반복하중을 받는 압전 복합재료 작동기의 피로 특성

헤리 세티아완* 구남서** 윤광준**

Degradation Prediction of Piezo-Composite Actuator under Cyclic Electric Field

Hery Setiawan* Nam Seo Goo** Kwang Joon Yoon**

ABSTRACT

This paper presents the fatigue characteristics of LIPCA (**LI**ghtweight **P**iezo-**C**omposite **A**ctuator) device system. The LIPCA device system is composed of a piezoelectric ceramic layer and fiber reinforced lightweight composite layers. Typically a PZT ceramic layer is sandwiched by a top fiber layer with low CTE (coefficient of thermal expansion) and base layers with high CTE. The advantages of the LIPCA design are weight reduction by using the lightweight fiber reinforced plastic layers without compromising the generation of high force and large displacement and design flexibility by selecting the fiber direction and the size of prepreg layers. To predict the degradation of actuation performance of LIPCA due to fatigue, the cyclic electric loading tests using PZT specimens were performed and the strain for a given excitation voltage was measured during the test. The results from the PZT fatigue test were implemented into CLPT (Classical Laminated Plate Theory) model to predict the degradation of LIPCA's actuation displacement. The fatigue characteristic of PZT was measured using a test system composed of a supporting jig, a high voltage power supplier, data acquisition board, PC, and evaluated.

Keywords : LIPCA(**LI**ghtweight **P**iezo-**C**omposite **A**ctuator), piezoelectric actuator, fatigue, degradation

1. INTRODUCTION

Smart actuators can be used to actuate control surfaces of aircrafts and missiles, to suppress the vibration of large space structures, or to actuate robots, and so on. Many studies have already focused on developing small, powerful, and reliable smart actuators. Piezo materials have been identified as one of the best resources, however, their small actuation displacement is still an obstacle that needs to be overcome.

Some representative piezoelectric actuators include the bimorph developed by ACX Co., RAINBOW (**R**educed **A**nd **IN**ternally **B**iased **O**xide **W**afer) [1,2], THUNDER (**TH**in layer **UN**imorph **D**riv**ER**) [3,4], and LIPCA (**LI**ght weight **P**iezo-**C**omposite **A**ctuator) [5-8].

THUNDER is generally regarded as the best piezoelectric actuator, yet it is a little heavy for mesoscale aerospace applications, because it is made of metals such as stainless steel and aluminum, plus, it is relatively difficult and complex to make, requiring an additional adhesive layer (LaRC-SI) to bond the constituent layers and the repoling of the PZT wafer after being cured at a high temperature (325°C) at which point its piezoelectricity disappears [9]. In contrast, the LIPCA involves a simple manufacturing procedure using light-weight fiber reinforced composite materials, such as carbon/epoxy and glass/epoxy, a relatively low temperature (177°C), and no adhesive layers, as the epoxy resin itself is a good bonding material. In addition, the weight can be sufficiently reduced for application in active devices.

Since actuators are repeatedly operated during their lifetime, their fatigue properties need to be investigated. However, relatively few studies have focused on predicting the fatigue life and performance degradation of piezoelectric actuators [10, 11]. It is because the primary concern is to enhance the static actuation displacement and fatigue studies are time consuming, since at least a million cycles of actuations are necessary to obtain one data point.

Accordingly, the present paper focuses on a degradation prediction of the fatigue properties of LIPCA actuators based on the PZT fatigue characteristic, where a special experimental system is designed to characterize the PZT fatigue response [12].

2. PZT DEGRADATION TEST

2.1 Specimen

For a degradation test, PZT 5H ceramic was chosen, which was made by CTS Corporation and the size of the specimen was 72x23x0.5 mm. The strain gauge was used to measure the strain due to the applied voltage. Figure 1 shows the specimen for the test.

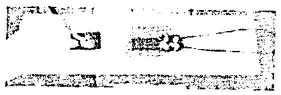

Figure 1. Specimen for PZT degradation test

2.2 Test Equipments

A special test system was designed to accurately measure any temporal change in the strain actuation performance. The measuring system, as shown in Figure 2, consisted of a Face International TD-2 power supply, Curiosity Technology CTA-1000 Dynamic Signal Conditioning Strain Amplifier, and HP 54662A oscilloscope. To analyze and restore digital data to a PC, a DAQ data acquisition system board (National Instrument PCI-6024E) and Lab VIEW program were used.

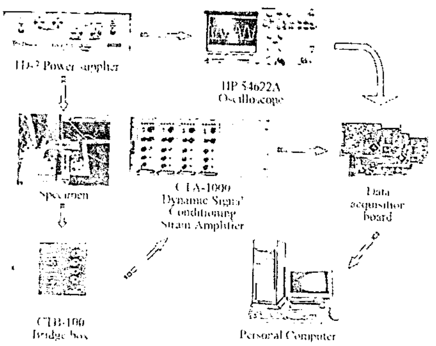

Figure 2. Experimental set-up for PZT degradation test

The PZT degradation test was performed under 500 Vp-p, at 50 Hz frequency.

2.3 Test Result

From PZT degradation test, we obtained the strain degradation after PZT was loaded by cyclic electrical field for several millions cycles. Furthermore, the degradation of the piezoelectric constant d_{31} then could be observed from the test. Figure 3 shows the result of the PZT degradation test.

After loaded for 7 million cycles, the PZT strain was reduced for about 5% from the initial strain where N (number of cycle) is equal to one. This PZT strain degradation indicated that the piezoelectric constant was also degraded.

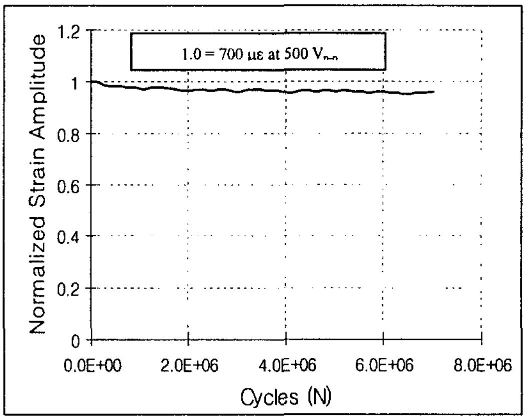

Figure 3. Result of PZT degradation test

3. LIPCA's ACTUATION FORMULATION

Since LIPCA actuators are composite materials, the formulation for prediction of actuation displacement is generated from the Classical Laminated Plate Theory [13] to get a simple model. The constitutive equations for unsymmetrical laminates in the inverse form can be written as follows:

$$\begin{Bmatrix} \varepsilon^0 \\ \kappa \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix}^{-1} \begin{Bmatrix} N + N^a + N^T \\ M + M^a + M^T \end{Bmatrix}, \quad \ldots(1)$$

where [*A*], [*B*], and [*D*] are the extensional matrix, the coupling stiffness matrix, and the bending stiffness matrix, and {*N*}, and {*M*} are the external mechanical resultant forces and moments respectively. The resultant electro active forces and moments $\{N^a\}$, $\{M^a\}$ and thermal forces and moments $\{N^T\}$, $\{M^T\}$ are defined as equations (2) in term of stress distribution through the thickness of piezo-composite laminate, due to presence of *V* and temperature change.

Then, we simplify the CLPT model by treating the actuator as one dimensional (1-D) problem where the width of the actuator is assumed to be small enough compared to the length.

* 석사과정,건국대학교 대학원 항공우주공학과
** 교수, 건국대학교 기계항공공학부
책임저자: kjyoon@konkuk.ac.kr

$$\begin{Bmatrix} N^a \\ M^a \end{Bmatrix} = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \left[\bar{Q}\right]^k \left\{\bar{d}\right\}^k V_z^k \begin{Bmatrix} 1 \\ z \end{Bmatrix} dz$$

$$\begin{Bmatrix} N^T \\ M^T \end{Bmatrix} = \sum_{k=1}^{n} \int_{z_{k-1}}^{z_k} \left[\bar{Q}\right]^k \left\{\bar{\alpha}\right\}^k \Delta T \begin{Bmatrix} 1 \\ z \end{Bmatrix} dz \qquad \ldots(2)$$

In the present formulation, we assumed that:

$$N_y = N_{xy} = N_y^a = N_{xy}^a = N_y^T = N_{xy}^T = 0$$
$$M_y = M_{xy} = M_y^a = M_{xy}^a = M_y^T = M_{xy}^T = 0. \qquad \ldots(3)$$

Substitution of equation (3) into equation (1) yields:

$$\begin{Bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_{xy}^o \\ \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{Bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{16} & b_{11} & b_{21} & b_{61} \\ a_{12} & a_{22} & a_{26} & b_{12} & b_{22} & b_{62} \\ a_{16} & a_{26} & a_{66} & b_{16} & b_{26} & b_{66} \\ b_{11} & b_{21} & b_{61} & d_{11} & d_{12} & d_{16} \\ b_{12} & b_{22} & b_{62} & d_{12} & d_{22} & d_{26} \\ b_{16} & b_{26} & b_{66} & d_{16} & d_{26} & d_{66} \end{bmatrix} \begin{Bmatrix} N_x + N_x^a + N_x^T \\ 0 \\ 0 \\ M_x + M_x^a + M_x^T \\ 0 \\ 0 \end{Bmatrix}. \qquad \ldots(4)$$

For the case of simply supported unimorph piezo-actuator, the maximum displacement occurred at the mid-span. When there is only electric loading without any mechanical and thermal loading, the actuator's amplitude deflection can be written as follows:

$$\Delta w = \frac{E_p . d_{31} . \Delta V . (b_{11} + d_{11} \bar{a}) . L^2}{8}, \qquad \ldots(5)$$

where $\bar{a}$ is the distance to the centroid of the PZT patch of a unimorph actuator, E_p is Young's modulus of the PZT ceramic, d_{31} is the PZT strain constant, and L is the length of the actuator. In this work, we define $\left|b_{11} + d_{11}\bar{a}\right|$ as an actuation coefficient of laminated beam, and denoted as C_{ulb} [13].

With using equation (5) and the result of PZT degradation test, we can predict the actuation degradation of the actuator based on PZT degradation test data. The test data can be employed into the CLPT model with simply considering the $d_{31}.\Delta V$ term in equation (5) as the PZT strain due to the applied voltage, and denoted as ε^a.

Also we assume that the host structure of the actuator remains as its initial condition, and does not experience any degradation during loading. The only layer among the entire actuator lay-up that the degradation takes place due to applied cyclic electrical voltage assumed to be the PZT layer.

4. RESULTS AND DISCUSSION

Figure 4 shows the time history of the actuation displacement for LIPCA-C2 from experimental data and based on the prediction using equation (5) and PZT degradation test.

From the measurement, it can be seen that after about 5.5 million cycles the actuation displacement of LIPCA was reduced for about 10% from its initial actuation (N=1), while the prediction shows that the actuation displacement was reduced for only about 4%. The difference between experiment and prediction results is about 6%. This difference indicates that the actuation degradation of LIPCA is not only due to PZT strain degradation, but also due to LIPCA's composite structure fatigue behavior. This can be figured out by considering the equation (5), which has been used to predict the actuation degradation of LIPCA. In the equation (5) the fatigue behavior of LIPCA's composite structure was not considered in the prediction. LIPCA's composite structure was assumed to have no change in its properties during the loading cycles.

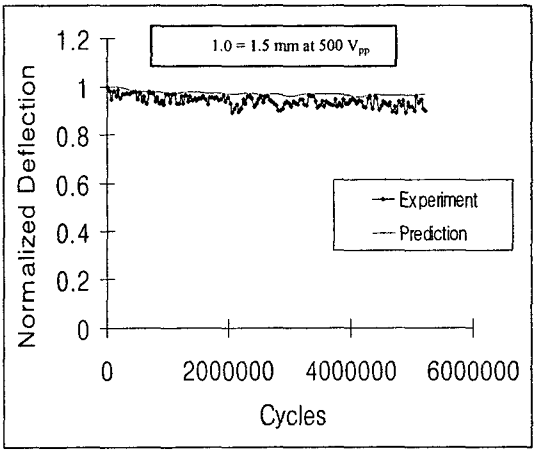

Figure 4. Experiment and prediction result of LIPCA's degradation

Furthermore from the result above, it can be concluded that for LIPCA, about 40% of LIPCA's actuation degradation is due to the PZT degradation and about 60% of the remaining degradation is due to fatigue characteristic of LIPCA's composite structure. The possible damages due to fatigue in composite layers are including matrix crack, fibre/matrix interface failure, delamination, and so on.

For comparison, Figure 5 shows the time history of the actuation displacement for THUNDER from experimental data and from prediction using equation (5) and the PZT degradation test.

Similarly with the LIPCA case, THUNDER also had some degradation in its actuation after loaded by the cyclic electric field for several million cycles. In the THUNDER case, after 5 million cycles the actuation was reduced for about 9.5% (from the experiment), and about 4.5% (from the prediction).

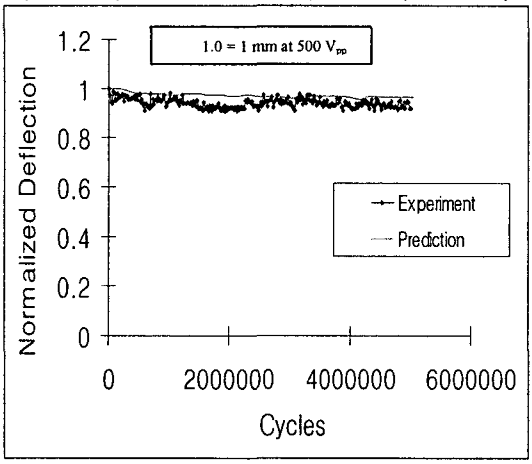

Figure 5. Experiment and prediction of THUNDER's degradation

5. CONCLUSION

The fatigue behavior of LIPCA actuators was predicted via an empirical formulation using the CLPT and experimental study of PZT fatigue characteristic. The actuation displacement of LIPCA decreased with the repeated application of an electric field as well as the PZT strain actuation. The prediction result was compared with experimental measurement for verification. The comparison shows that about 40% LIPCA's actuation degradation is due to PZT degradation. For complete prediction of the LIPCA's fatigue characteristic, we are now working on inclusion of structural degradation of LIPCA lay-ups in addition to fatigue characteristic of the PZT wafer. The model should be able to more accurately predict the LIPCA's fatigue characteristic.

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