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APPENDIX A

The reduced rigidity quantities are as follows:

$$K_{11} = A_{22} - \frac{A_{12}^2}{A_{11}}, \qquad K_{12} = A_{26} - \frac{A_{12}A_{16}}{A_{11}} = K_{21}, \qquad K_{13} = 2K_{12}\frac{A_C}{\beta},$$

$$K_{14} = B_{22} - \frac{A_{12}B_{12}}{A_{11}} = K_{41}, \qquad K_{22} = A_{66} - \frac{A_{16}^2}{A_{11}}, \qquad K_{23} = 2K_{22}\frac{A_C}{\beta},$$

$$K_{24} = B_{26} - \frac{A_{16}B_{12}}{A_{11}} = K_{42}, \qquad K_{43} = 2K_{24}\frac{A_C}{\beta}, \qquad K_{44} = D_{22} - \frac{B_{12}^2}{A_{11}},$$

$$K_{51} = B_{26} - \frac{B_{16}A_{12}}{A_{11}}, \qquad K_{52} = B_{66} - \frac{B_{16}A_{16}}{A_{11}}, \qquad K_{53} = 2K_{52}\frac{A_C}{\beta},$$

$$K_{54} = D_{26} - \frac{B_{12}B_{16}}{A_{11}}$$

where A_{ij}, B_{ij} and D_{ij} denote local stretching, stretching-bending coupling and bending rigidity quantities, respectively.

The inertia terms are

$$I_1 = \oint\left(\ddot{u}_o - y\ddot{\varphi}\right)m_o\,ds, \quad I_2 = \oint\left(\ddot{v}_o - x\ddot{\varphi}\right)m_o\,ds,$$

$$I_3 = \oint\left(\ddot{w}_o + x\ddot{\theta}_y + y\ddot{\theta}_x - F_w\ddot{\varphi}'\right)m_o\,ds,$$

$$I_4 = \oint\left[\left(x^2 + y^2\right)\ddot{\varphi} - y\ddot{u}_o + x\ddot{v}_o\right]m_o\,ds,$$

$$I_5 = \oint\left[x\ddot{w}_o + x^2\ddot{\theta}_y + xy\ddot{\theta}_x - xF_w(s)\ddot{\varphi}'\right]m_o\,ds + \oint\left[\left(\frac{dy}{ds}\right)^2\ddot{\theta}_y - \frac{dx}{ds}\frac{dy}{ds}\ddot{\theta}_x - \frac{dy}{ds}a(s)\ddot{\varphi}'\right]m_2\,ds,$$

$$I_7 = \oint\left[y\ddot{w}_o + y^2\ddot{\theta}_x + xy\ddot{\theta}_y - yF_w(s)\ddot{\varphi}'\right]m_o\,ds + \oint\left[\left(\frac{dx}{ds}\right)^2\ddot{\theta}_x - \frac{dx}{ds}\frac{dy}{ds}\ddot{\theta}_y - \frac{dx}{ds}a(s)\ddot{\varphi}'\right]m_2\,ds,$$

$$I_9 = \oint\left[-F_w(s)\ddot{w}_o - xF_w(s)\ddot{\theta}_y - yF_w(s)\ddot{\theta}_x + F_w^{\,2}\ddot{\varphi}'\right]m_o\,ds$$

$$+\oint\left[\frac{dx}{ds}\,a(s)\ddot{\theta}_x - a(s)\frac{dy}{ds}\ddot{\theta}_y + a^2(s)\ddot{\varphi}\right]m_2\,ds$$

where

$$(m_o, m_2) = \sum_{k=1}^{N}\int_{h(k-1)}^{h(k)} \rho_{(k)}\left(1, n^2\right)dn$$

denote the mass terms.

The rigidity terms are symmetric, $a_{ij} = a_{ji}(i, j = \overline{1,7})$ and have the expressions

$$a_{11} = \oint K_{11}ds, \qquad a_{12} = \oint\left(xK_{11} + K_{14}\frac{dy}{ds}\right)ds,$$

$$a_{13} = \oint\left(yK_{11} - K_{14}\frac{dx}{ds}\right)ds, \qquad a_{14} = \oint K_{12}\frac{dx}{ds}\,ds,$$

$$a_{15} = \oint K_{12}\frac{dy}{ds}\,ds, \qquad a_{16} = -\oint\left[K_{11}F_w(s) - K_{14}\,a(s)\right]ds,$$

$$a_{17} = \oint K_{13}\,ds,$$

$$a_{22} = \oint\left(K_{11}x^2 + 2x\,K_{14}\frac{dy}{ds} + K_{44}\frac{dy}{ds}\frac{dy}{ds}\right)ds,$$

$$a_{23} = \oint\left(K_{11}xy - xK_{14}\frac{dx}{ds} + yK_{14}\frac{dy}{ds} - K_{44}\frac{dx}{ds}\frac{dy}{ds}\right)ds,$$

$$a_{24} = \oint\left(xK_{12}\frac{dx}{ds} + K_{24}\frac{dx}{ds}\frac{dy}{ds}\right)ds, \; a_{25} = \oint\left(x\,K_{12}\frac{dy}{ds} + K_{24}\frac{dy}{ds}\frac{dy}{ds}\right)ds,$$

$$a_{26} = -\oint\left(xK_{11}F_w + xK_{14}\,a + F_wK_{14}\frac{dy}{ds} + K_{44}\,a\frac{dy}{ds}\right)ds,$$

$$a_{27} = \oint\left(x\,K_{13} + K_{43}\frac{dy}{ds}\right)ds, \; a_{33} = \oint\left(K_{11}y^2 - 2yK_{14}\frac{dx}{ds} + K_{44}\frac{dx}{ds}\frac{dx}{ds}\right),$$

$$a_{34} = \oint\left(yK_{12}\frac{dx}{ds} - K_{24}\frac{dx}{ds}\frac{dx}{ds}\right)ds, \; a_{35} = \oint\left(yK_{12}\frac{dy}{ds} - K_{24}\frac{dy}{ds}\frac{dy}{ds}\right)ds,$$

$$a_{36} = -\oint\left(yK_{11}F_w + yK_{14}\,a - F_wK_{14}\frac{dx}{ds} - K_{44}\,a\frac{dx}{ds}\right)ds,$$

$$a_{37} = \oint\left(yK_{13} - K_{43}\frac{dx}{ds}\right)ds, \quad a_{44} = \oint\left(K_{22}\frac{dx}{ds}\frac{dx}{ds} + A_{44}\frac{dy}{ds}\frac{dy}{ds}\right)ds$$

$$a_{45} = \oint \left(K_{22} \frac{dx}{ds}\frac{dy}{ds} - A_{44} \frac{dx}{ds}\frac{dy}{ds} \right) ds \,,$$

$$a_{46} = -\oint \left(F_w K_{21} \frac{dx}{ds} + K_{24}\, a \frac{dx}{ds} \right) ds, \quad a_{47} = \oint K_{23} \frac{dx}{ds}\, ds \,,$$

$$a_{55} = \oint \left(K_{22} \frac{dy}{ds}\frac{dy}{ds} + A_{44} \frac{dx}{ds}\frac{dx}{ds} \right) ds \,, \quad a_{56} = -\oint \left(F_w K_{21} \frac{dy}{ds} + K_{24}\, a \frac{dy}{ds} \right) ds \,,$$

$$a_{57} = \oint K_{23} \frac{dy}{ds}\, ds, \quad a_{66} = \oint \left(K_{11} F_w^2 + 2K_{14} F_w a + K_{44}\, a^2 \right) ds,$$

$$a_{67} = -\oint \left(K_{13} F_w + K_{43}\, a \right) ds \,, \quad a_{77} = \oint 2 \frac{A_C}{\beta} K_{23}\, ds .$$

The reduced mass terms are as follows:

$$\left(b_1, b_4, b_5, b_{10} \right) = \oint m_o \left(1, y^2, x^2, F_w^2 \right) ds,$$

$$\left(b_{14}, b_{15}, b_{18} \right) = \oint m_2 \left[\left(\frac{dx}{ds} \right)^2, \left(\frac{dy}{ds} \right)^2, a^2 \right] ds .$$

APPENDIX B

STRUCTURE MODEL DATA

Table B.1 - Properties of Graphite/Epoxy

properties	Graphite/Epoxy
E_L (psi)	30e6
E_T (psi)	0.75e6
G_{LT} (psi)	0.37e6
G_{TT} (psi)	0.45e6
μ_{TT}	0.25
μ_{LT}	0.25
ρ (lb sec^2/in^4)	14.3e-5

Table B.2 - Properties of Transverse Isotropy Material

properties	Transverse Isotropy
E_L (psi)	30e6
E_T (psi)	75e5
G_{TT} (psi)	6e5
μ_{TT}	0.25
μ_{LT}	0.25
ρ (lb sec^2/in^4)	14.3e-5

where subscripts L and T denote directions parallel and transverse to the fibers respectively.

APPENDIX C

PIEZOELECTRIC MATERIAL PROPERTIES

Table C - Physical Properties of PZT-4

Thickness(in)	
t^a	0.00787
Elastic Coefficients(psi)	
C_{11}	2.016e7
C_{12}	1.128e7
C_{13}	1.077e7
C_{33}	1.668e7
C_{44}	3.713e6
Piezoelectric Co.(lb/in V)	
e_{31}	-0.0297
e_{33}	0.0862
e_{15}	0.0725
Poisson Ratio	
ν	0.31
Density(lb sec^2/in^4)	
ρ	7.0135e-4
Electrical Permittivity(Farad/in)	
ξ_{33}^{p}	3.048e-10

APPENDIX D

The first six normalized eigenmodes of an unactivated cantilevered thin-walled beam in transversal motion. The characteristics of the beam are provided in Fig. 4.1.

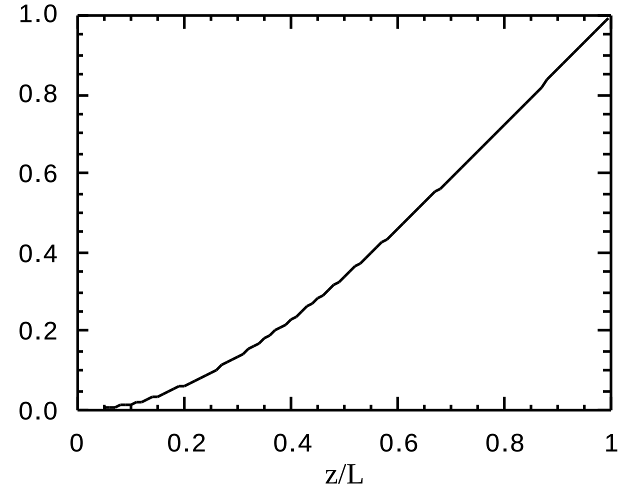

Fig. D1 First mode: $0.9088\eta^2 - 0.4159\eta^3 - 0.0010256\eta^4 + 0.00038\eta^5 + 0.0309\eta^6 - 0.00568\eta^7$

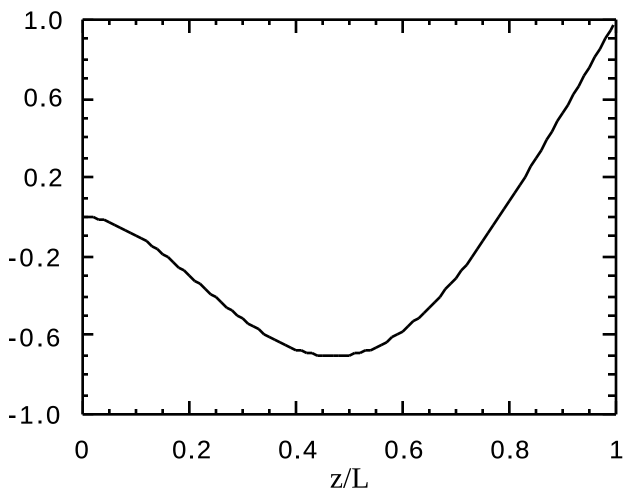

Fig. D2 Second mode: $0.3163\eta^2 - 0.50203\eta^3 + 0.00412\eta^4 - 0.06199\eta^5 + 0.5967\eta^6 - 0.5169\eta^7$

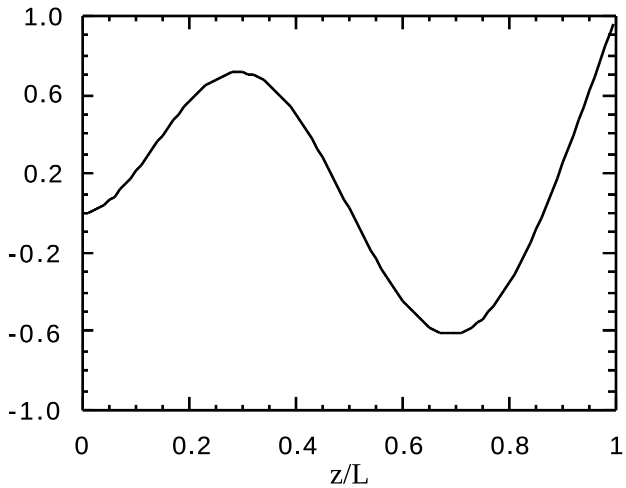

Fig. D3 Third mode: $0.02067\eta^2 - 0.05397\eta^3 + 0.0104\eta^4 - 0.08375\eta^5 + 0.4966\eta^6 - 0.7341\eta^7$

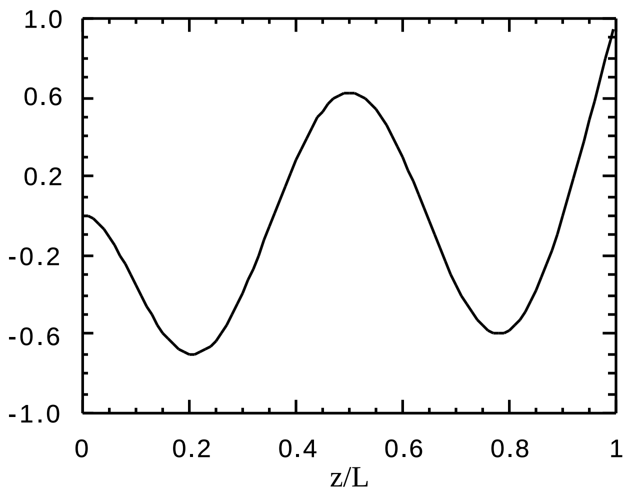

Fig. D4 Fourth mode: $0.00515\eta^2 - 0.004849\eta^3 - 0.1317\eta^4 + 0.4958\eta^5 - 0.7165\eta^6 + 0.4609\eta^7$

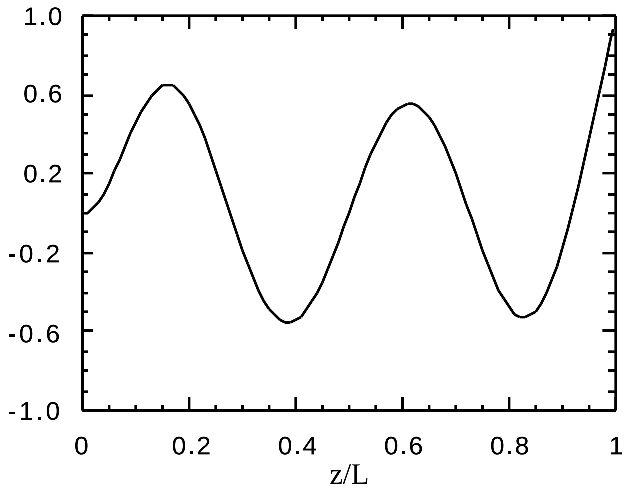

Fig. D5 Fifth mode: $0.000703\eta^2 + 0.00168\eta^3 - 0.05903\eta^4 + 0.2797\eta^5 - 0.5940\eta^6 + 0.6532\eta^7$

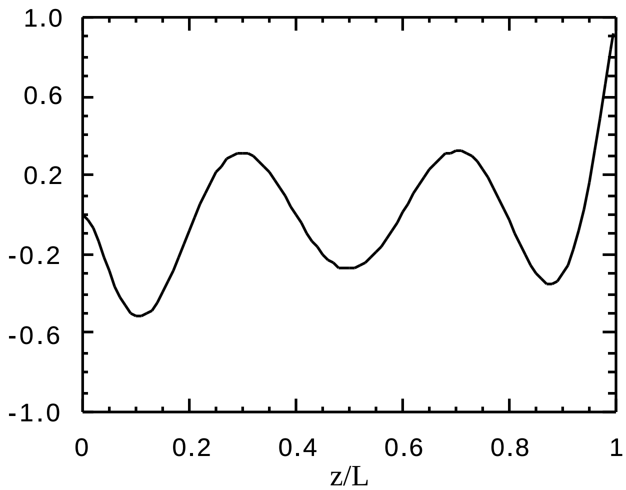

Fig. D6 Sixth mode: $-0.003926\eta^2 + 0.04809\eta^3 - 0.2257\eta^4 + 0.5303\eta^5 - 0.6707\eta^6 + 0.4451\eta^7$

VITA

Sungsoo Na was born in May 10, 1963 in Seoul, Korea. He graduated from Korea University with a B.S. in 1986, and a M.S. in 1988, both in Mechanical Engineering.

After graduation, he worked as a teaching assistant in the Precision Engineering Department at Korea Advanced Institute Science and Technology (KAIST). While in KAIST, he taught undergraduate courses in CAD/CAM lab and experimental stress analysis.

He earned a Ph.D degree in Fall 1997 at the Department of Engineering Science and Mechanics at Virginia Polytechnic Institute and State University, Blacksburg, Virginia. While in Blacksburg, he served as an administrative committee member at Korean Baptist Church for four and a half years as well as the President of Korean Student Association for 1995-1996.

Dr. Na is going to join the faculty members of University of Korea Industrial Technology which is located in the city of Ansan, Korea in January 1998.

With his wife Dong-Eun Park, he has two daughters, Sangwon and Sang-Yoon.