行政院國家科學委員會補助專題研究計畫 ■ 成 果 報 告
□期中進度報告

磁縮致動層疊板殼之 GDQ 法熱振動研究

The GDQ Method of Thermal Vibration Laminated Shell with Actuating Magnetostrictive Layers

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執行單位：修平技術學院機械工程系

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一、　　中英文摘要：

磁縮材料層疊板殼之熱振動研究利用一般化微分級數(GDQ)方法來做電腦分析與計算。在熱應力應變方程式中含有線性溫度變化及具有速度回授的磁致伸縮層材料項。含有位移之 Love's 理論的動態微分方程式先利用 GDQ 法來做正規化和離散化，可得到動態離散方程式。我們分析兩端固定之層殼邊界條件，承受兩種分別具有和非具有速度回授之振動研究。最後我們得到電腦計算之層殼間熱應力值及層殼壁中心位移值。我們發現具有速度回授之適當增益值 $k_c c(t)$ 能有效地減少及控制磁縮材料層疊板殼之熱振動位移和應力的大小。

關鍵詞：磁縮材料、層疊板殼、熱振動、一般化微分級數、GDQ、速度回授。

Abstract

The research of magnetostrictive material in a laminated shell under thermal vibration was computed by using the generalized differential quadrature (GDQ) method. In the thermoelastic stress-strain equations that contain the terms linear temperature rise and the magnetostrictive material with velocity feedback. The dynamic equilibrium differential equations with displacements were normalized and discretized into the dynamic discretized equations by the GDQ method. Two edges of laminated shell with clamped boundary conditions were considered. The values of interlaminar thermal stresses and center displacement of shell with and without velocity feedback were calculated, respectively. We find that with velocity feedback and with suitable values of $k_c c(t)$ can reduce the amplitude of displacement and stresses to a smaller value.

Keywords: magnetostrictive material, laminated shell, thermal vibration, generalized differential quadrature, GDQ, velocity feedback.

二、報告內容

1. 前言

在 2003 年我們已經成功地以 GDQ 電腦計算方法來分析含有剪變形層疊板之熱振動及熱彎曲 [6-7]，得知層疊板中心位置之層間熱應力值與最大變形量都隨著邊長厚度比值之減少而增加。2005 年我們以 GDQ 電腦計算方法做熱套管之熱振動分析，得到自然頻率、位移和熱應力值[8]。在以往之國科會研究計畫中，2006 年我們正以 GDQ 法做磁縮材料層疊板之電腦計算計振動研究, 2004 年我們以 GDQ 電腦計算方法做層疊壓電板殼的分析，2002 年我們以 GDQ 電腦計算方法做壓電材料的分析，已在 2006 發表[9]。現在，我們將更進一步以一般化微分級數(GDQ)的電腦計算方法來做磁縮材料層疊板殼之熱振動作用下的層間熱應力及其位移變形量之分析與研究。

2. 研究計畫之背景及目的

本研究計畫之背景：磁縮材料層疊板殼之熱振動作用在 GDQ 法電腦計算之研究方面，到目前尚未有文獻發表。功能梯度材料(Functionally Gradient Material, FGM)是目前機械工程材料新發展驅勢之一。在每一種類的 FGM 中都有其特有的一些功能層，如：壓電

的、磁縮的、電縮的、外形記憶的，在各種剖面中都具有智慧結構的一些特有控制功能[3-4]。當磁縮材料在受磁力和機械力作用下可產生磁性與彈性之交互藕合功能，而Terfenol-D 是目前可實際應用的磁縮材料之一，常運用到感測器和致動器上[5]。

本研究計畫之目的：利用 GDQ 法來做磁縮材料層疊板殼受到熱負載、機械負載、磁縮負載和兩端固定邊界條件下的應力函數、變形函數分佈之熱振動電腦數值計算分析。

本計畫之重要性及國內外有關研究情況：磁縮材料將可提供感測器和致動器上之快速反應功能，並應用到相關設備上。在2006, Lee和Reedy以及Rostam-Abadi對磁縮材料致動層疊板殼做非線性有限元素法分析[1]，發現Terfenol-D磁縮材料可達成橫方向位移量的阻尼作用。在2005年，有Lee 和Reddy以有限元素法(Finite Element Method, FEM)做磁縮材料層疊板受到熱負載、機械負載的非線性反應數值解分析[5] ，發現溫度可以減低變形量的振幅和週期。2005年，Pradhan用解析方式做FGM磁縮材料層疊板殼的振動研究[3] ，發現磁縮材料層應盡量放置於離中心面遠一點之處，並製作薄一點以得到較佳功能。在2003年, Kumar , Ganesan , Swarnamani , Padmanabhan 用有限元素法計算磁縮材料層疊板殼主動控制，發現了磁縮材料最大阻尼位置是在板殼最大位移點處[2]。在2003年，我們以GDQ法來做分別含有剪變形層疊板之熱振動及熱彎曲的研究[6-7]，順利得知層疊板中心位置之層間熱應力值與最大變形量都隨著邊長厚度比值之減少而增加。在2005年，我們以GDQ電腦計算方法做熱套管之熱振動分析，得到自然頻率、位移和熱應力值[8]。在2007年，我們以GDQ電腦計算方法做磁縮材料層疊板之熱振動分析，發現可以用增益值來控制位移量的大小[12]。目前磁縮材料層疊板殼之GDQ法求中心位置最大變形量和層間熱應力時間暫態反應值仍未被發表。在GDQ法中，在某一點的偏微函數值可以用一相關之所有離散點的權衡級數函數值來近似表示[10][11]。GDQ法是由Shu 和Richards在1990所提出。

3. 研究方法 GDQ method

We used the GDQ method to approximate the derivatives of function [6]. The GDQ method was presented by Shu and Richards in 1990 and can be restated that: the derivative of a smooth function at a discrete point in a domain can be discretized by using an approximated weighting linear sum of the function values at all the discrete points in the direction [10][11].

4. 結果與討論 Some numerical results and discussions

We used the following coordinate for the grid point in the GDQ computation.

$$x_i = 0.5[1-\cos(\frac{i-1}{N-1}\pi)]L,\ i=1,2,...,N$$

We consider the total three-layer $(0^{\circ m}/90^{\circ}/0^{\circ})$ cross-ply laminated shell with the upper surface magnetostrictive layer, the inner layer and outer layer of typical host materials. The superscript of m denotes magnetostrictive material. Each layer has the same thickness. The material properties of the typical inner, outer of host material and magnetostrictive material are listed in the following Table 1. The magnetostrictive Terfenol-D coupling moduli is $e_{31}=e_{32}=E^m d^m$ and $E^m = 26.5GPa$, $d^m = 1.67\times 10^{-8} mA^{-1}$.

Table 1 Properties of typical host and Terfenol-D

Properties	Typical host		Terfenol-D
	Inner	Outer	
$\frac{E_1}{E_2}$	25	40	1
$\frac{G_{12}}{E_2}$	0.5	0.6	$\frac{13.25}{26.5}$
ν_{12}	0.15	0.27	0.0
$\rho(lb/in^3)$	0.087	0.283	0.334179
$\alpha_x(1/{}^\circ F)$	6×10^{-6}	6.5×10^{-6}	12×10^{-6}
$\alpha_\theta(1/{}^\circ F)$	6×10^{-6}	6.5×10^{-6}	12×10^{-6}

We firstly to investigate the dynamic convergence of the frequency parameter f^* and center displacement $W(L/2)$ with $R/h=500$, $L/R=10$, circumferential wave number $n=4$, $T_0=100^\circ F$, $\theta=1$ radian, time $t=1$ sec and $k_c c(t)=0$ under clamped-clamped boundary condition. Table 2 shows that f^* and $W(L/2)$ with respect to N for $(0^{\circ m}/90^\circ/0^\circ)$ laminated magnetostrictive shell. We find that the N = 73 grid point has the good convergence results and can be used further in the GDQ computation of time responses for deflection and stress with suitable $k_c c(t)$ values to reduce the amplitude of displacement.

Table 2 Dynamic convergence for $(0^{\circ m}/90^\circ/0^\circ)$, by the GDQ method

N	f^*	$W(L/2)$
23	0.0128564	0.944165
41	0.0128571	0.913904
49	0.0128564	0.914536
73	0.0128564	0.915959

Fig. 1 shows that dominant normal displacement W along X under $\Delta T=\frac{A_{11}}{R^2}T_0x$, $T_0=100^\circ F$, $\theta=1$ radian, time $t=1$ sec, N = 73, for $(0^{\circ m}/90^\circ/0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of displacement W is large when without velocity feedback $k_c c(t)$ = 0. We find that with velocity feedback and with suitable values $k_c c(t)$ = 10^6 can reduce the amplitude of displacement to a smaller value. Fig. 2 shows that dominant thermal stress $\bar{\sigma}_\theta=\sigma_\theta/E_2$ on $Z=-1/6$ along X under $\Delta T=\frac{A_{11}}{R^2}T_0x$, $T_0=100^\circ F$, $\theta=1$ radian, time $t=1$ sec, N = 73, for $(0^{\circ m}/90^\circ/0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of thermal stress $\bar{\sigma}_\theta$ is large when without velocity feedback $k_c c(t)$ = 0. We find that with velocity feedback and with suitable values $k_c c(t)$ = 10^6 can also reduce the amplitude of thermal stress $\bar{\sigma}_\theta$ to a smaller value. Fig. 3 shows that dominant normal displacement W along X under $\Delta T=\frac{A_{11}}{R^2}T_0x$, $T_0=100^\circ F$, $\theta=1$ radian, time $t=1$ sec, N = 73, for $(0^{\circ m}/0^\circ/0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of displacement W is large when without velocity feedback $k_c c(t)$ = 0. We find that with velocity feedback and with suitable values $k_c c(t)$ = 10^6 can reduce the amplitude of displacement to a smaller value. Fig. 4 shows that dominant thermal stress $\bar{\sigma}_x = \sigma_x / E_2$ on $Z = -1/6$ along X under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $\theta = 1$ radian, time $t = 1$ sec, N = 73, for $(0^{\circ m} / 0^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. We find that without velocity feedback and with suitable values $k_c c(t) =$ 10^6 almost have the same amplitude of thermal stress $\bar{\sigma}_x$ at time $t = 1$ sec.

Fig. 5 shows that dominant normal displacement W along X under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, with respect to T_0 =$0^\circ F$, $250^\circ F$, $500^\circ F$, respectively, without velocity feedback $k_c c(t) =$ 0, $\theta = 1$ radian, time $t = 1$ sec, N = 73, for $(0^{\circ m} / 90^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of displacement W is larger when $T_0 = 500^\circ F$. We find that the higher values of temperature get the higher amplitude of displacement. Fig. 6 shows that dominant thermal stress $\bar{\sigma}_\theta$ on $Z = -1/6$ along X under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, with respect to T_0 =$0^\circ F$, $250^\circ F$, $500^\circ F$, respectively, without velocity feedback $k_c c(t) =$ 0, $\theta = 1$ radian, time $t = 1$ sec, N = 73, for $(0^{\circ m} / 90^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of thermal stress $\bar{\sigma}_\theta$ is larger when $T_0 = 500^\circ F$. We find that the higher values of temperature get the higher amplitude of thermal stress $\bar{\sigma}_\theta$. Fig. 7 shows that dominant normal displacement W along X under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, with respect to T_0 =$0^\circ F$, $250^\circ F$, $500^\circ F$, respectively, without velocity feedback $k_c c(t) =$ 0, $\theta = 1$ radian, time $t = 1$ sec, N = 73, for $(0^{\circ m} / 0^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of displacement W is larger when $T_0 = 500^\circ F$. We find that the higher values of temperature get the higher amplitude of displacement. Fig. 8 shows that dominant thermal stress $\bar{\sigma}_x$ on $Z = -1/6$ along X under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, with respect to T_0 =$0^\circ F$, $250^\circ F$, $500^\circ F$, respectively, without velocity feedback $k_c c(t) =$ 0, $\theta = 1$ radian, time $t = 1$ sec, N = 73, for $(0^{\circ m} / 0^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. The amplitude of thermal stress $\bar{\sigma}_x$ is larger when $T_0 = 500^\circ F$. We find that the higher values of temperature get the higher amplitude of thermal stress $\bar{\sigma}_x$.

Fig. 9 shows that the time response of dominant normal displacement W at $X = 0.543578$ with respect to time $t = 1$, 100, 200, 300, 400, and 500 sec, respectively, under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $\theta = 1$ radian, N = 73, without velocity feedback $k_c c(t) =$ 0 and with suitable values $k_c c(t) =$ 10^6, for $(0^{\circ m} / 90^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. We find that with velocity feedback and with suitable values $k_c c(t) =$ 10^6 can reduce the amplitude of displacement to a smaller value. Fig. 10 shows that the time response of dominant thermal stress $\bar{\sigma}_\theta$ at $X = 0.543578$, $Z = -1/6$ with respect to time $t = 1$, 100, 200, 300, 400, and 500 sec, respectively, under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $\theta = 1$ radian, N = 73, without velocity feedback $k_c c(t) =$ 0 and with suitable values $k_c c(t) =$ 10^6, for $(0^{\circ m} / 90^\circ / 0^\circ)$ laminated magnetostrictive shell by using the GDQ method. We find that with velocity feedback and with suitable values $k_c c(t) =$ 10^6 can reduce the amplitude of thermal stress $\bar{\sigma}_\theta$ to a smaller value. Fig. 11 shows that the time response of dominant normal displacement W at $X = 0.768650$ with respect to time $t = 1$, 100, 200, 300, 400, and 500 sec, respectively, under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $\theta = 1$ radian, N = 73, without velocity feedback $k_c c(t)$ = 0 and with suitable values $k_c c(t)$ = 10^6, for $(0^{\circ m}/0^\circ/0^\circ)$ laminated magnetostrictive shell by using the GDQ method. We find that with velocity feedback and with suitable values $k_c c(t)$ = 10^6 can reduce the amplitude of displacement to a smaller value. Fig. 12 shows that the time response of dominant thermal stress $\bar{\sigma}_x$ at $X = 0.768650$, $Z = -1/6$ with respect to time $t = 1$, 100, 200, 300, 400, and 500 sec, respectively, under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $\theta = 1$ radian, N = 73, without velocity feedback $k_c c(t)$ = 0 and with suitable values $k_c c(t)$ = 10^6, for $(0^{\circ m}/0^\circ/0^\circ)$ laminated magnetostrictive shell by using the GDQ method. We find that with velocity feedback and with suitable values $k_c c(t)$ = 10^6 can reduce the amplitude of thermal stress $\bar{\sigma}_x$ to a smaller value.

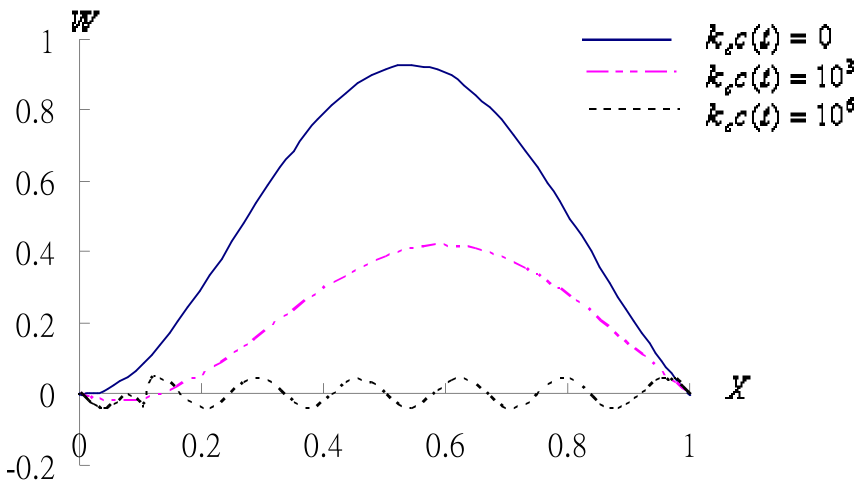

Fig. 1. W along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $t = 1$ sec, for $(0^{\circ m}/90^\circ/0^\circ)$

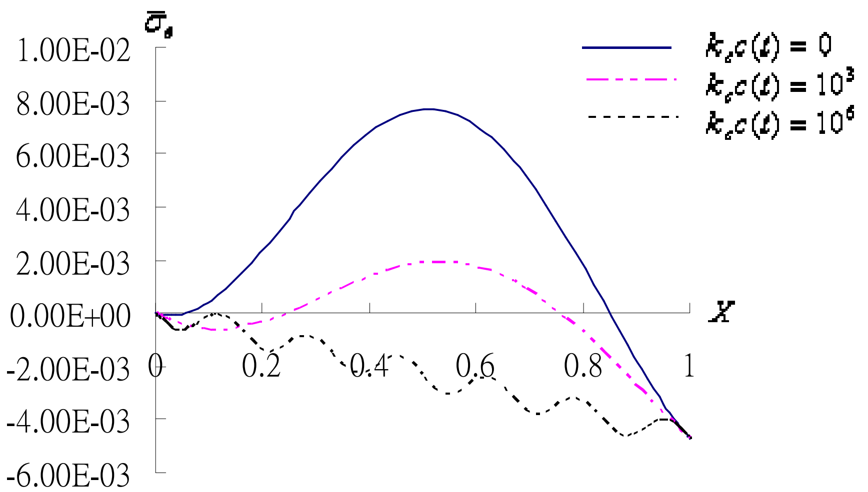

Fig. 2. $\bar{\sigma}_\theta$ on $Z = -1/6$ along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $t = 1$ sec, $(0^{\circ m}/90^\circ/0^\circ)$

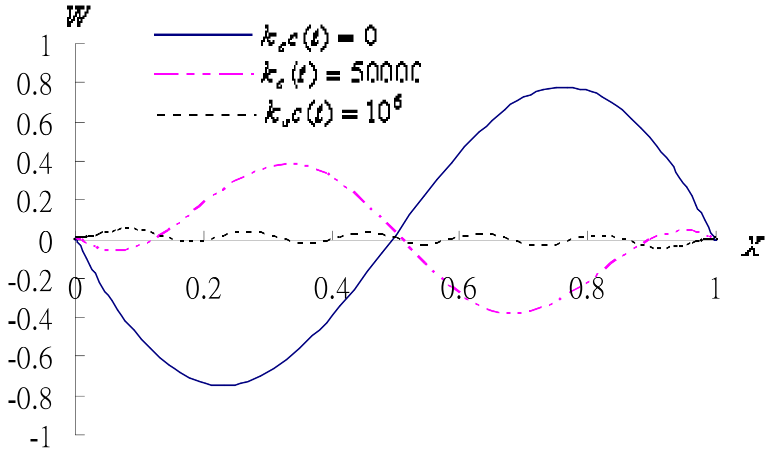

Fig. 3. W along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $T_0 = 100^\circ F$, $t = 1$ sec, for $(0^{\circ m}/0^\circ/0^\circ)$

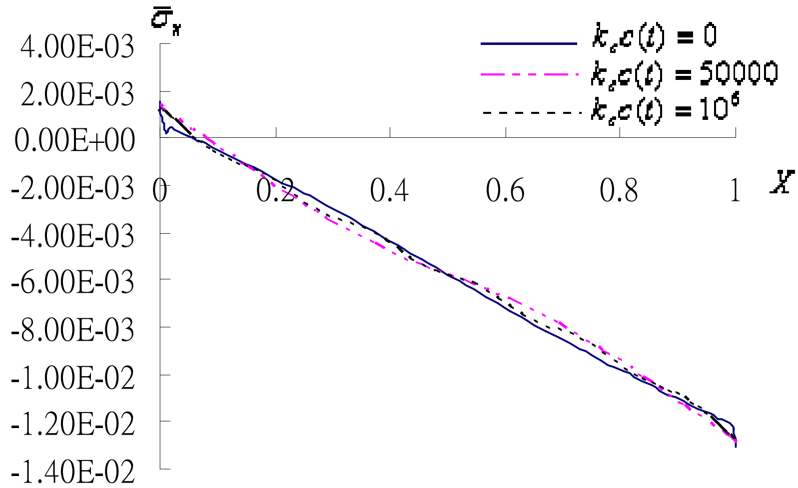

Fig. 4. $\bar{\sigma}_x$ on $Z = -1/6$ along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $t = 1$sec, for $(0^{\circ m}/0^\circ/0^\circ)$

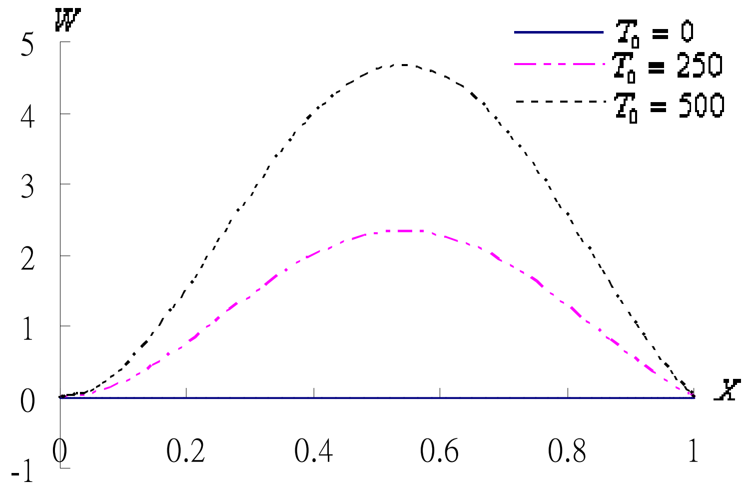

Fig. 5. W along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $k_c c(t) = 0$, $t = 1$ sec, for $(0^{\circ m}/90^\circ/0^\circ)$

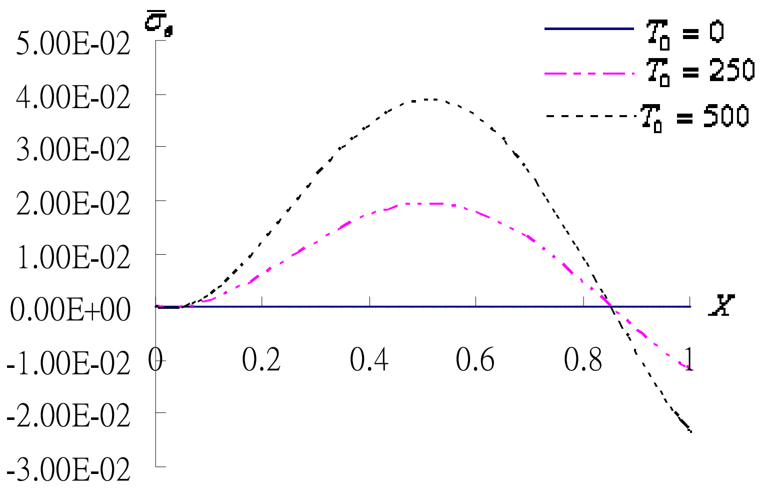

Fig. 6. $\bar{\sigma}_\theta$ on $Z=-1/6$ along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $k_c c(t) = 0$, $t = 1\,\text{sec}$, $(0^{\circ m}/90^\circ/0^\circ)$

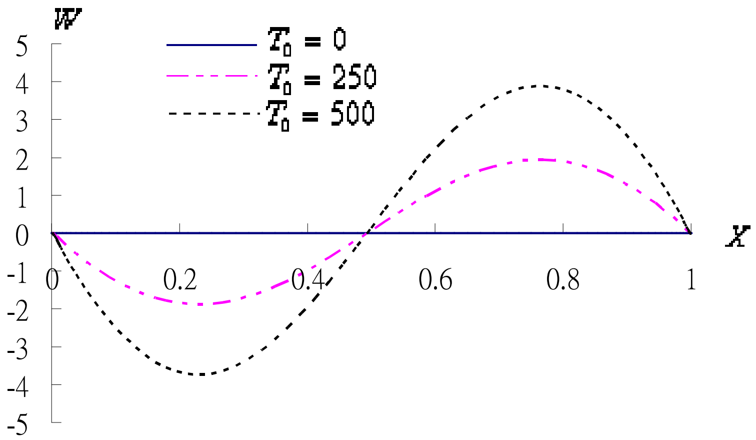

Fig. 7. W along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $k_c c(t) = 0$, $t = 1$ sec , for $(0^{\circ m}/0^\circ/0^\circ)$

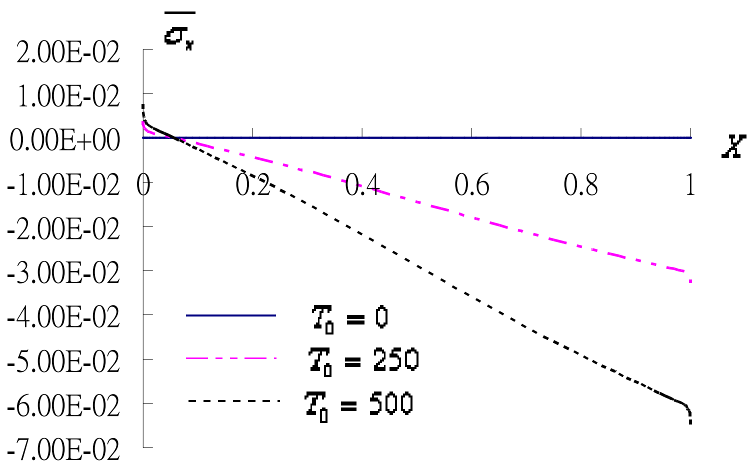

Fig. 8. $\bar{\sigma}_x$ on $Z=-1/6$ along X under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $k_c c(t) = 0$, $t = 1\,\text{sec}$, $(0^{\circ m}/0^\circ/0^\circ)$

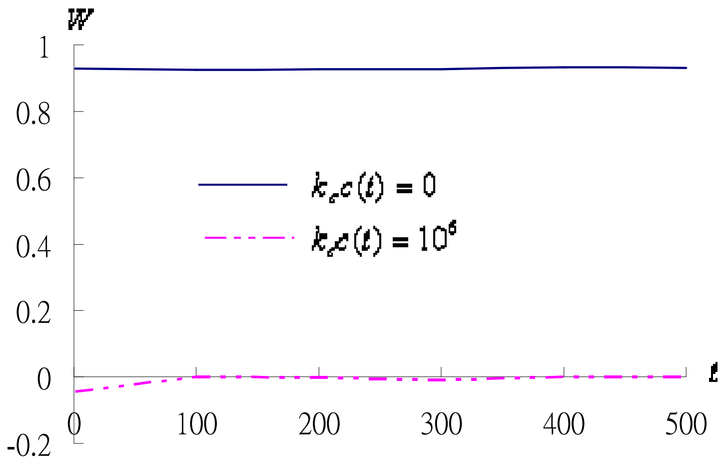

Fig. 9. W at $X = 0.543578$ vs. time t, under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $\theta = 1$ radian, $(0^{\circ m}/90^{\circ}/0^{\circ})$

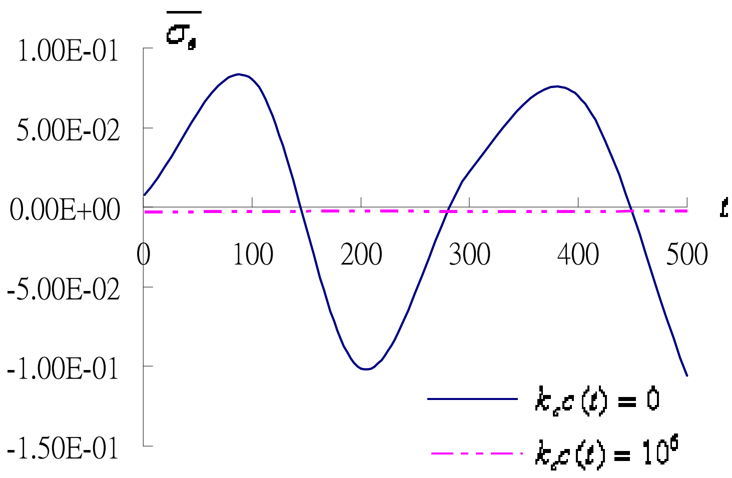

Fig. 10. $\bar{\sigma}_\theta$ at $X = 0.543578$, $Z = -1/6$ vs. time t, under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $(0^{\circ m}/90^{\circ}/0^{\circ})$

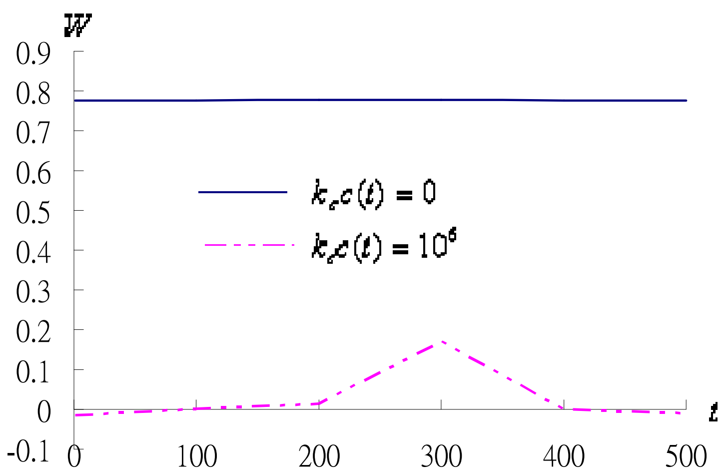

Fig. 11. W at $X = 0.768650$ vs. time t, under $\Delta T = \dfrac{A_{11}}{R^2} T_0 x$, $\theta = 1$ radian, $(0^{\circ m}/0^{\circ}/0^{\circ})$

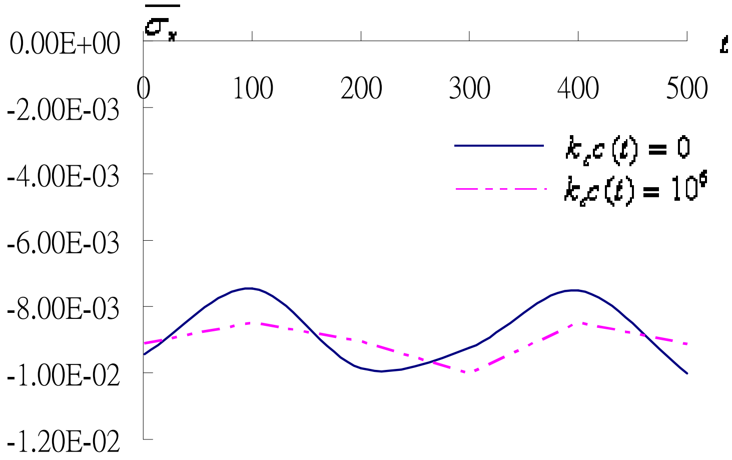

Fig. 12. $\overline{\sigma}_x$ at $X = 0.768650$, $Z = -1/6$ vs. time t, under $\Delta T = \frac{A_{11}}{R^2} T_0 x$, $(0^{\circ m}/0^{\circ}/0^{\circ})$

5. 結論與建議 Conclusions

The GDQ method can be successfully applied to compute the time responses of displacement and stresses in the laminated magnetostrictive shell subjected to thermal vibration. We find that with velocity feedback and with suitable values of $k_c c(t)$ can reduce the amplitude of displacement and stresses to a smaller value. The higher values of temperature get the higher amplitude of displacement and stresses.

6. 參考文獻 References

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三、計畫成果自評:

研究內容與原計畫之相符程度高、達成預期目標之情況高、研究成果具有學術及應用價值、適合在國外學術期刊(如 IJSS)發表、我們主要發現為: 具有速度回授之適當增益值 $k_c c(t)$ 能有效地減少及控制磁縮材料層疊板殼之熱振動位移和應力的大小。 綜合評估是一項非常有價值的研究成果。