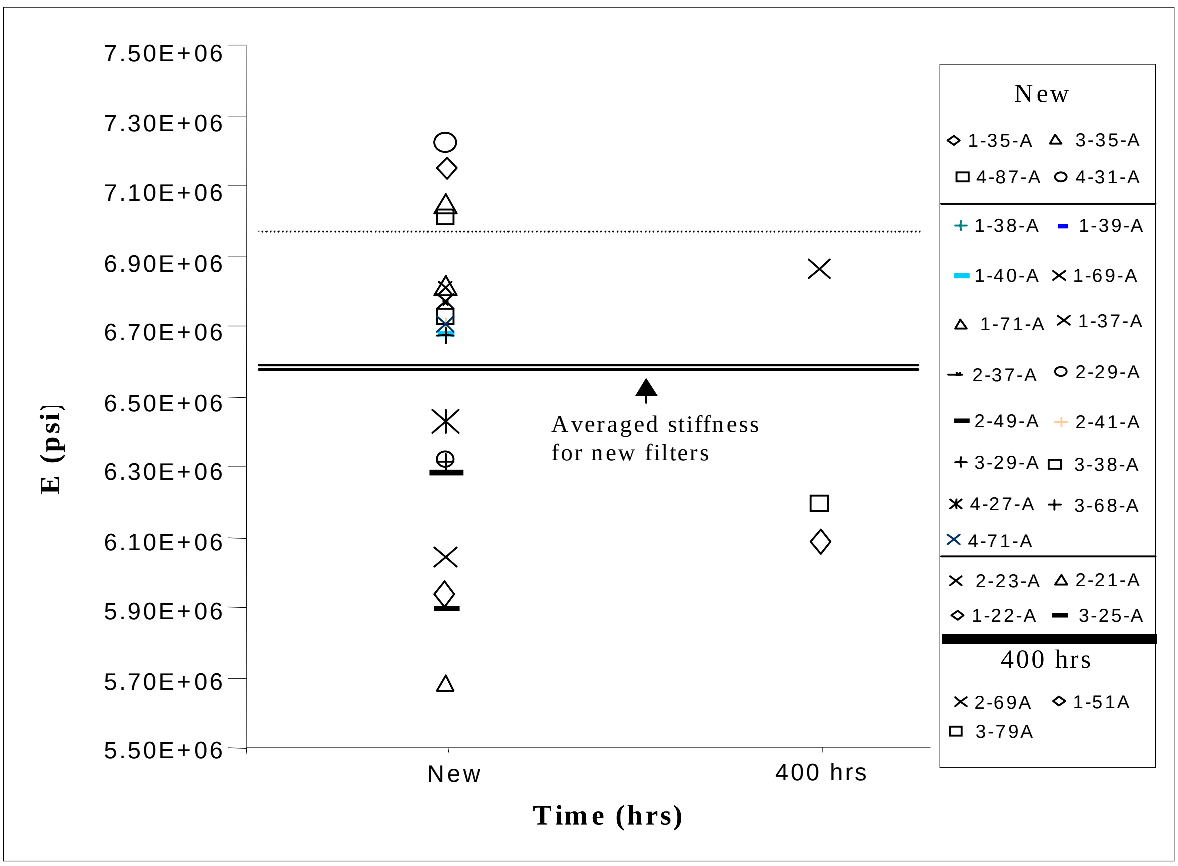

Figure 2. Young's Modulus Comparison Between New and 400 hrs Refractron 326 Filters

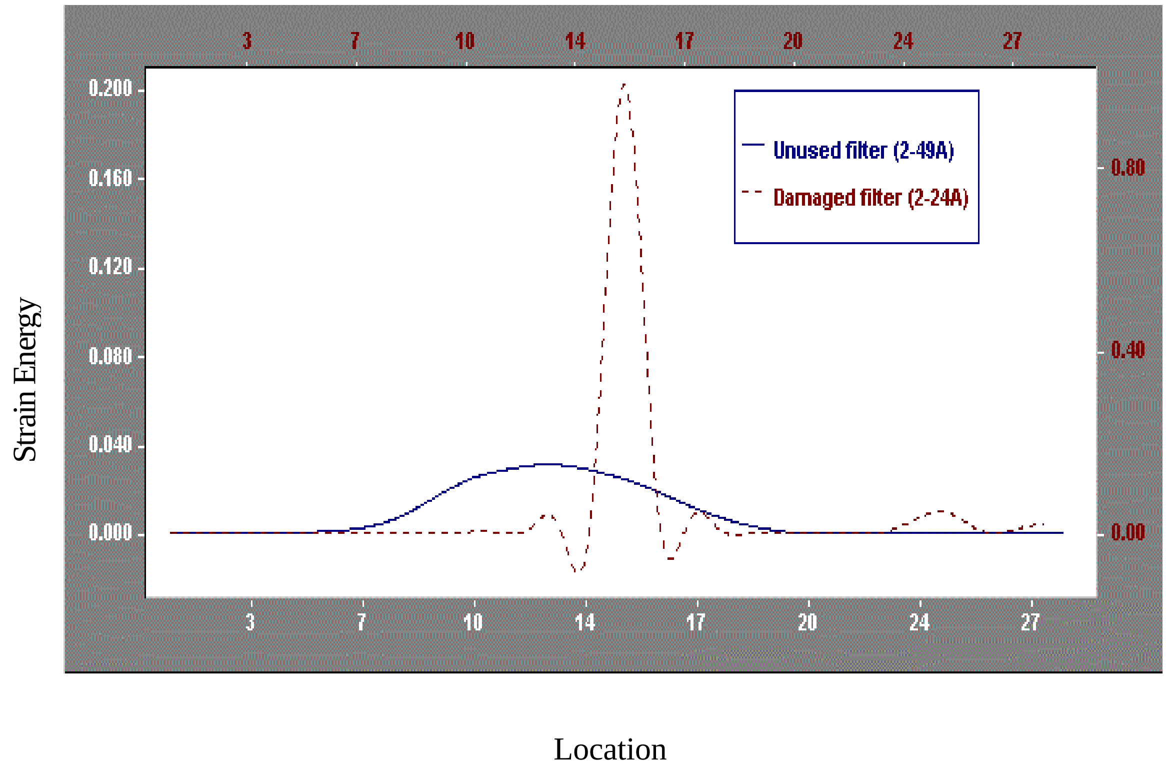

Figure 3. Strain Energy of Mode 1 for New (2-49A) and Damaged (2-24A) Pall 326 Filters

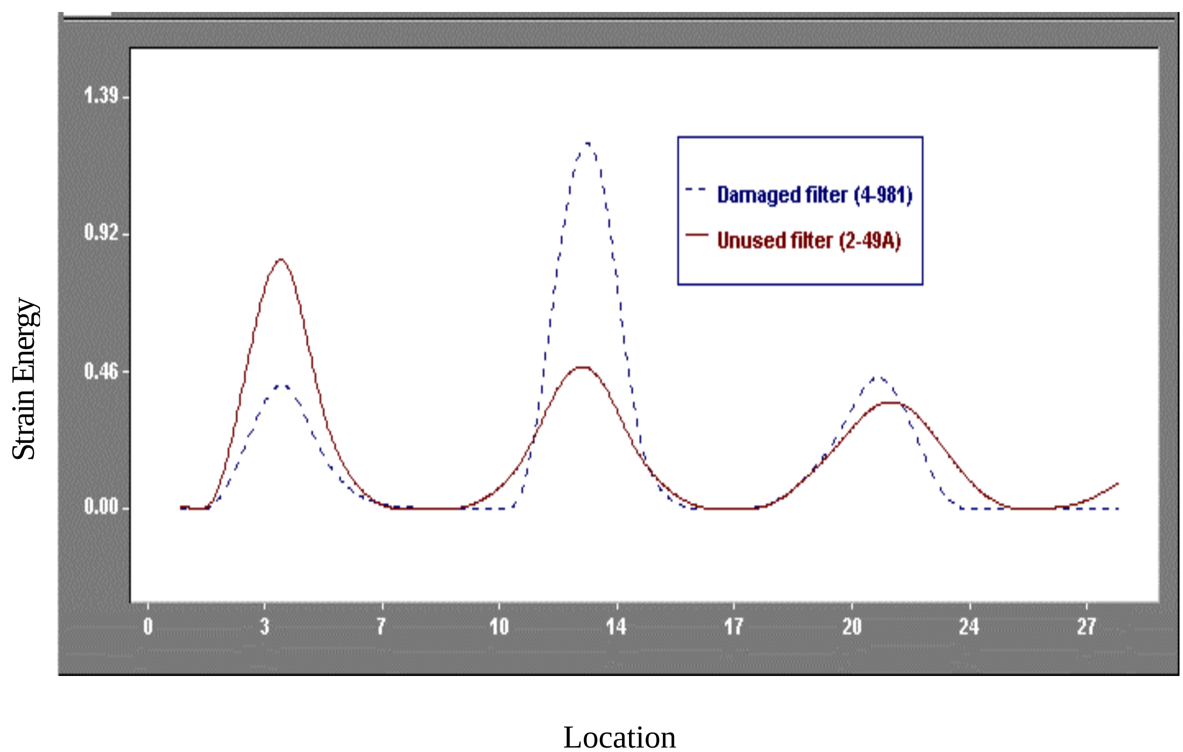

Figure 4. Strain Energy of Mode 3 for New (2-49A) and Damaged (4-981) Pall 326 Filters

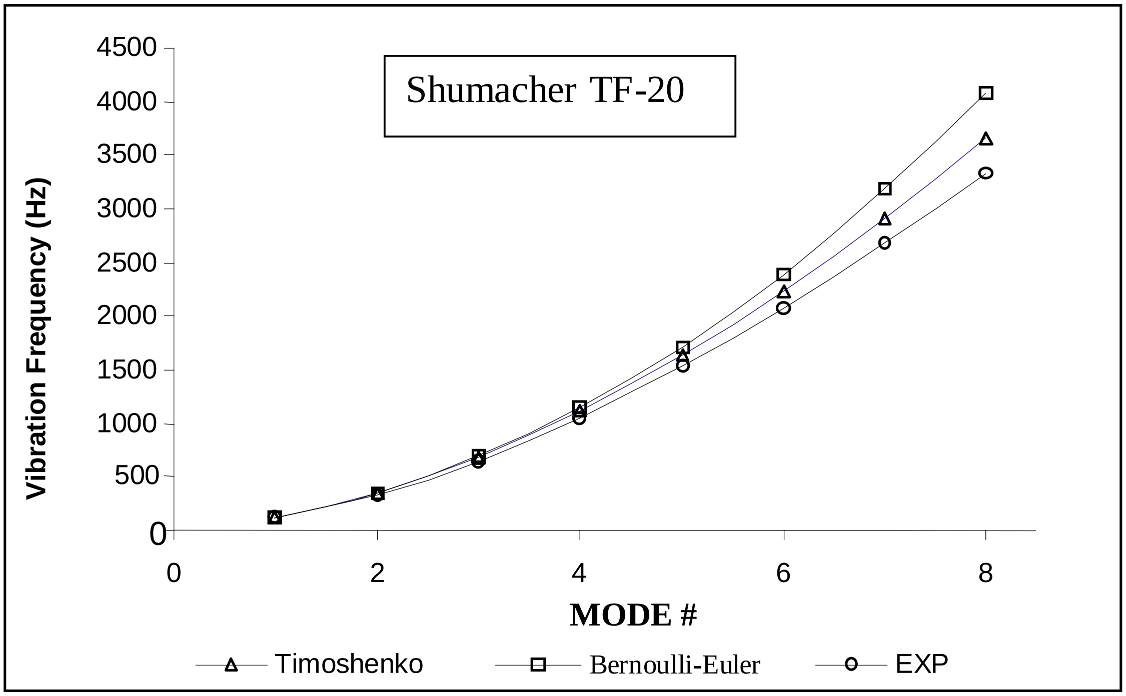

Figure 5. Comparison of Experimental, Bernoulli-Euler, and Timoshenko Results for New Shumacher TF-20 Group