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FINITE ELEMENT STRUCTURAL MODEL OF A LARGE, THIN, COMPLETELY FREE, FLAT PLATE

SURESH M. JOSHI AND NELSON J. GROOM

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NASA
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SUMMARY

A finite element structural model of a 30.48 m x 30.48 m x 2.54 mm (100 ft x 100 ft x 0.1 in) completely free aluminum plate is described and modal frequencies and mode-shape data for the first 44 modes are presented. An explanation of the procedure for using the modal data is also presented. The model should prove useful for the investigation of controller design approaches for large flexible structures.

INTRODUCTION

Many of the future missions planned in the Shuttle era require space structures of very large size. These missions include Earth observation systems, space power stations, space processing facilities, electronic mail systems, and personal communication systems (ref. 1). The development of structures of the size being contemplated for these missions will require new technology in many areas. One of the most important areas is control systems design. The basic problems involved in the control of large space structures (LSS) have been discussed in the literature (for example refs. 2-4). In order to develop and evaluate the required controller design approaches for solving these problems, it is necessary to have a mathematical model of an LSS. The model should be realistic enough to include important structural characteristics of an LSS but at the same time should be simple enough to be manageable. A model of a long slender uniform free-free beam was used in reference 3. However, this model is essentially one-dimensional and does not include important dynamic characteristics such as multiple modes with the same modal frequency. A structure that has the characteristics of closely spaced modes with repeated frequencies is the flat plate. This paper describes a finite element structural model of a 30.48 m x 30.48 m x 2.54 mm (100 ft x 100 ft x 0.1 in) completely free aluminum plate. An explanation of the procedure for using the model is also presented. The model was computed by using the NASA SPAR computer program (ref. 5). Modal frequency and mode-shape data of the plate were obtained for the first 44 modes and are presented in an appendix of this paper. Because of the volume of the data, it was impractical to provide a hard copy of the appendix. It has therefore been put on microfilm and a copy is attached to the inside of the back cover.

SYMBOLS

f	external force vector defined in eqn. (3)
f_a	actuator force used in example
F_k	external force vector at joint k, defined in eqn. (4)
F_{z_k}	z-axis external force at joint k
m	$= n_J \, n_{DOF}$
n_{DOF}	number of degrees of freedom per joint
n_J	number of joints
n_q	number of modes
p_i	scaled modal amplitude for ith mode, defined in eqn. (8)
q	modal amplitude vector
q_i	modal amplitude of mode i in normal coordinates
T_{x_k}	external torque (x-axis) acting at joint k
T_{y_k}	external torque (y-axis) acting at joint k
t_a	actuator torque used in example
y_i	displacement vector at mode i, defined eqn. (5)
z_k	total z-axis displacement at joint k
$z_{i,k}$	z-axis displacement at joint k due to mode i
Φ	mode-shape matrix
$\hat{\Phi}_k$	n_q x 3 submatrix of Φ corresponding to joint k (eqn. 6)
ϕ_{jk}	n_q-dimensional vector which gives the displacement at joint k (eqn. 5)
θ_{x_k}	total x-rotation at joint k
θ_{y_k}	total y-rotation at joint k

$\theta_{x_{i,k}}$ x-rotation at joint k due to mode i

$\theta_{y_{i,k}}$ y-rotation at joint k due to mode i

Λ coefficient matrix of q in eqn. (1)

ψ_{1i}, ψ_{2i} components of mode-shape matrix corresponding to z-axis translations and y-axis rotation due to mode i, used in the illustrative example

ψ'_{1i}, ψ'_{2i} defined in eqns. (9) and (10)

ω_i modal frequency of mode i

MATHEMATICAL MODEL

The plate was divided into 24 x 24 equal square plate elements as shown in figure 1. Figure 2 shows the 625 numbered joints (nodes) resulting from the mesh. The NASA SPAR computer program (ref. 5) was used to obtain the first 44 modal frequencies and mode shapes. The structural model can be represented as:

$$\ddot{q} + \Lambda q = \Phi^T f \tag{1}$$

where q is the n_q-dimensional modal amplitude vector in normal coordinates, Λ is a diagonal matrix whose entries are the squares of the natural frequencies, Φ is the m x n_q mode-shape matrix, where

$$m = n_J \, n_{DOF} \tag{2}$$

n_J being the number of joints, and n_{DOF} is the number of degrees of freedom per joint. In the present model, $n_J = 625$ and $n_{DOF} = 3$ resulting in $m = 1875$. The degrees of freedom are: z-axis translation (perpendicular to the plane of the plate), and rotations about the x and y axes.

The m x 1 generalized external force vector f is given by

$$f = (F_1^T, F_2^T, \ldots, F_{n_J}^T)^T \tag{3}$$

$$F_k = (F_{z_k}, T_{x_k}, T_{y_k})^T, \quad k = 1, 2, \ldots, n_J \tag{4}$$

F_{z_k}, T_{x_k}, T_{y_k} being the z-axis external force, and x- and y-axis external torques acting on the plate at joint k.

The displacements at joint k are given by

$$y_k = \begin{bmatrix} z_k \\ \theta_{x_k} \\ \theta_{y_k} \end{bmatrix} = \begin{bmatrix} \phi_{1k}^T \\ \phi_{2k}^T \\ \phi_{3k}^T \end{bmatrix} q \qquad (k = 1, 2, \ldots, n_J) \tag{5}$$

where ϕ_{jk} $(j = 1, 2, 3)$ is the jth row of the $3 \times n_q$ matrix $\hat{\Phi}_k^T$ which is a submatrix of Φ:

$$\Phi = \begin{bmatrix} \hat{\Phi}_1^T \\ \hat{\Phi}_2^T \\ \hat{\Phi}_{n_J}^T \end{bmatrix}_{m \times n_q} \tag{6}$$

z_k, θ_{x_k}, θ_{y_k} respectively denote the z-axis displacement and x- and y-axis angular displacements (rotations) at joint k.

MODAL DATA

Table I shows the natural frequencies of modes 1-44. The mode-shape data consist of all the elements of Φ, which consists of $n_J\, n_{DOF}\, n_q$ numbers (= 82,500 numbers), and is presented in the appendix. Because of the large volume of the mode-shape data, the appendix has been put on microfilm and a copy is attached to the inside of the back cover of this report. It should be noted that English units are used in the SPAR program.

APPLICATION OF MODAL DATA

The procedure for using the modal data is presented in this section. Table II shows a sample page of the mode-shape data. A user would normally need the mode-shape data only at a few joints. For example, if there is a force actuator at joint 199, a torque actuator at joint 190 (about y-axis), a position sensor at joint 196, and a two-axis attitude sensor at joint 200, the corresponding equations for mode i are:

$$\ddot{q}_i + \omega_i^2 q_i = \psi_{1i} f_a + \psi_{2i} t_a \tag{7}$$

where f_a and t_a represent force (lb) and torque (lb-in) and $\psi_{1i} = \hat{\Phi}_{199}(i,1)$ and $\psi_{2i} = \hat{\Phi}_{190}(i,3)$ ($\hat{\Phi}_k(i,j)$ denotes the i-j element of $\hat{\Phi}_k$). For mode no. 16 (i = 16), from table II,

$$\psi_{1,16} = -0.241 \quad \text{and} \quad \psi_{2,16} = 0.007693$$

Thus to obtain $\hat{\Phi}(i,j)$ the user would look under mode i, find the row corresponding to joint k, and read the number under column j (j = 1, 2, 3). The contributions of mode 16 to the translational displacement at joint 196 and rotational displacements at joint 200 are:

$$z_{16,196} = -0.012755 \quad q_{16} \quad \text{(inches)}$$

$$\theta_{x_{16,200}} = -0.0021583 \quad q_{16} \quad \text{(radians)}$$

$$\theta_{y_{16,200}} = 0.002657 \quad q_{16} \quad \text{(radians)}$$

The total displacement at a joint is the sum of the displacements due to all modes (all q_i's).

In order to use torque in lb-ft and translational displacement in ft in the above example, the elements of Φ corresponding to torque, or rotation (i.e., the colums labeled THETA-X and THETA-Y in the mode-shape data) should be multiplied by $\sqrt{12}$ and those corresponding to force, or displacement (i.e., the column labeled HZ IN/IN) should be divided by $\sqrt{12}$. To illustrate, define

$$p_i = q_i/\sqrt{12} \tag{8}$$

$$\psi'_{1i} = \psi_{1i}/\sqrt{12} \tag{9}$$

$$\psi'_{2i} = \psi_{2i}\sqrt{12} \tag{10}$$

Equation (7) can then be written as

$$\ddot{p}_i + \omega_i^2 \; p_i = \psi'_{1i} \; f_a + \psi'_{2i} \; t'_a \tag{11}$$

where t'_a is torque in lb-ft. For mode 16

$$\psi'_{1,16} = -\frac{0.241}{\sqrt{12}} \quad \text{and} \quad \psi'_{2,16} = 0.007693 \; (\sqrt{12}\,)$$

The contributions of mode 16 to the translational displacement at joint 196 and rotational displacements at joint 200 become

$$z_{16,196} = -\left(\frac{0.012755}{\sqrt{12}}\right) p_{16} = -\left(\frac{0.012755}{\sqrt{12}}\right) \frac{q_{16}}{\sqrt{12}} \quad \text{(ft)}$$

$$\theta_{x_{16,200}} = -0.0021583\ (\sqrt{12})\ p_{16} = -0.0021583\ (\sqrt{12})\ \frac{q_{16}}{\sqrt{12}}\ \text{(rad)}$$

$$\theta_{y_{16,200}} = 0.002657\ (\sqrt{12})\ p_{16} = 0.002657\ (\sqrt{12})\ \frac{q_{16}}{\sqrt{12}}\ \text{(rad)}$$

Thus the transformed model will have the same form as eqns. (1) and (5) with q replaced by p, and all units will be in the ft-lb-sec system.

Figure 3 presents the first 44 mode-shapes of the plate. These figures should be helpful in giving the user a better understanding of the modal characteristics. For example, the figures can be used for visually determining approximate actuator/sensor placement in order to maximize or minimize the effect of certain modes.

CONCLUDING REMARKS

In order to provide a mathematical model for use in the development and evaluation of controller design approaches for large space structures, a finite element structural model of a large, thin, completely free aluminum plate has been developed. The model has been described and modal frequencies and mode-shape data for the first 44 modes presented. An explanation of the procedure for using the data has also been presented. The model should be useful to researchers working in the area of large space structures control.

REFERENCES

1. Anon.: Outlook for Space. NASA SP-386 and SP-387, January 1976.

2. Balas, Mark J.: Active Control of Flexible Systems. Proceedings of the Symposium on Dynamics and Control of Large Flexible Spacecraft. Blacksburg, VA, June 1977.

3. Joshi, Suresh M.; and Groom, Nelson J.: Design of Reduced-Order Controllers for Large Flexible Space Structures. Proceedings of the 16th Annual Allerton Conference on Communication, Control, and Computing, Urbana, IL, October 1978.

4. Joshi, Suresh M.; and Groom, Nelson J.: Stability Bounds for the Control of Large Space Structures. Journal of Guidance and Control, Vol. 2, No. 4, July-August 1979, pages 349-351.

5. Whetstone, W. D.: SPAR Structural Analysis System Reference Manual. NASA CR-158970, December 1978.

TABLE I.- COMPUTED NATURAL FREQUENCIES OF PLATE STRUCTURAL MODEL

MODE	FREQ(RAD/SEC)	FREQ(HZ)
1	.54999E-01	.87534E-02
2	.80024E-01	.12736E-01
3	.99111E-01	.15774E-01
4	.14211E+00	.22618E-01
5	.14211E+00	.22618E-01
6	.24948E+00	.39707E-01
7	.24948E+00	.39707E-01
8	.26008E+00	.41392E-01
9	.28286E+00	.45018E-01
10	.31515E+00	.50157E-01
11	.43068E+00	.68545E-01
12	.43068E+00	.68545E-01
13	.47824E+00	.76114E-01
14	.50003E+00	.79583E-01
15	.53689E+00	.85449E-01
16	.53689E+00	.85449E-01
17	.62422E+00	.99347E-01
18	.65958E+00	.10497E+00
19	.68808E+00	.10951E+00
20	.80973E+00	.12887E+00
21	.80973E+00	.12887E+00
22	.83371E+00	.13269E+00
23	.87377E+00	.13906E+00
24	.87982E+00	.14003E+00
25	.87982E+00	.14003E+00
26	.99216E+00	.15791E+00
27	.99216E+00	.15791E+00
28	.11483E+01	.18275E+00
29	.11922E+01	.18974E+00
30	.11996E+01	.19093E+00
31	.12194E+01	.19407E+00
32	.12250E+01	.19497E+00
33	.12532E+01	.19946E+00
34	.12532E+01	.19946E+00
35	.13742E+01	.21872E+00
36	.14082E+01	.22412E+00
37	.14871E+01	.23668E+00
38	.14871E+01	.23668E+00
39	.16059E+01	.25558E+00
40	.16059E+01	.25558E+00
41	.16972E+01	.27012E+00
42	.16972E+01	.27012E+00
43	.17111E+01	.27233E+00
44	.17523E+01	.27889E+00

TABLE II.- SAMPLE PAGE FROM MODE-SHAPE DATA FOR PLATE STRUCTURAL MODEL

STRUCTURAL MODAL DATA OF 100FT X 100FT X 0.1IN F-F-F-F ALUMINUM PLATE(CONTD)

STRUCTURAL MODE NO. 16 FREQUENCY= .53689348E+00 RAD/SEC(.85449E-01 HZ)

JOINT	COORDINATES FT	HZ IN/IN	THETA-X RAD/IN	THETA-Y RAD/IN	JOINT	COORDINATES FT	HZ IN/IN	THETA-X RAD/IN	THETA-Y RAD/IN
151	(75.00, 0.00)	.78373E-01	.10470E-02	.31789E-03	152	(75.00, 4.17)	.13871E+00	.13065E-02	.54097E-04
153	(75.00, 8.33)	.20533E+00	.12996E-02	-.23017E-03	154	(75.00, 12.50)	.26469E+00	.10193E-02	-.50262E-03
155	(75.00, 16.67)	.30391E+00	.50258E-03	-.72433E-03	156	(75.00, 20.83)	.31313E+00	-.16548E-03	-.86006E-03
157	(75.00, 25.00)	.28768E+00	-.86523E-03	-.88721E-03	158	(75.00, 29.17)	.22925E+00	-.14658E-02	-.80149E-03
159	(75.00, 33.33)	.14579E+00	-.18523E-02	-.61835E-03	160	(75.00, 37.50)	.50016E-01	-.19510E-02	-.36991E-03
161	(75.00, 41.67)	-.43013E-01	-.17449E-02	-.98421E-04	162	(75.00, 45.83)	-.11895E+00	-.12786E-02	.15249E-03
163	(75.00, 50.00)	-.16705E+00	-.64964E-03	.34662E-03	164	(75.00, 54.17)	-.18236E+00	.11693E-04	.46231E-03
165	(75.00, 58.33)	-.16671E+00	.56883E-03	.49634E-03	166	(75.00, 62.50)	-.12832E+00	.90738E-03	.46395E-03
167	(75.00, 66.67)	-.80052E-01	.95861E-03	.39488E-03	168	(75.00, 70.83)	-.36750E-01	.71321E-03	.32664E-03
169	(75.00, 75.00)	-.12198E-01	.22203E-03	.29633E-03	170	(75.00, 79.17)	-.16378E-01	-.41676E-03	.33304E-03
171	(75.00, 83.33)	-.53669E-01	-.10821E-02	.45256E-03	172	(75.00, 87.50)	-.12249E+00	-.16622E-02	.65584E-03
173	(75.00, 91.67)	-.21664E+00	-.20903E-02	.93223E-03	174	(75.00, 95.83)	-.32842E+00	-.23805E-02	.12677E-02
175	(75.00,100.00)	-.45355E+00	-.26633E-02	.16603E-02	176	(70.83, 0.00)	.64179E-01	.86952E-03	-.83308E-03
177	(70.83, 4.17)	.11403E+00	.10732E-02	-.99704E-03	178	(70.83, 8.33)	.16842E+00	.10529E-02	-.12107E-02
179	(70.83, 12.50)	.21604E+00	.80525E-03	-.14166E-02	180	(70.83, 16.67)	.24625E+00	.36403E-03	-.15631E-02
181	(70.83, 20.83)	.25106E+00	-.19721E-03	-.16093E-02	182	(70.83, 25.00)	.22696E+00	-.77663E-03	-.15316E-02
183	(70.83, 29.17)	.17578E+00	-.12641E-02	-.13280E-02	184	(70.83, 33.33)	.10459E+00	-.15644E-02	-.10182E-02
185	(70.83, 37.50)	.24427E-01	-.16175E-02	-.63975E-03	186	(70.83, 41.67)	-.51888E-01	-.14122E-02	-.24049E-03
187	(70.83, 45.83)	-.11227E+00	-.98963E-03	.13113E-03	188	(70.83, 50.00)	-.14784E+00	-.43519E-03	.43546E-03
189	(70.83, 54.17)	-.15477E+00	.13846E-03	.64918E-03	190	(70.83, 58.33)	-.13504E+00	.61444E-03	.76930E-03
191	(70.83, 62.50)	-.96090E-01	.89581E-03	.81277E-03	192	(70.83, 66.67)	-.49249E-01	.92556E-03	.81214E-03
193	(70.83, 70.83)	-.74532E-02	.69811E-03	.80802E-03	194	(70.83, 75.00)	.17406E-01	.25973E-03	.84030E-03
195	(70.83, 79.17)	.16828E-01	-.30275E-03	.94004E-03	196	(70.83, 83.33)	-.12755E-01	-.88295E-03	.11241E-02
197	(70.83, 87.50)	-.69674E-01	-.13826E-02	.13941E-02	198	(70.83, 91.67)	-.14817E+00	-.17413E-02	.17414E-02
199	(70.83, 95.83)	-.24100E+00	-.19660E-02	.21576E-02	200	(70.83,100.00)	-.34352E+00	-.21583E-02	.26570E-02

Y

576	552	528	504	480	456	432	408	384	360	336	312	288	264	240	216	192	168	144	120	96	72	48	24
575	551	527	503	479	455	431	407	383	359	335	311	287	263	239	215	191	167	143	119	95	71	47	23
574	550	526	502	478	454	430	406	382	358	334	310	286	262	238	214	190	166	142	118	94	70	46	22
573	549	525	501	477	453	429	405	381	357	333	309	285	261	237	213	189	165	141	117	93	69	45	21
572	548	524	500	476	452	428	404	380	356	332	308	284	260	236	212	188	164	140	116	92	68	44	20
571	547	523	499	475	451	427	403	379	355	331	307	283	259	235	211	187	163	139	115	91	67	43	19
570	546	522	498	474	450	426	402	378	354	330	306	282	258	234	210	186	162	138	114	90	66	42	18
569	545	521	497	473	449	425	401	377	353	329	305	281	257	233	209	185	161	137	113	89	65	41	17
568	544	520	496	472	448	424	400	376	352	328	304	280	256	232	208	184	160	136	112	88	64	40	16
567	543	519	495	471	447	423	399	375	351	327	303	279	255	231	207	183	159	135	111	87	63	39	15
566	542	518	494	470	446	422	398	374	350	326	302	278	254	230	206	182	158	134	110	86	62	38	14
565	541	517	493	469	445	421	397	373	349	325	301	277	253	229	205	181	157	133	109	85	61	37	13
564	540	516	492	468	444	420	396	372	348	324	300	276	252	228	204	180	156	132	108	84	60	36	12
563	539	515	491	467	443	419	395	371	347	323	299	275	251	227	203	179	155	131	107	83	59	35	11
562	538	514	490	466	442	418	394	370	346	322	298	274	250	226	202	178	154	130	106	82	58	34	10
561	537	513	489	465	441	417	393	369	345	321	297	273	249	225	201	177	153	129	105	81	57	33	9
560	536	512	488	464	440	416	392	368	344	320	296	272	248	224	200	176	152	128	104	80	56	32	8
559	535	511	487	463	439	415	391	367	343	319	295	271	247	223	199	175	151	127	103	79	55	31	7
558	534	510	486	462	438	414	390	366	342	318	294	270	246	222	198	174	150	126	102	78	54	30	6
557	533	509	485	461	437	413	389	365	341	317	293	269	245	221	197	173	149	125	101	77	53	29	5
556	532	508	484	460	436	412	388	364	340	316	292	268	244	220	196	172	148	124	100	76	52	28	4
555	531	507	483	459	435	411	387	363	339	315	291	267	243	219	195	171	147	123	99	75	51	27	3
554	530	506	482	458	434	410	386	362	338	314	290	266	242	218	194	170	146	122	98	74	50	26	2
553	529	505	481	457	433	409	385	361	337	313	289	265	241	217	193	169	145	121	97	73	49	25	1

X

Figure 1.- Location of elements for plate structural model.

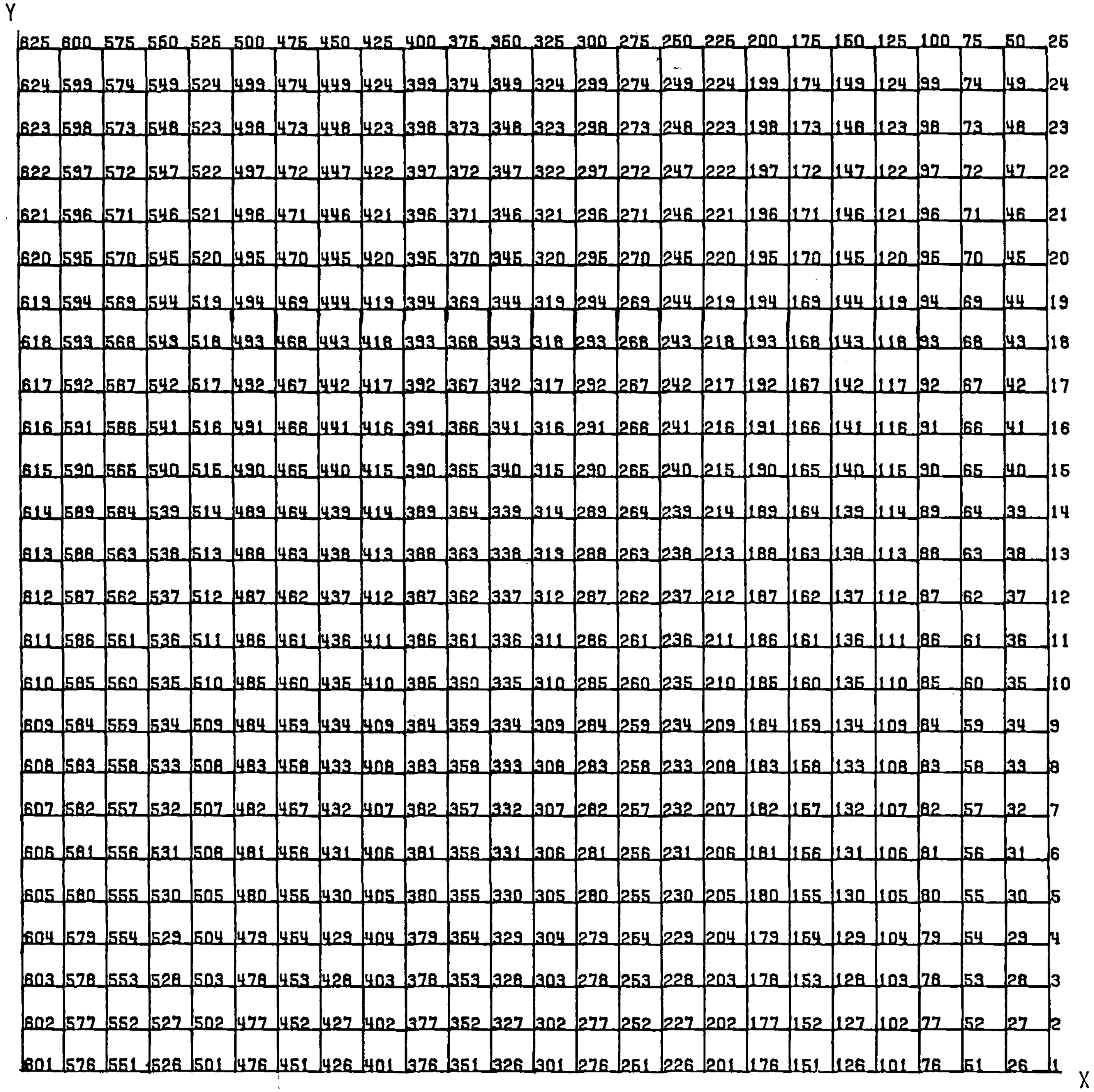


Figure 2.- Location of joints for plate structural model.

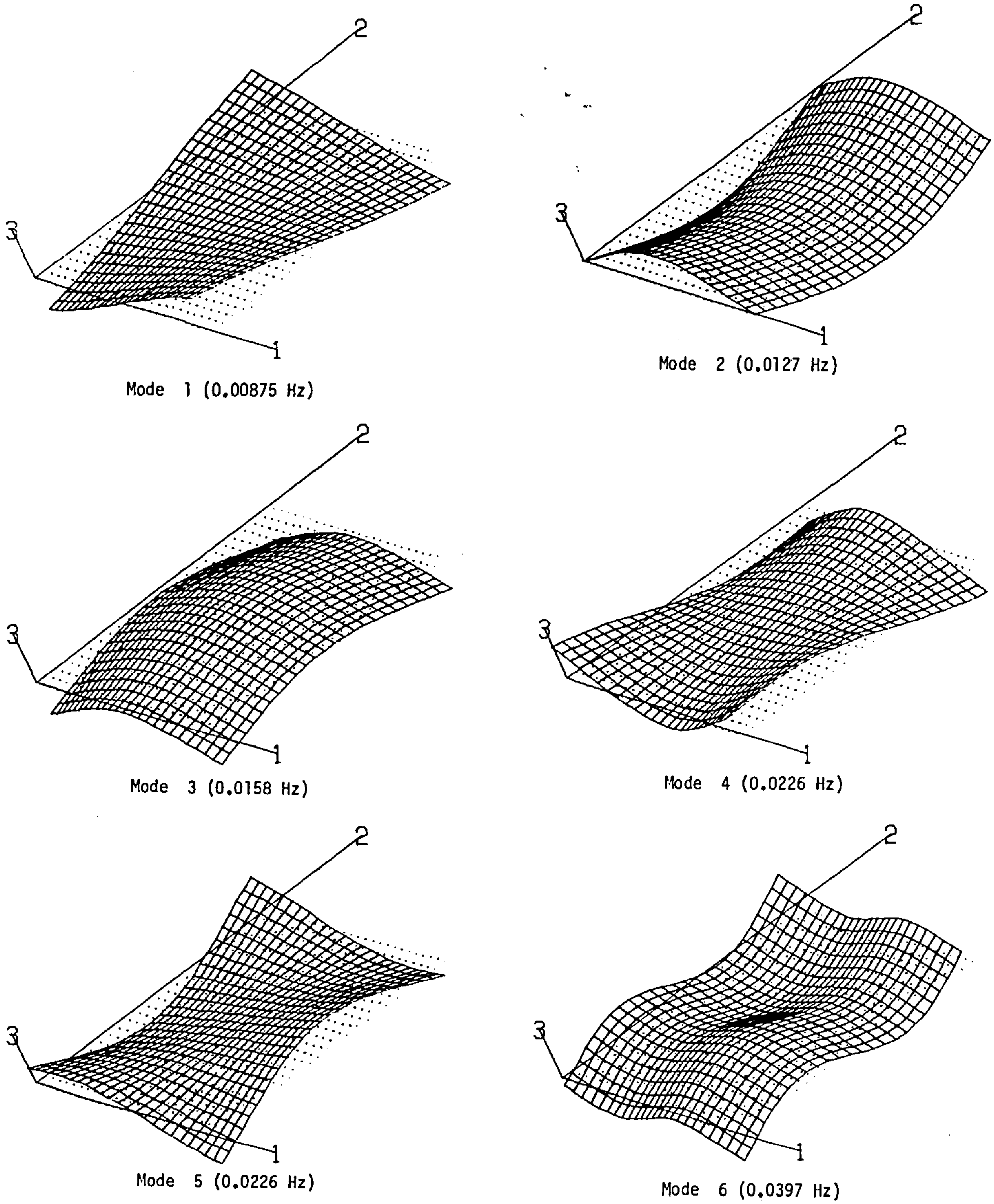
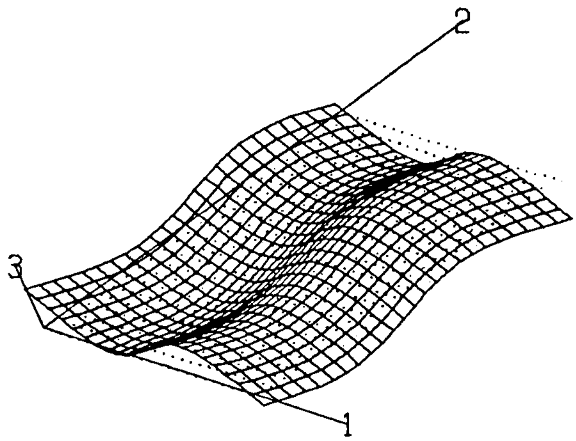
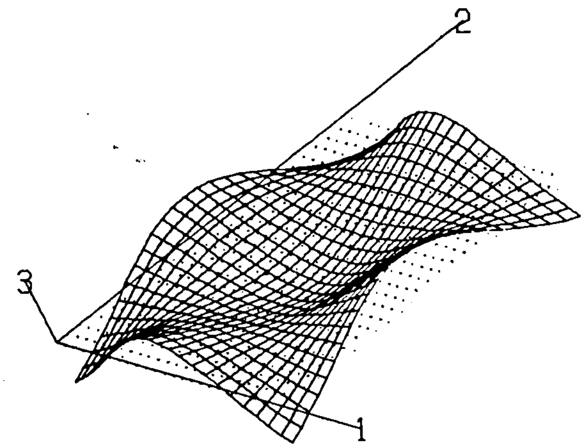


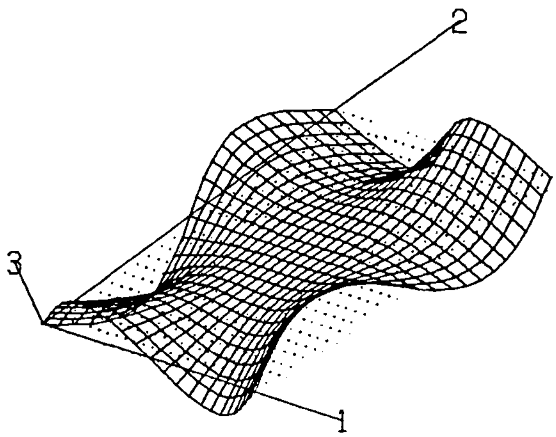
Figure 3.- Plate structural model mode-shapes.



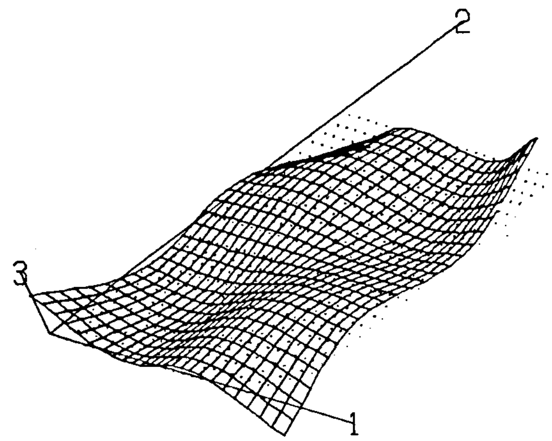
Mode 7 (0.0397 Hz)



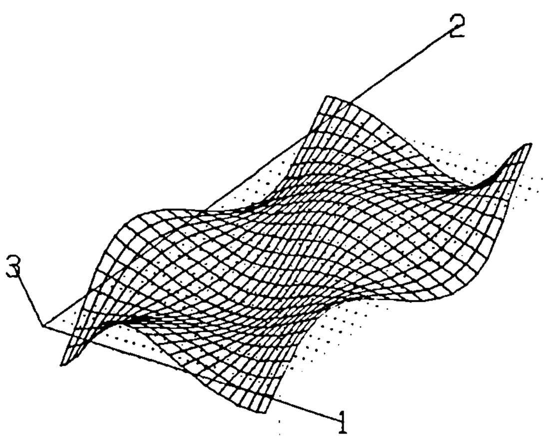
Mode 8 (0.0414 Hz)



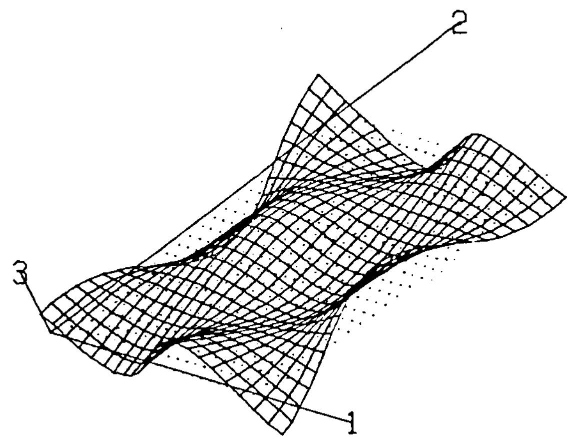
Mode 9 (0.0450 Hz)



Mode 10 (0.0502 Hz)

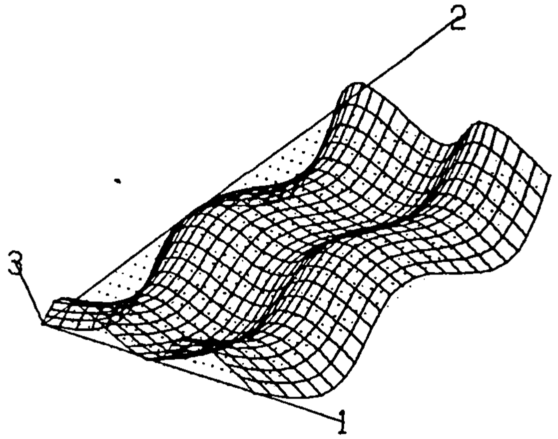


Mode 11 (0.0685 Hz)

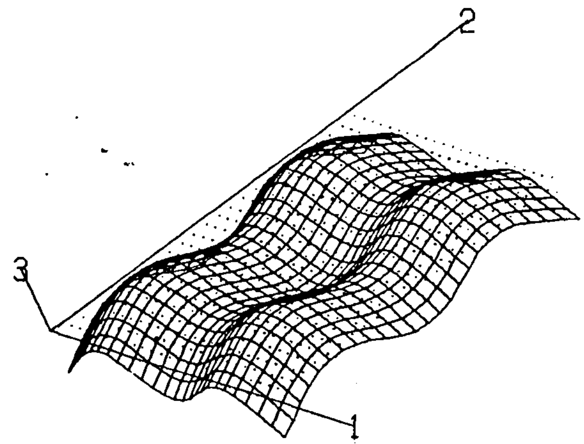


Mode 12 (0.0685 Hz)

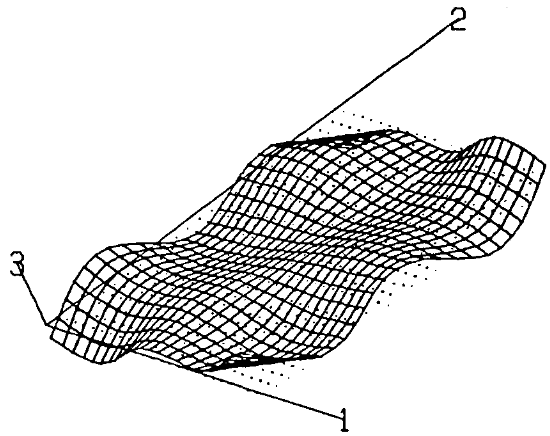
Figure 3.- Continued.



Mode 13 (0.0761 Hz)



Mode 14 (0.0796 Hz)



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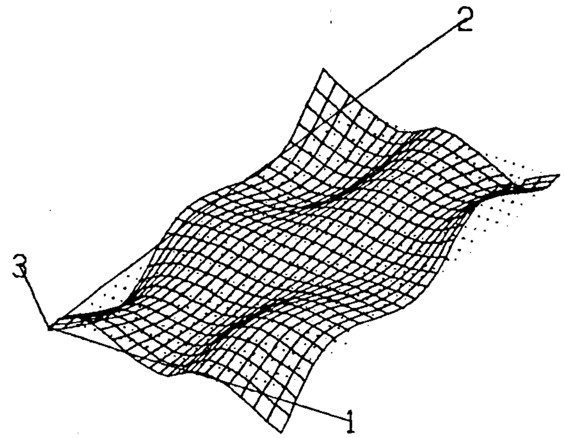
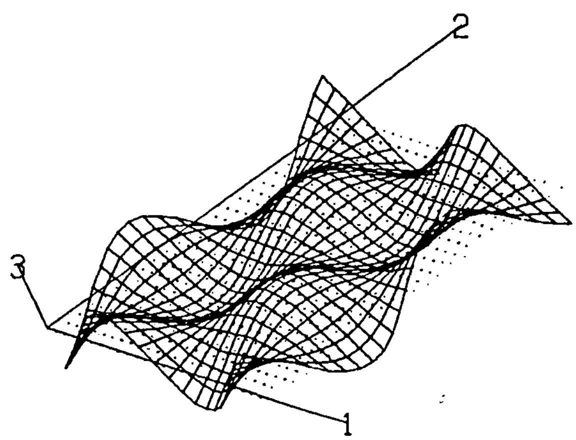
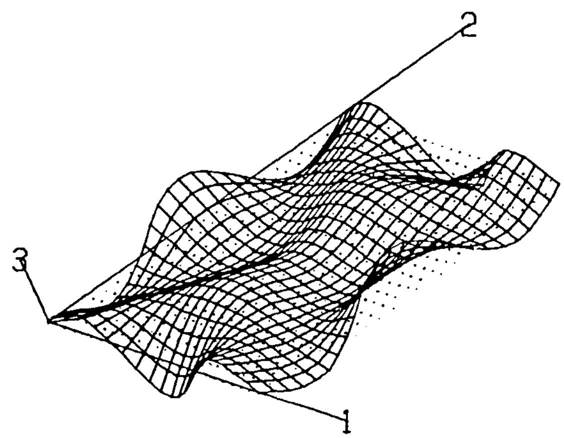


Mode 16 (0.0854 Hz)

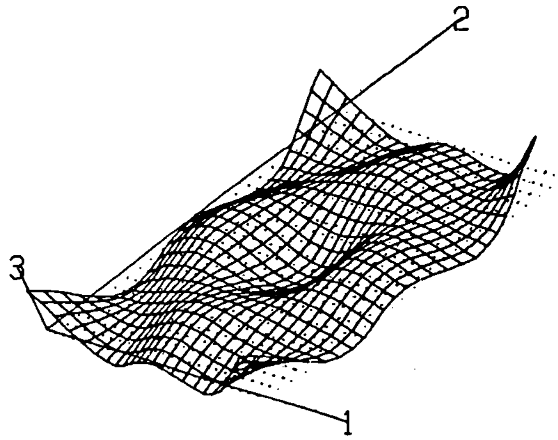


Mode 17 (0.0993 Hz)

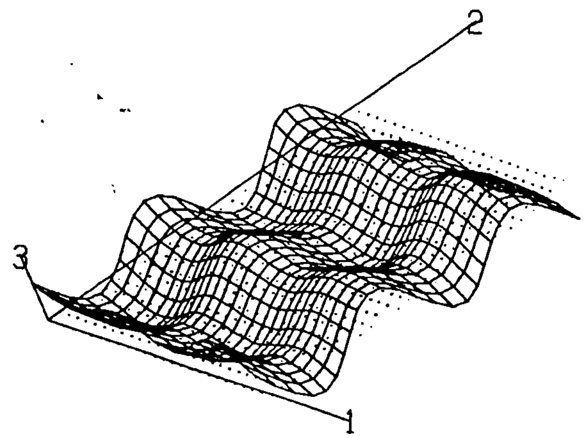


Mode 18 (0.105 Hz)

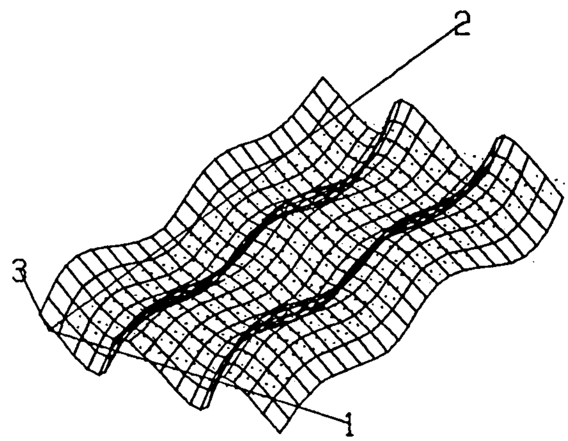
Figure 3.- Continued.



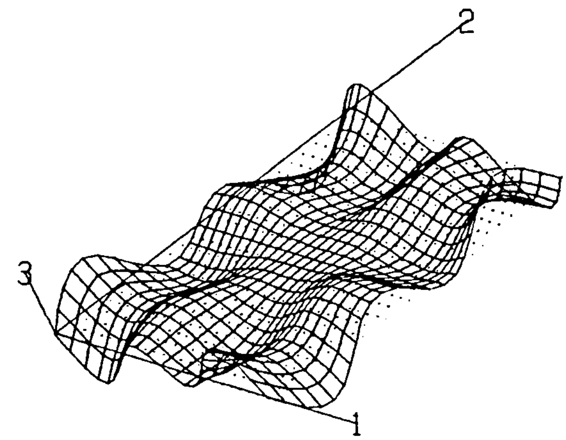
Mode 19 (0.109 Hz)



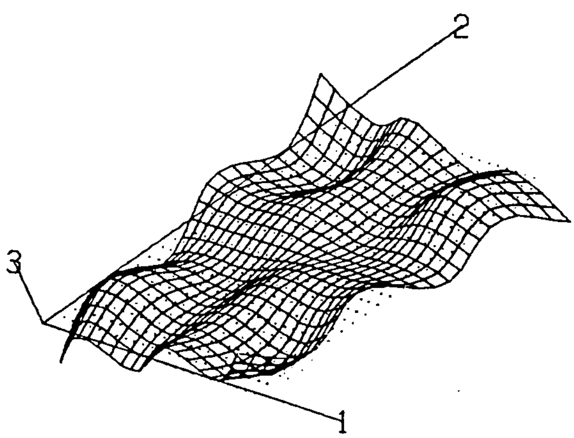
Mode 20 (0.129 Hz)



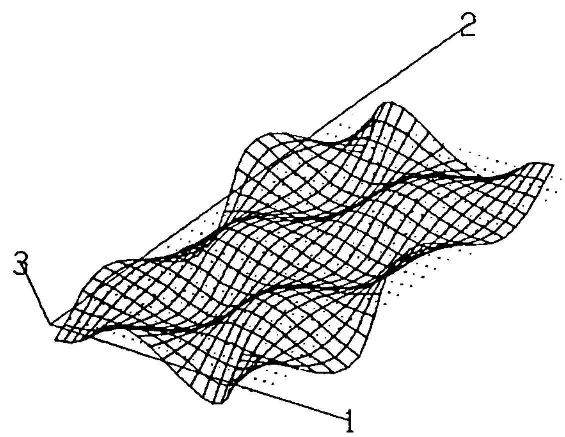
Mode 21 (0.129 Hz)



Mode 22 (0.133 Hz)

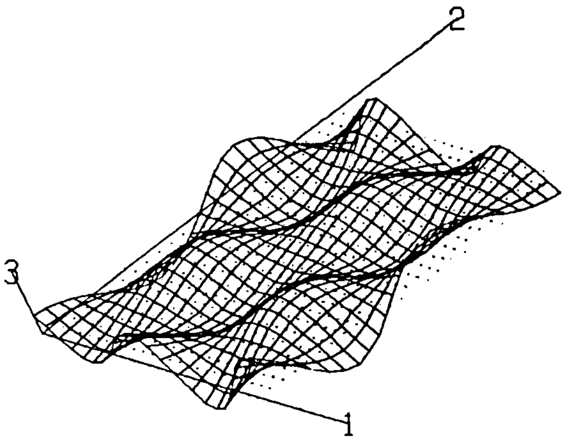


Mode 23 (0.139 Hz)



Mode 24 (0.140 Hz)

Figure 3.- Continued.



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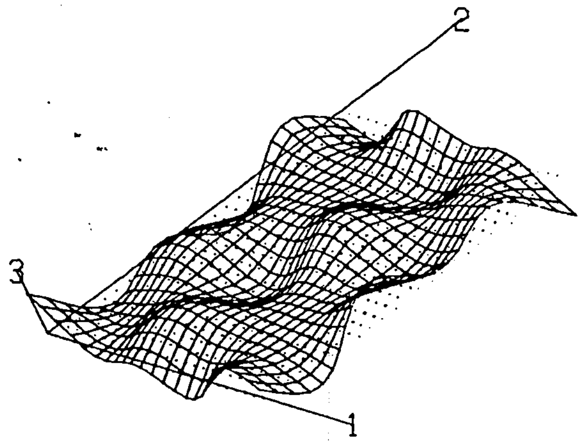
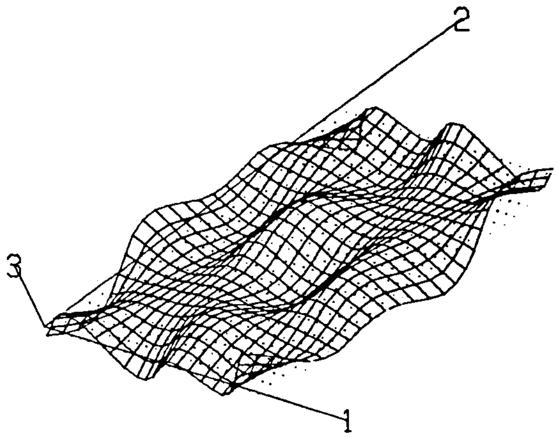
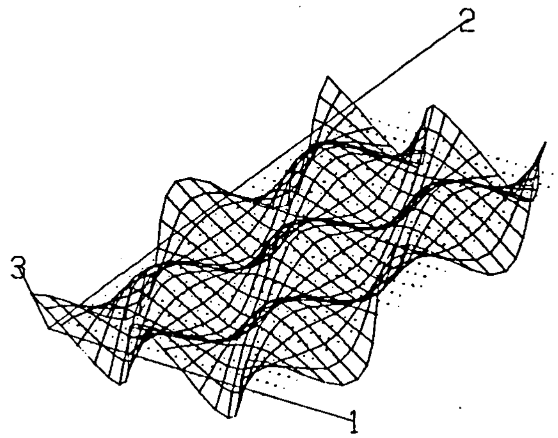


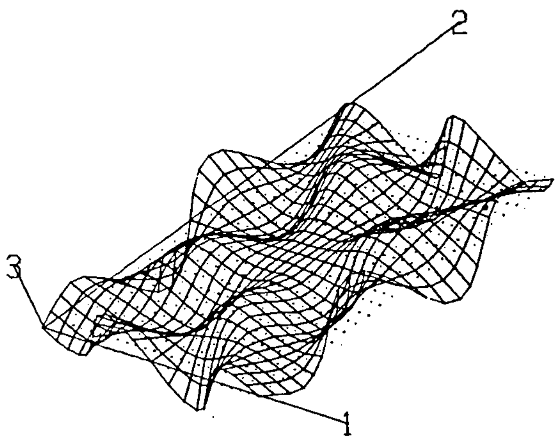
Mode 26 (0.158 Hz)



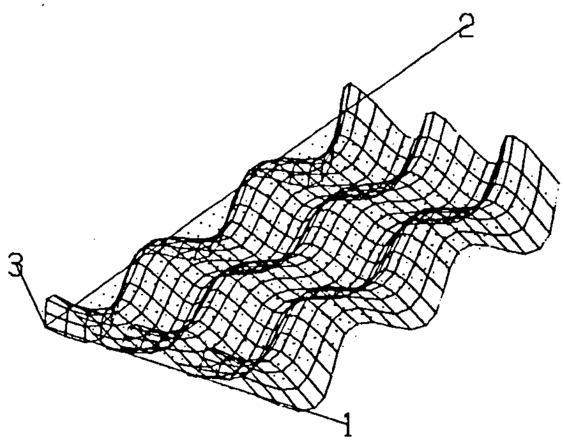
Mode 27 (0.158 Hz)



Mode 28 (0.183 Hz)

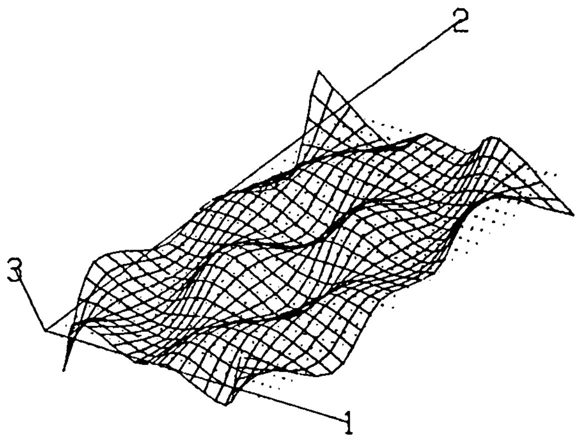


Mode 29 (0.190 Hz)

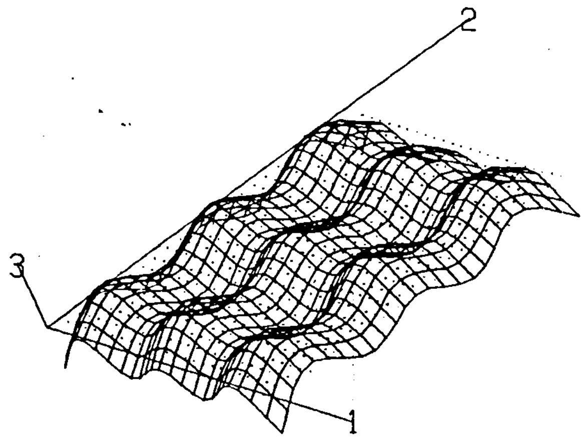


Mode 30 (0.191 Hz)

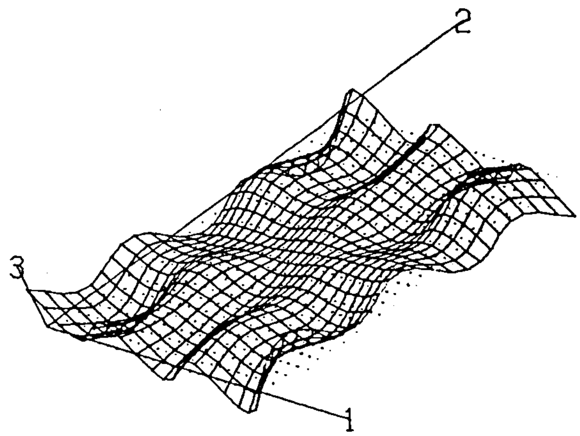
Figure 3.- Continued.



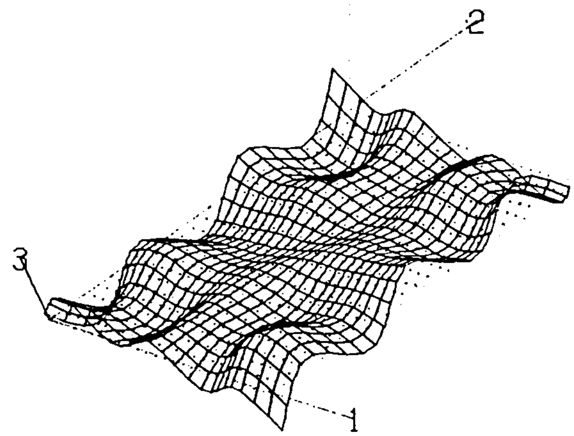
Mode 31 (0.194 Hz)



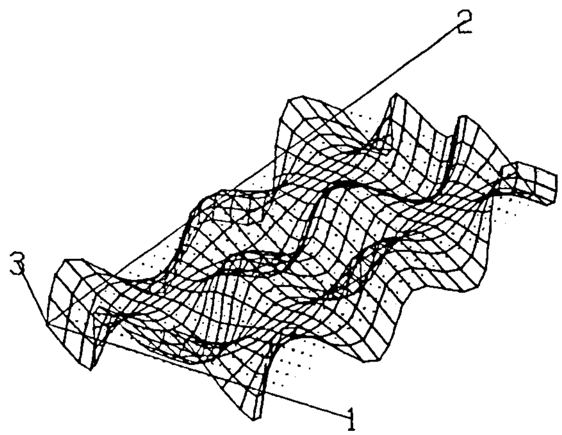
Mode 32 (0.195 Hz)



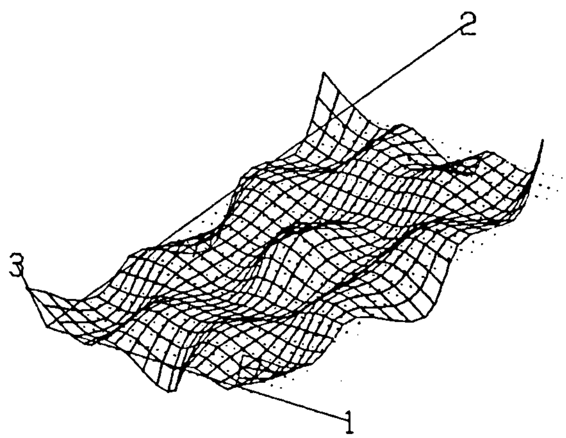
Mode 33 (0.199 Hz)



Mode 34 (0.199 Hz)

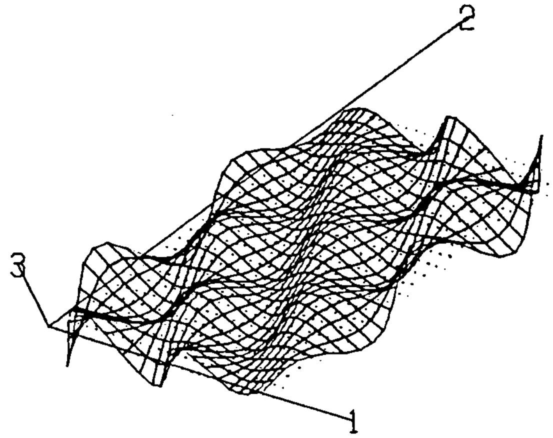


Mode 35 (0.219 Hz)

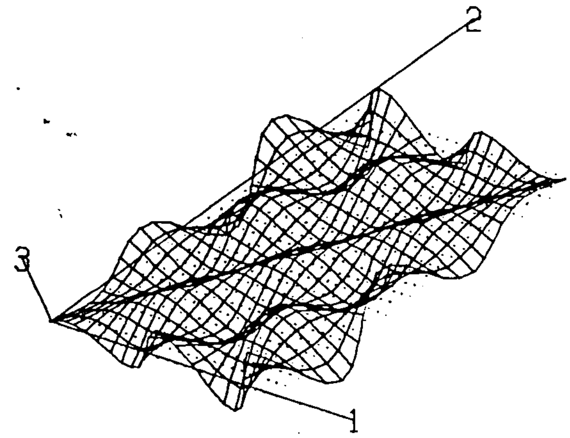


Mode 36 (0.224 Hz)

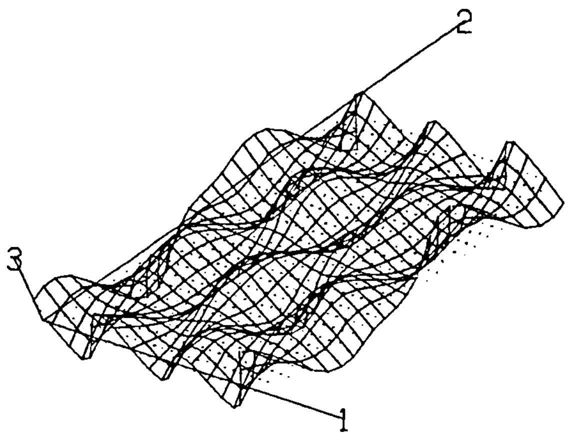
Figure 3.- Continued.



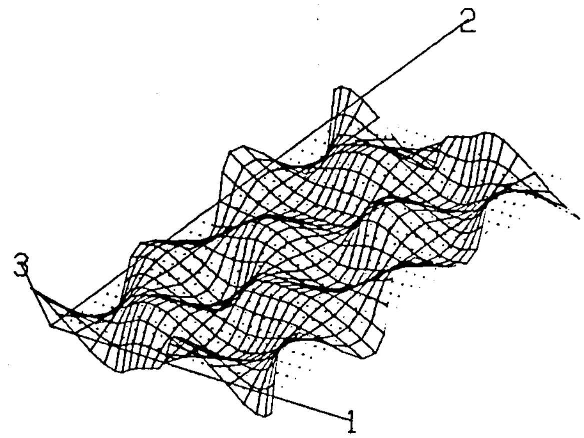
Mode 37 (0.237 Hz)



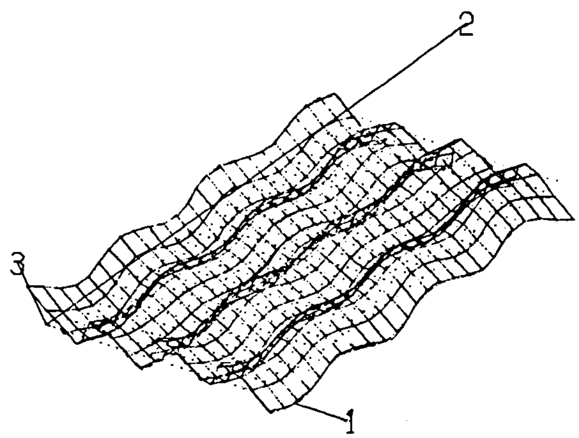
Mode 38 (0.237 Hz)



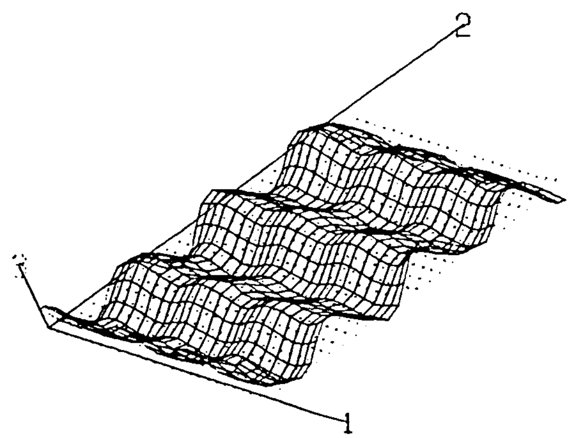
Mode 39 (0.256 Hz)



Mode 40 (0.256 Hz)

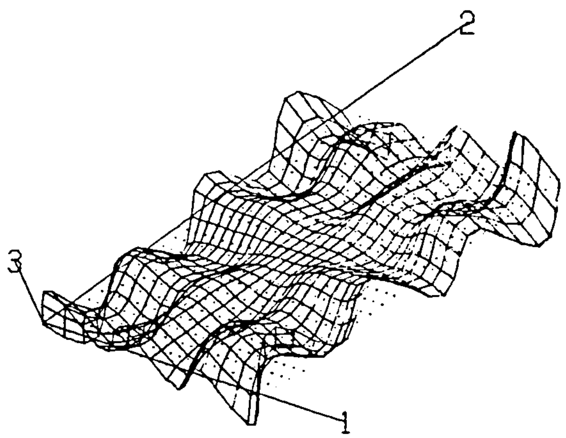


Mode 41 (0.270 Hz)

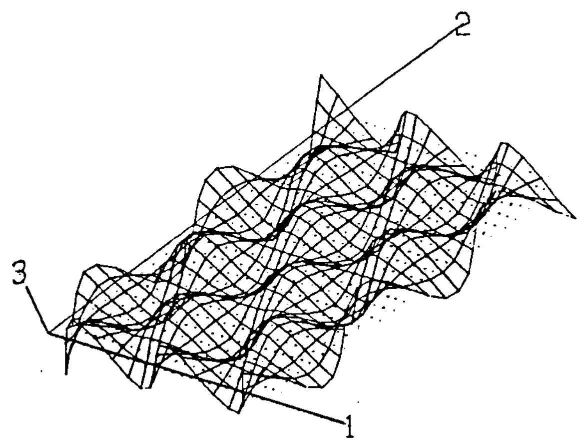


Mode 42 (0.270 Hz)

Figure 3.- Continued.



Mode 43 (0.272 Hz)



Mode 44 (0.279 Hz)

Figure 3.- Concluded.

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Suresh M. Joshi is with Vigyan Research Associates, Inc.

16. Abstract

A finite element structural model of a 30.48 m x 30.48 m x 2.54 mm (100 ft x 100 ft x 0.1 in) completely free aluminum plate is described and modal frequencies and mode-shape data for the first 44 modes are presented. An explanation of the procedure for using the data is also presented. The model should prove useful for the investigation of controller design approaches for large flexible space structures.

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