Active

Project #: E-16-676 Cost share #: Rev #: 0
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Work type : RES
Contract#: AGMT DTD 10/2/91 Mod #: Document : AGR
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: N/A
Main project #: PE #: N/A

Project unit: AERO ENGR Unit code: 02.010.110
Project director(s):
KLEIN S S AERO ENGR (404)894-3060

Sponsor/division names: COMPOSITE TECH INCORPORATED / STOCKTON, CA
Sponsor/division codes: 202 / 112

Award period: 911001 to 920930 (performance) 921031 (reports)

Sponsor amount	New this change	Total to date
Contract value	38,000.00	38,000.00
Funded	38,000.00	38,000.00
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Does subcontracting plan apply ?: N

Title: EVALUATION OF COMPOSITE ROTOR BLADE REPAIRS USING MODAL ANALYSIS TECHNIQUES

PROJECT ADMINISTRATION DATA

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Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A N/A supplemental sheet
Equipment title vests with: Sponsor GIT X
NONE PROPOSED.
Administrative comments -
INITIATION OF ONE YEAR, COST-REIMBURSEMENT PROJECT.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 09/02/92

Project No. E-16-676   Center No. 10/24-6-R7340-0A0

Project Director KLEIN S S   School/Lab AERO ENGR

Sponsor COMPOSITE TECH INCORPORATED/STOCKTON, CA

Contract/Grant No. AGMT DTD 10/2/91   Contract Entity GTRC

Prime Contract No. ______

Title EVALUATION OF COMPOSITE ROTOR BLADE REPAIRS USING MODAL ANALYSIS TECHNIQU

Effective Completion Date 920930 (Performance) 921031 (Reports)

Closeout Actions Required:	Y/N	Date Submitted
Final Invoice or Copy of Final Invoice	Y	
Final Report of Inventions and/or Subcontracts	N	
Government Property Inventory & Related Certificate	N	
Classified Material Certificate	N	
Release and Assignment	N	
Other ______	N	

Comments ______

Subproject Under Main Project No. ______

Continues Project No. ______

Distribution Required:

Project Director	Y
Administrative Network Representative	Y
GTRI Accounting/Grants and Contracts	Y
Procurement/Supply Services	Y
Research Property Managment	Y
Research Security Services	N
Reports Coordinator (OCA)	Y
GTRC	Y
Project File	Y
Other ______	N
______	N

MODAL TESTS

OF

REPAIRED AND UNREPAIRED BLACKHAWK ROTOR BLADES

Sponsored by

COMPOSITE TECHNOLOGY, INC.
111 VAL DERVIN PARKWAY
STOCKTON, CA. 95206

CONTRACT AGMT DTD 10/2/91

February 1992

SCHOOL OF AEROSPACE ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY

Atlanta, Georgia 30332-0150

INTRODUCTION

Existing Army requirements call for the whirl tower balancing of helicopter blades after repairs have been made. This is a costly and time consuming process especially since there are only three whirl towers available in the United States. Composite Technology, Inc., has developed a composite repair method which does not require expensive whirl tower testing of the repaired blades.

The purpose of Georgia Tech's involvement in this task is to use modal testing methods to determine if the repair process has significantly affectd the dynamic properties of the blades. Three repaired and three unrepaired Blackhawk blades were subjected to modal tests to determine their natural frequencies, mode shapes, and damping.

The modal tests outlined in this report were performed under contract E16-676 with Composite Technology Inc., 902 East Scotts Avenue, Stockton, California, 95203; Technical monitor Mr. Dana H. Kerrick.

All tests, data reduction, data analysis, and reporting were conducted by Steven Klein and Neil R. Weston.

SUMMARY

This report documents the modal tests of three unrepaired and three repaired Blackhawk rotor blades carried out by the School of Aerospace Engineering of the Georgia Institute of Technology.

The natural frequencies of the three unrepaired blades were averaged for each equivalent mode and that baseline was used for a comparison with the natural frequency of a repaired blade for the same mode. No significant differences were found that set the mode shapes and natural frequencies of the repaired blades apart from their unrepaired counterparts.

Enclosed are descriptions and results for modal tests of the six test articles consisting of tabulations of estimated natural frequencies and damping values as well as plots of the corresponding mode shapes.

TABLE OF CONTENTS

I. DISCUSSION OF RESULTS

NATURAL FREQUENCIES AND MODE SHAPES

The goal of any modal identification test is to determine the natural frequencies as well as the associated mode shapes and damping values of the test article. Figure 1 provides a quick overview of all the mode shapes and their corrresponding natural frequencies for each blade within the bandwidth of interest.

The shown mode shapes represent the deflection pattern of the blades when excited at the stated natural frequency. The displayed shape is a view of the leading edge frozen in one extreme deflection since the blade is actually vibrating about the neutral position. While most modes show a singly predominant mode, there were some cases of coupled modal behavior at some of the higher frequencies. In those cases the mode shape was frozen at a deflection pattern which is most characteristic of the associated mode shape.

It can easily be seen from the side-by-side display of the 18 mode shapes of each blade that there is no significant difference between all the tested blades when the shapes of equivalent modes (in the same row) are compared. In addition, no qualitative difference in mode shapes between the unrepaired blades (in the first three columns of Figure 1) and the repaired blades (in the last three columns) can be detected.

The same mode shapes contained in Figure 1 are also enclosed as full size plots in Appendices B through G. It is important to point out that each of the mode shapes provided is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between modes.

A quantitative comparison can easily be made by comparing the numerical values of the detected modes. Table 1 provides a side-by-side listing of these values along with a description of the mode shape when appropriate. The various bending natural frequencies are very easily identifable along with the first torsional natural frequency. A mean baseline natural frequency was established for each of the 18 modes by averaging the results from the tests of the unrepaired blades, and the standard deviation for each of the natural frequencies for the unrepaired blades was computed. Appendix A provides the details and equations used in computing the statistical quantities. The mean values and standard deviatons are listed in the first two columns of Tables 2 and 3. Table 2 also contains corresponding natural frequencies for each repaired blade along with the deviation of that frequency from the baseline mean value, and a description in per cent of that same value. By scanning those percentages for blade SN. A007-03068 it can be seen that most natural frequencies of that blade deviate from the mean in the neighborhood of 2.9% while only one mode has a value above 4% (4.752%). Blade SN. A007-02773 has also one mode deviating from the mean by over 4% (4.516%) while the average of all modes amounts to approximately 1.9%. A similar pattern is visible for blade SN. A007-00680 with two modes deviating by more than 4% (4.840%, 4.633%) while the average of all modes deviates by about 1.0%. Figures 4,5, and 6 present plots of the measured natural frequencies for each the repaired blades plotted against the mean natural frequencies for the unrepaired blades. These plots show visually the small amount of random deviation of the measured natural frequencies of the repaired blades about the mean values for the unrepaired blades.

When looking at the deviations of the unrepaired blades from the mean of those three blades as shown in Table 3, it can be seen that blade SN. A007-01637 deviates by a maximum of 3.096% for one mode while the average for all modes lies in the neighborhood 0.846%. Blade SN. A007-00855 has one mode deviating from the mean by 4.503% while the average deviation is in the proximity of 0.986%. Blade SN. A007-00885 again shows a deviation above 4% (4.228%) while the average for all modes lies at 0.70%.

DAMPING

Table 4 lists the natural frequencies and their corresponding damping values for the six tested blades at each mode. The value for damping is the most difficult of the modal parameters to estimate. Due to its sensitivity to factors in the test configuration, test procedure, and parameter estimation, confidence in the value of damping parameters is not as great as for the natural frequencies and mode shapes. In this experimental study the damping values were used to determine the validity of identified modes. All modes with physically unrealistic damping values were eliminated from consideration.

II. CONCLUSIONS

The following conclusions can be drawn from the results presented above:

- The average per cent deviation of natural frequencies for one of the repaired blades (1.018%, blade SN. A007-00680) is virtually identical to one of the unrepaired blades (0.986%, blade SN. A007-00855).

- Natural frequencies of both repaired and unrepaired blades show maximum deviations from the mean for individual modes between 4% and 5%, but not higher.

- No qualitative differences can be detected between the mode shapes of repaired and unrepaired blades.

- No significant differences can be detected between the natural frequencies of repaired and unrepaired blades.

- No trend, such as a consistent raising or lowering of the natural frequencies due to the repair process, was detected.

- The repair process did not appear to significantly affect the modal properties of the blades.

III. TEST CONFIGURATION

DESCRIPTION OF THE TEST SPECIMEN

\A total of six Blackhawk rotor blades manufactured by Sikorsky Aircraft were evaluated in this test. Three of the blades were unrepaired and represent the general blade population with several hundred hours of flighttime each. They received a paint touch up and were balanced statically and dynamically prior to testing. Three blades with different after body repairs carried out by Composite Technology, Inc., were also tested. All of them were also balanced prior to testing. The following repairs were carried out on the tested blades:

BLADE SN. A007-03068: 1328 hours since new

> Two patches installed, both 4227 mm from the center of rotation and 205 mm aft of the pitch axis on the top and bottom side of the blade, 5 and 8 inches in diameter, respectively.

BLADE SN. A007-02773: 801 hours since new

> One single patch installed, 6619 mm from the center of rotation and 190 mm aft of the pitch axis on the bottom side of the blade, 8 inches in diameter.

BLADE SN. A007-00680: 715 hours since new

> One single patch installed, 5182 mm from the center of rotation and 175 mm aft of the pitch axis on the bottom side of the blade, 6 inches in diameter.

Hours since new for the unrepaired blades are as follows:

BLADE SN. A007-01637:	1128 hours since new
BLADE SN. A007-00855:	695 hours since new
BLADE SN. A007-00885:	913 hours since new

TEST SETUP

The tests was carried out with the blades suspended from the laboratory ceiling by low stiffness elastic (bungee) cords as illustrated in Figure 2. This arrangement simulates a "free-free" test article and has several advantages over other mounting arrangements: It is relatively inexpensive and simple when compared to a test structure which simulates the cantilevered blade mounting of the helicopter hub. This simple "free-free" configuation allows us to determine differences in the dynamic properties of the indvidual blades without the influence of complex boundary conditions. Since the objective of this test was to determine any relative difference in the dynamic characteristics between repaired and unrepaired blades, the boundary conditions are irrelevant as long as all blades are tested in an identical configuration.

A single electrodynamic shaker placed on the laboratory floor was used to introduce a broadband excitation force through a stinger into the suspended blade structure. Vibration levels during the excitational test were measured with accelerometers in 22 locations on the lower surface of the blade as shown in Figure 3. All accelerometers were placed at equally spaced radial stations and approximately one inch from the leading and trailing edges of the blade. Table 4 provides the coordinates used for the geometry model of the modeshape display. The exciter was attached to the blade on the leading edge of the upper surface as shown in Figure 2 to excite all relevant vibrational modes. One test was also carried out by attaching the shaker to the trailing edge of the upper surface, however, no additional modes beyond those already identified were excited. A random signal with a 128 Hz bandwidth generated by the GenRad was used to drive the shaker.

This set-up provided torsional as well as beamwise (flapwise) bending frequencies of the blades. Edgewise (in-plane) bending natural frequencies were not excited and are not of interest for this comparison.

The response signals from the accelerometers and the force transducer in the shaker attachment were channeled to a GenRad 2515 structural analyzer for acquisition and processing. The GenRad 'RTA' program was utilized to acquire the data in the form of frequency response functions. The Hanning spectral window was applied to reduce spectral leakage and ensemble averaging of acquired data was used to improve the signal to noise ratio. Coherence functions for each frequency response function were examined to insure the quality of the test data.

The "Modal Plus" (version 9.0) software which uses the polyreference identification algorithm was used to identify natural frequencies, damping ratios, and complex mode shapes of the blades.

All accelerometers and load cells were factory calibrated before the test. Copies of the calibration certificates are enclosed in Appendix H. Special accelerometer mounting pads were fabricated to fit the contour of the blade and assure that the axes of all pickups are parallel within five degrees. These mounting pads were bonded with an epoxy adhesive to a layer of double-sided tape which was applied directly onto the blade's surface. This mounting method protects the surface finish of the blade. All mounting pads and suspension hardware were fabricated in the machine shop of the School of Aerospace Engineering. The test equipment used is also listed in Appendix H.

Since the suspended blade represents a double-supported pendulum, its natural frequencies were determined to make sure that they are not interfering with the flexible modes of the blades which are the object of this test. Tests placed the lateral pendulum natural frequency of the complete assembly at 0.2 Hz while the rotational pendulum motion had a natural frequency of 0.15 Hz. Both of those values are considerably below the first bending mode detected at 4.3-4.5 Hz.

An additional test was made to determine the influence of the bungee cord assembly by replacing it with a stainless steel cable. This test was carried out for blade A007-00680 and yielded the same results as the test carried out with the bungee cord suspension.

TEST PROCEDURE

Initial tests to determine the required excitation bandwidth were carried out with a broadband excitation frequency of 1024 Hz. Analysis of the detected natural frequencies revealed that associated modeshapes above 128 Hz involve primarily localized deflections of the trailing edge. The test and analysis was again carried out with a bandwidth of only 512 Hz enabling a better resolution for the natural frequencies in this range. This narrower bandwidth did not provide any additional information. In consultation with Mr. Dana Kerrick of Composite Technology, Inc., and Dr. Dana Taylor of the U.S. Army Aviation Systems Command, it was decidde to limit our measurement bandwidth to 128 Hz for all tests since the first torsional natural frequency of the blades, which is of major interest in this study, was detected in the 36 to 39 Hz range.

The results of all the tests summarized in this report were, therefore, carried out with a 128 Hz broadband excitation frequency.

FIGURES and TABLES

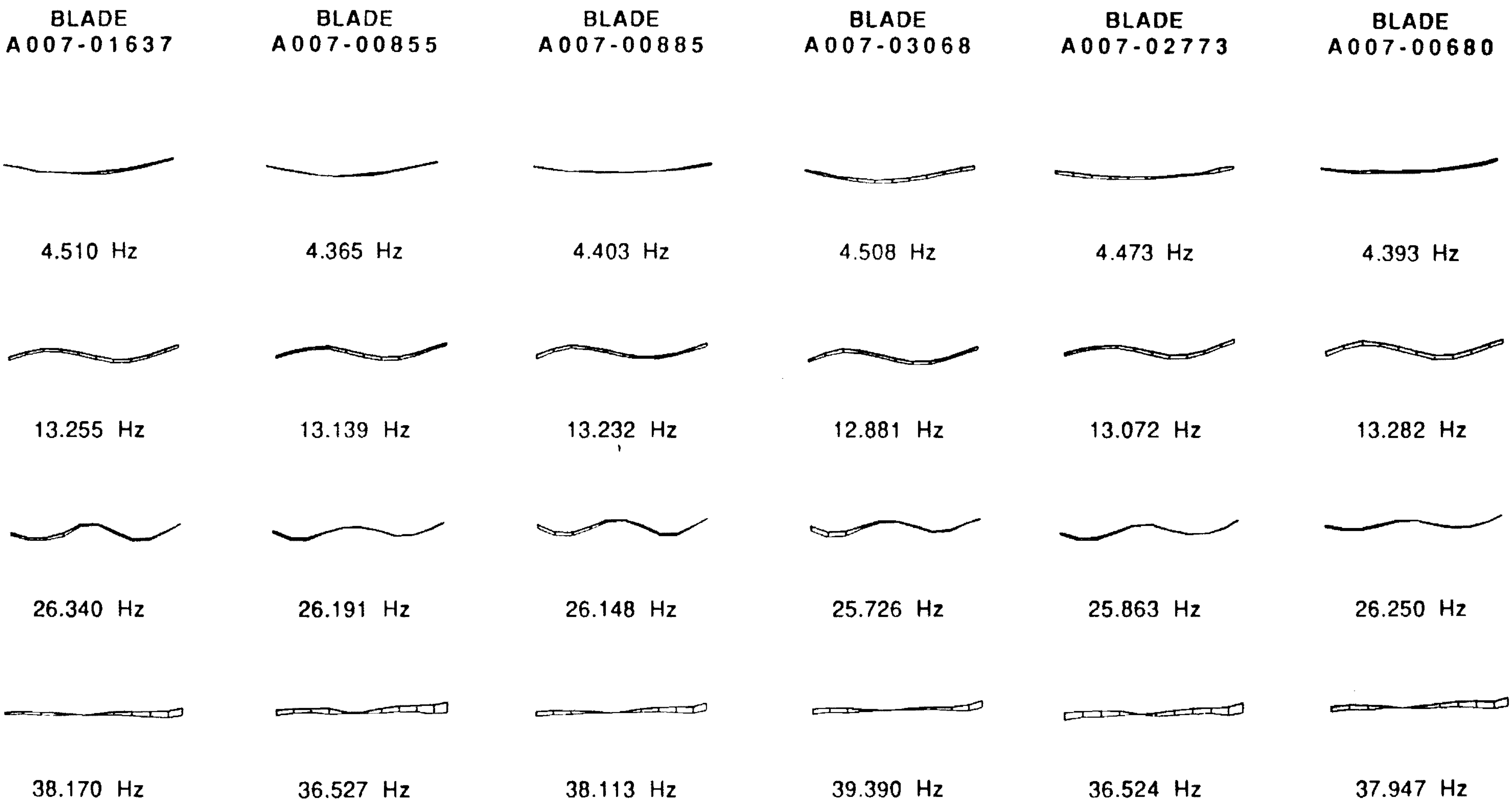


Figure 1: Overview of mode shapes and natural frequencies of the tested blades

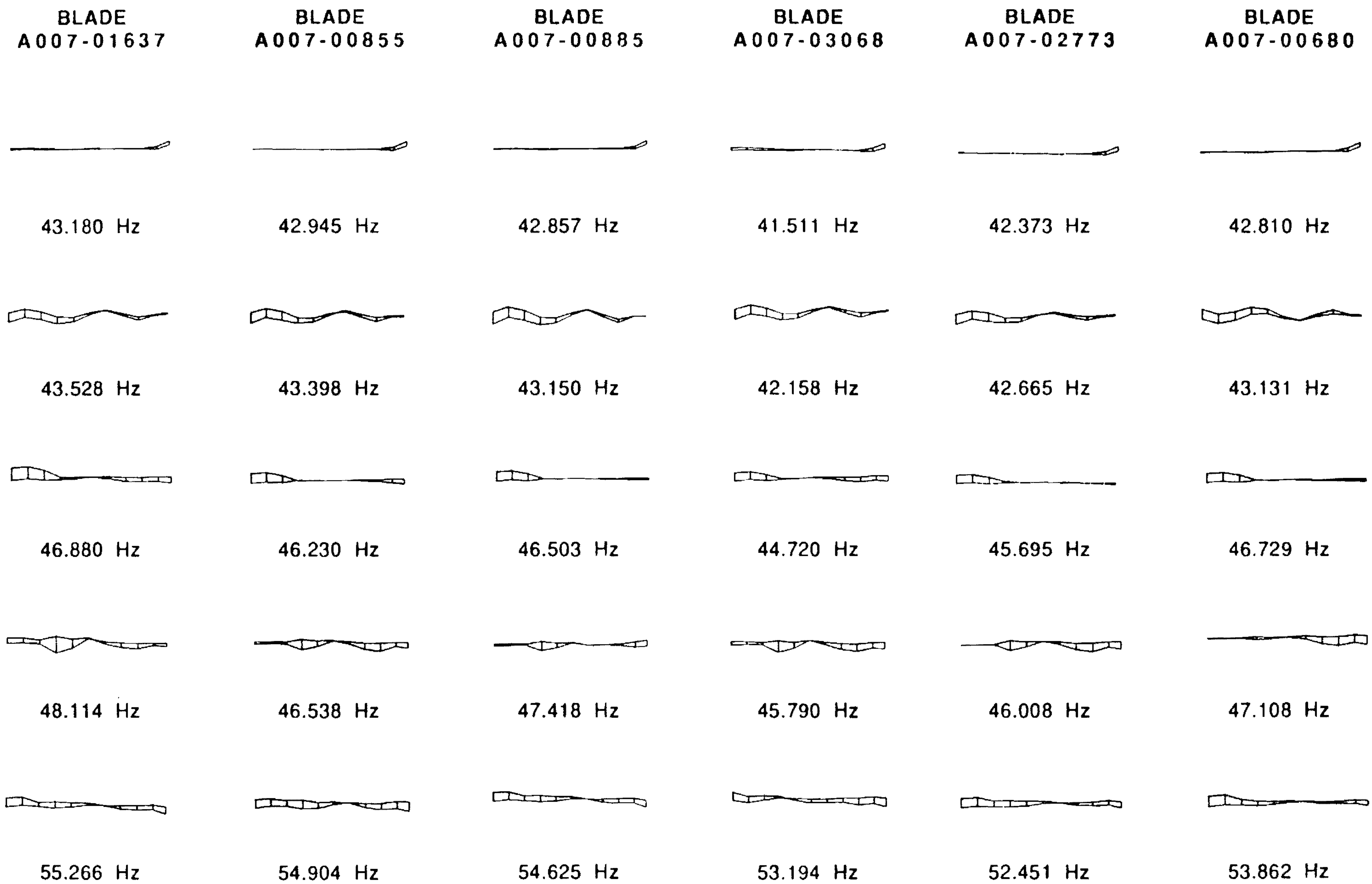


Figure 1 (continued): Overview of mode shapes and natural frequencies of the tested blades

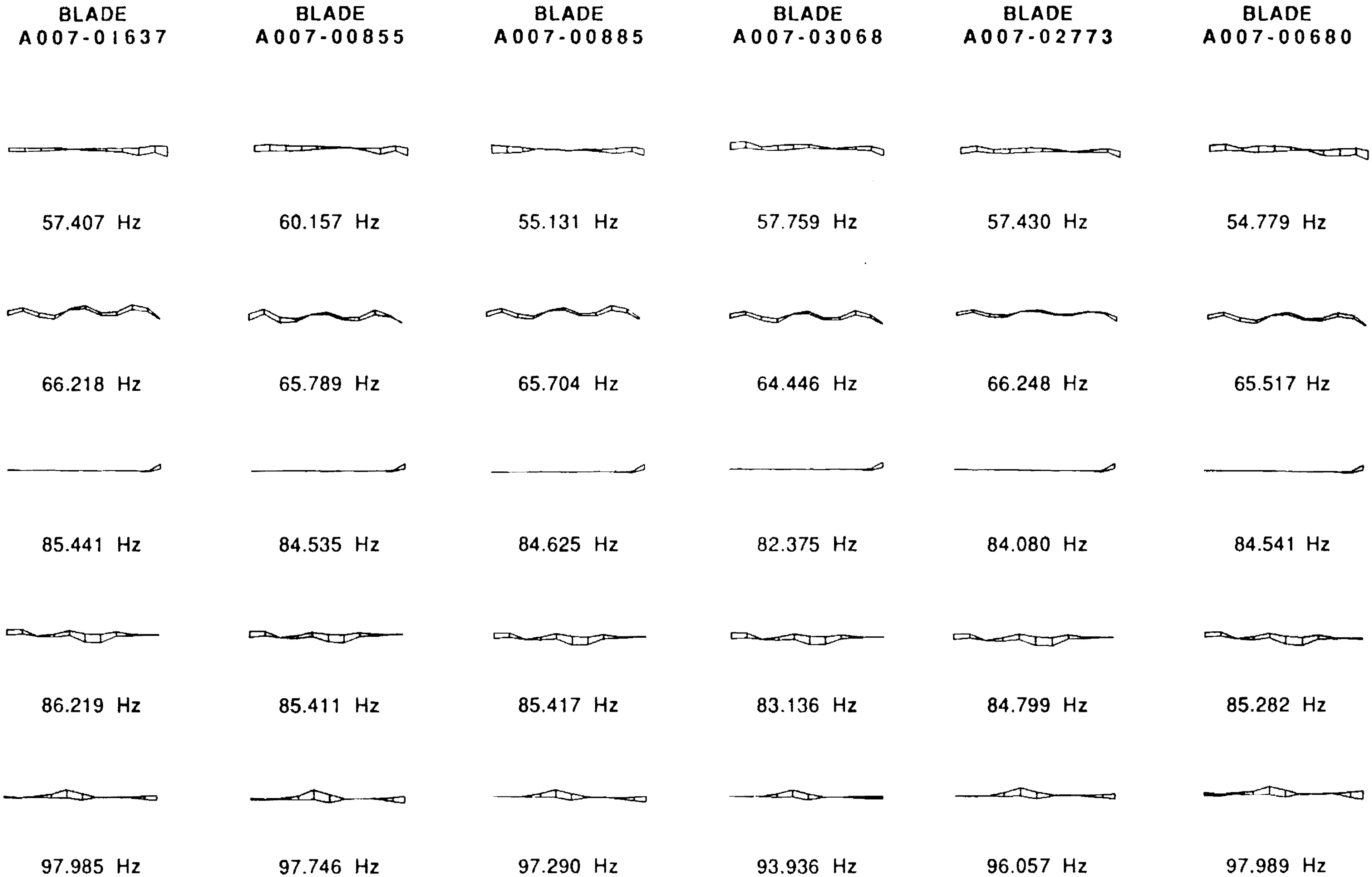


Figure 1 (continued): Overview of mode shapes and natural frequencies of the tested blades

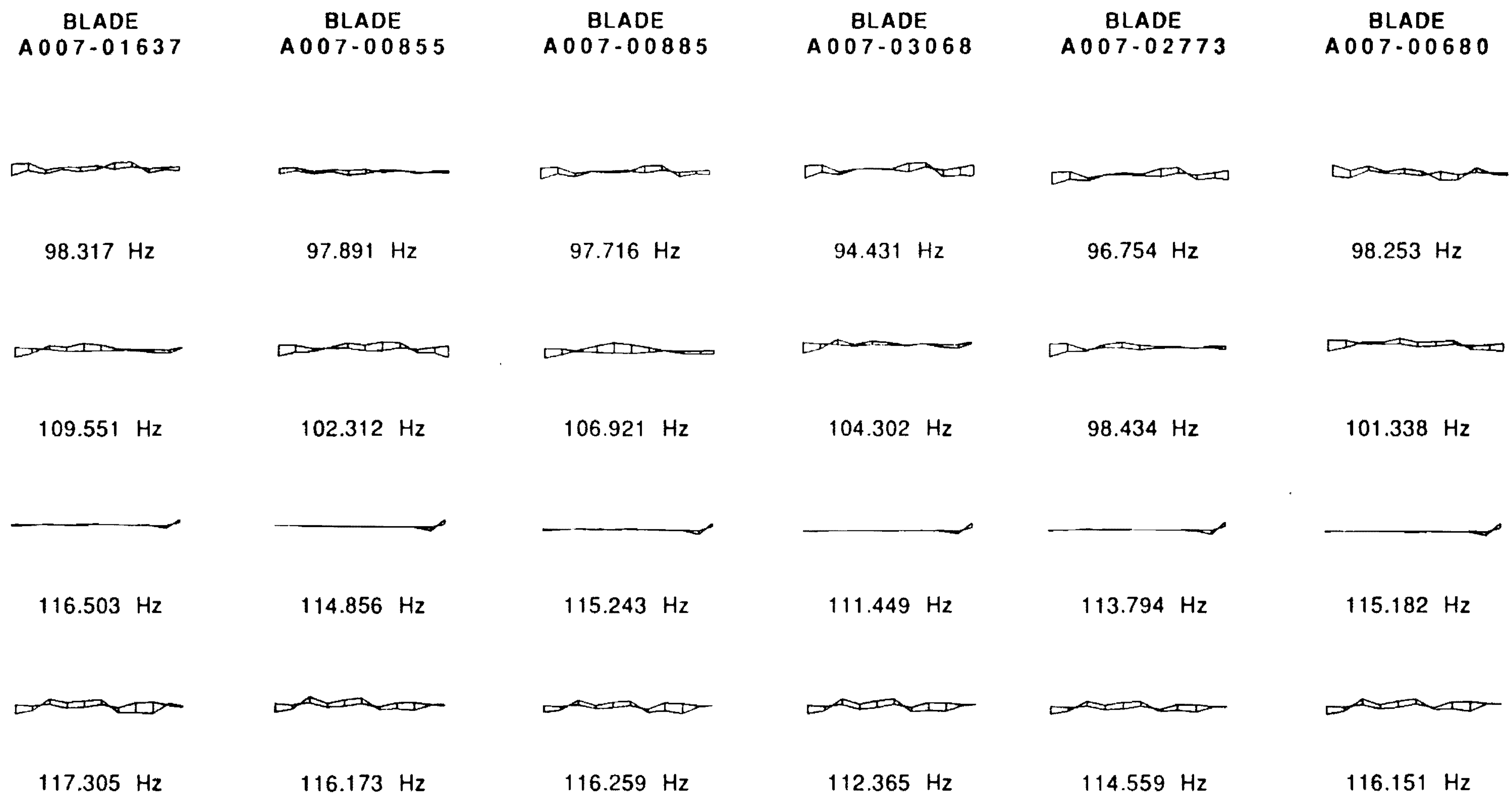


Figure 1 (continued): Overview of mode shapes and natural frequencies of the tested blades

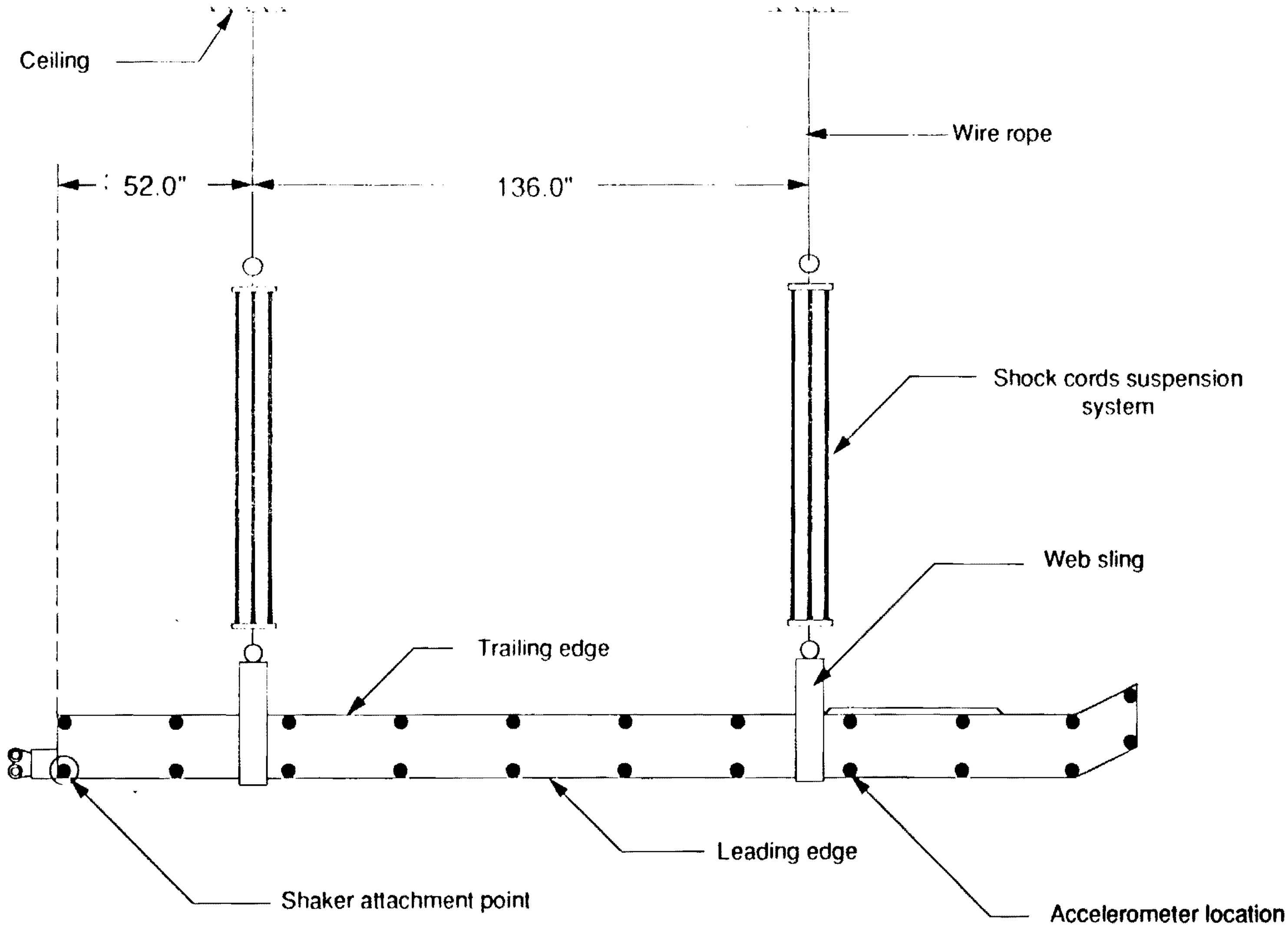


Figure 2: Blade suspension, accelerometer locations, and shaker attachment point (not drawn to scale)

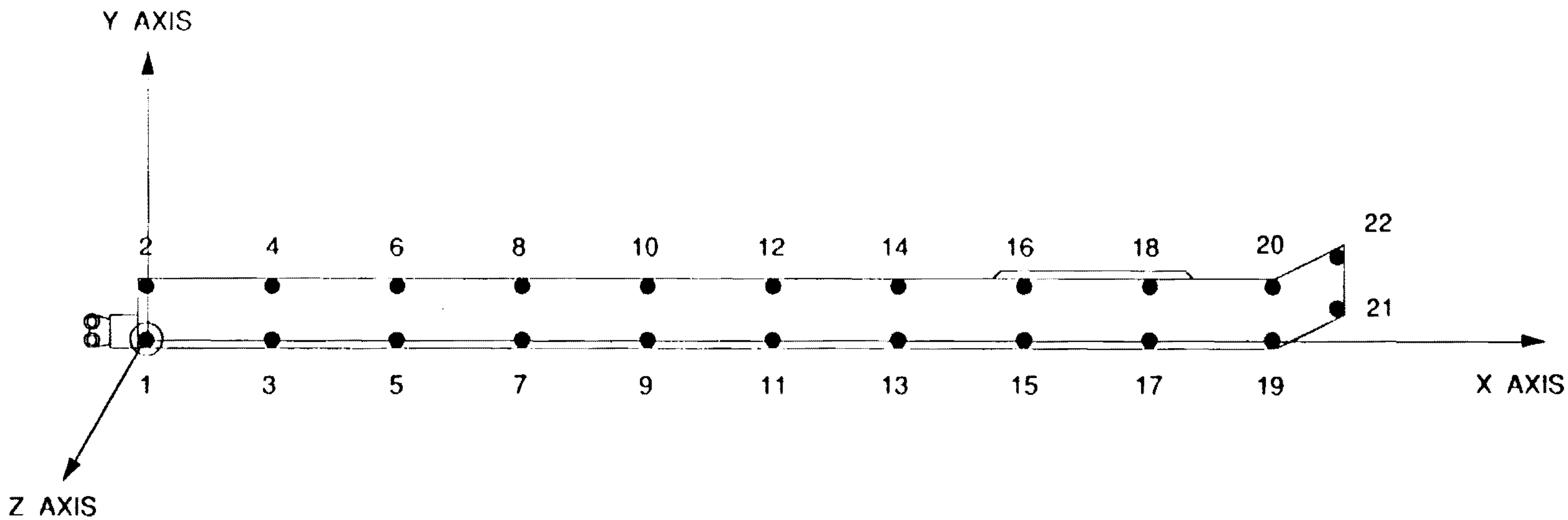


Figure 3: Blade coordinate system and accelerometer numbering (not drawn to scale)

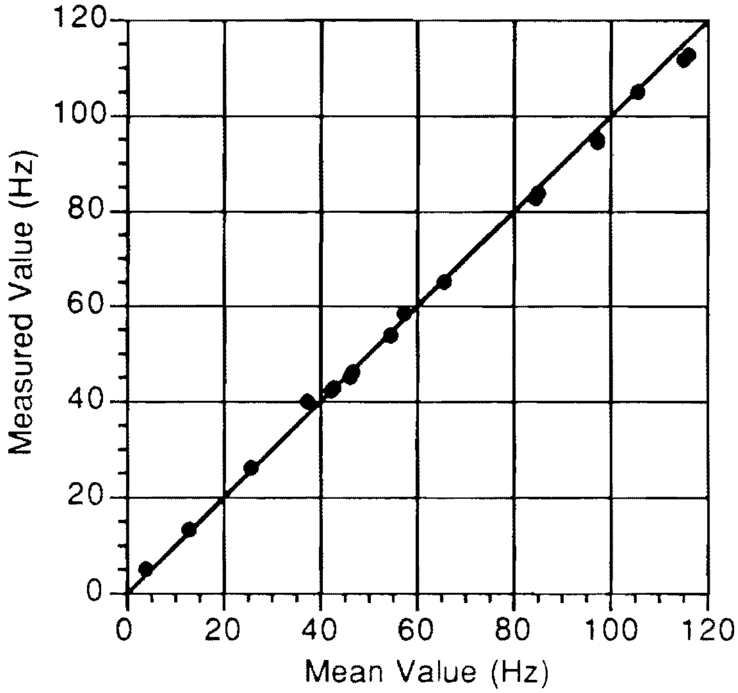


Figure 4: Natural frequencies of blade A007-03068 vs mean values

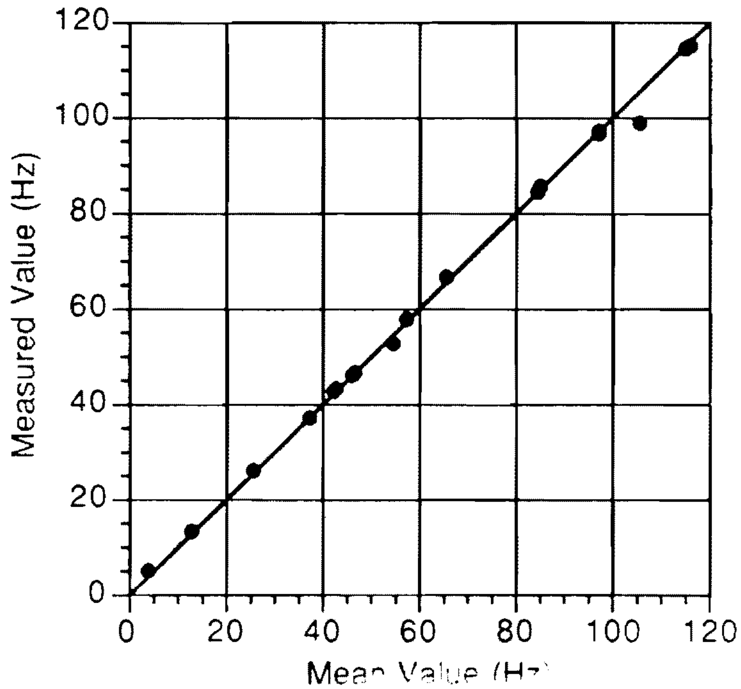


Figure 5: Natural frequencies of blade A007-02773 vs mean values

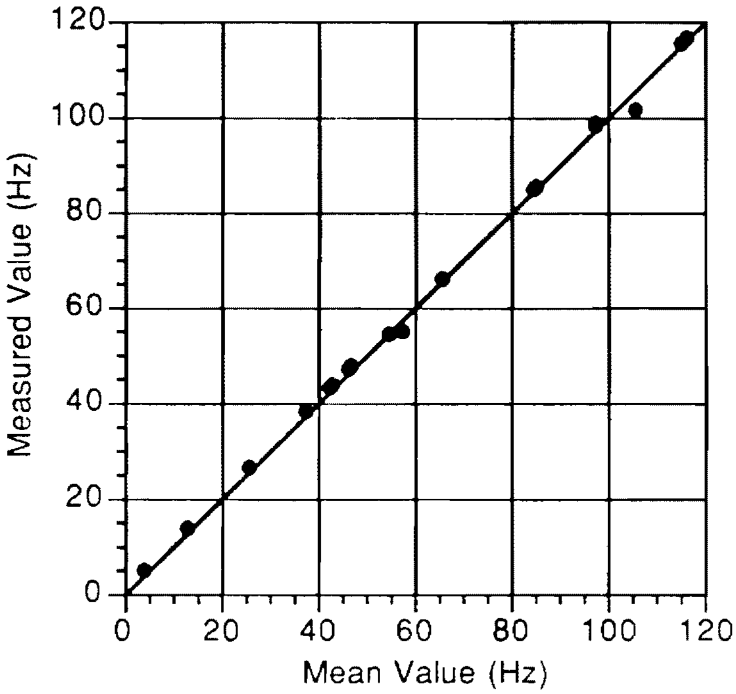


Figure 6: Natural frequencies of blade A007-00680 vs mean values

BLADE SN. A007-01637	BLADE SN. A007-00855	BLADE SN. A007-00885	BLADE SN. A007-03068 (repaired)	BLADE SN. A007-02773 (repaired)	BLADE SN. A007-00680 (repaired)	DESCRIPTION
4.510	4.365	4.403	4.508	4.473	4.393	1st bending mode characteristics
13.255	13.139	13.232	12.881	13.072	13.282	2nd bending mode characteristics
26.340	26.191	26.148	25.726	25.863	26.250	3rd bending mode characteristics
38.170	36.527	38.113	39.390	36.524	37.947	1st torsional mode characteristics
43.180	42.945	42.857	41.511	42.373	42.810	Tip motion only
43.528	43.398	43.150	42.158	42.665	43.131	4th bending mode characteristics
46.880	46.230	46.503	44.720	45.695	46.729	
48.114	46.538	47.418	45.790	46.008	47.108	
55.266	54.904	54.625	53.194	52.451	53.862	
57.407	60.157	55.131	57.759	57.430	54.779	
66.218	65.789	65.704	64.446	66.248	65.517	5th bending mode characteristics
85.441	84.535	84.625	82.375	84.080	84.541	Tip motion only
86.219	85.411	85.417	83.136	84.799	85.282	
97.985	97.746	97.290	93.936	96.057	97.989	
98.317	97.891	97.716	94.431	96.754	98.253	
109.551	102.312	106.921	104.302	98.434	101.338	
116.503	114.856	115.243	111.449	113.794	115.182	
117.305	116.173	116.259	112.365	114.559	116.151	

Table 1: Listing of the natural frequencies of the tested blades (Hz)

UNREPAIRED BLADES		BLADE SN. A007-03068			BLADE SN. A007-02773			BLADE SN. A007-00680		
MEAN NATURAL FREQUENCY	STANDARD DEVIATION (Hz)	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %
4.426	.075	4.508	.082	1.853	4.473	.047	1.062	4.393	-.033	-.746
13.209	.061	12.881	-.328	-2.483	13.072	-.137	-1.037	13.282	.073	.553
26.226	.101	25.726	-.500	-1.907	25.863	-.363	-1.384	26.250	.024	.092
37.603	.933	39.390	1.787	4.752	36.524	-1.079	-2.869	37.947	.344	.915
42.994	.167	41.511	-1.483	-3.449	42.373	-.621	-1.444	42.810	-.184	-.428
43.359	.192	42.158	-1.201	-2.770	42.665	-.694	-1.601	43.131	-.228	-.526
46.538	.326	44.720	-1.818	-3.906	45.695	-.843	-1.811	46.729	.191	.410
47.357	.790	45.790	-1.567	-3.309	46.008	-1.349	-2.849	47.108	-.249	-.526
54.932	.321	53.194	-1.738	-3.164	52.451	-2.481	-4.516	53.862	-1.070	-1.948
57.565	2.517	57.759	.194	.337	57.430	-.135	-.235	54.779	-2.786	-4.840
65.904	.276	64.446	-1.458	-2.212	66.248	.344	.522	65.517	-.387	-.587
84.867	.499	82.375	-2.492	-2.936	84.080	-.787	-.927	84.541	-.326	-.384
85.682	.465	83.136	-2.546	-2.971	84.799	-.883	-1.031	85.282	-.400	-.467
97.674	.353	93.936	-3.738	-3.827	96.057	-1.617	-1.656	97.989	.315	.323
97.975	.309	94.431	-3.544	-3.617	96.754	-1.221	-1.246	98.253	.278	.284
106.261	3.664	104.302	-1.959	-1.844	98.434	-7.827	-7.366	101.338	-4.923	-4.633
115.534	.861	111.449	-4.085	-3.536	113.794	-1.740	-1.506	115.182	-.352	-.305
116.579	.630	112.365	-4.214	-3.615	114.559	-2.020	-1.733	116.151	-.428	-.367
			1.930	2.916		1.344	1.933		.700	1.018
			(AVERAGE)	(AVERAGE)		(AVERAGE)	(AVERAGE)		(AVERAGE)	(AVERAGE)

Table 2: Deviations of natural frequencies of the repaired blades compared to the mean of the three unrepaired blades

UNREPAIRED BLADES		BLADE SN. A007-01637			BLADE SN. A007-00855			BLADE SN. A007-00885		
MEAN NATURAL FREQUENCY	STANDARD DEVIATION (Hz)	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %	NATURAL FREQUENCY (HZ)	DEVIATION FROM MEAN (HZ)	DEVIATION FROM MEAN %
4.426	.075	4.510	.084	1.898	4.365	-.061	-1.378	4.403	-.023	-.520
13.209	.061	13.255	.046	.348	13.139	-.070	-.530	13.232	.023	.174
26.226	.101	26.340	.114	.435	26.191	-.035	-.133	26.148	-.078	-.297
37.603	.933	38.170	.567	1.508	36.527	-1.076	-2.861	38.113	.510	1.356
42.994	.167	43.180	.186	.433	42.945	-.049	-.114	42.857	-.137	-.319
43.359	.192	43.528	.169	.390	43.398	.039	.090	43.150	-.209	-.482
46.538	.326	46.880	.342	.735	46.230	-.308	-.662	46.503	-.035	-.075
47.357	.790	48.114	.757	1.598	46.538	-.819	-1.729	47.418	.061	.129
54.932	.321	55.266	.334	.608	54.904	-.028	-.051	54.625	-.307	-.559
57.565	2.517	57.407	-.158	-.274	60.157	2.592	4.503	55.131	-2.434	-4.228
65.904	.276	66.218	.314	.476	65.789	-.115	-.174	65.704	-.200	-.303
84.867	.499	85.441	.574	.676	84.535	-.332	-.391	84.625	-.242	-.285
85.682	.465	86.219	.537	.627	85.411	-.271	-.316	85.417	-.265	-.309
97.674	.353	97.985	.311	.318	97.746	.072	.074	97.290	-.384	-.393
97.975	.309	98.317	.342	.349	97.891	-.084	-.086	97.716	-.259	-.264
106.261	3.664	109.551	3.290	3.096	102.312	-3.949	-3.716	106.921	.660	.621
115.534	.861	116.503	.969	.839	114.856	-.678	-.587	115.243	-.291	-.252
116.579	.630	117.305	.726	.623	116.173	-.406	-.348	116.259	-.320	-.274
			.546 (AVERAGE)	.846 (AVERAGE)		.610 (AVERAGE)	.986 (AVERAGE)		.358 (AVERAGE)	.602 (AVERAGE)

Table 3: Deviations of natural frequencies of the unrepaired blades compared to the mean of the three unrepaired blades

BLADE SN. A007-01637		BLADE SN. A007-00855		BLADE SN. A007-00885		BLADE SN. A007-03068		BLADE SN. A007-02773		BLADE SN. A007-00680	
NATURAL FREQUENCY (HZ)	DAMPING	NATURAL FREQUENCY (HZ)	DAMPING	NATURAL FREQUENCY (HZ)	DAMPING	NATURAL FREQUENCY (HZ)	DAMPING	NATURAL FREQUENCY (HZ)	DAMPING	NATURAL FREQUENCY (HZ)	DAMPING
4.510	0.0242	4.365	0.0313	4.403	0.0405	4.508	0.0433	4.473	0.0127	4.393	0.0209
13.255	0.0084	13.139	0.0065	13.232	0.0151	12.881	0.0148	13.072	0.0156	13.282	0.0100
26.340	0.0048	26.191	0.0028	26.148	0.0050	25.726	0.0084	25.863	0.0046	26.250	0.0075
38.170	0.0084	36.527	0.0080	38.113	0.0066	39.390	0.0113	36.524	0.0114	37.947	0.0091
43.180	0.0019	42.945	0.0065	42.857	0.0034	41.511	0.0059	42.373	0.0041	42.810	0.0028
43.528	0.0025	43.398	0.0043	43.150	0.0032	42.158	0.0071	42.665	0.0034	43.131	0.0029
46.880	0.0175	46.230	0.0059	46.503	0.0073	44.720	0.0164	45.695	0.0045	46.729	0.0041
48.114	0.0083	46.538	0.0075	47.418	0.0144	45.790	0.0087	46.008	0.0053	47.108	0.0031
55.266	0.0103	54.904	0.0117	54.625	0.0124	53.194	0.0159	52.451	0.0110	53.862	0.0284
57.407	0.0139	60.157	0.0165	55.131	0.0292	57.759	0.0189	57.430	0.0159	54.779	0.0305
66.218	0.0013	65.789	0.0025	65.704	0.0017	64.446	0.0035	66.248	0.0061	65.517	0.0020
85.441	0.0020	84.535	0.0024	84.625	0.0025	82.375	0.0023	84.080	0.0024	84.541	0.0026
86.219	0.0021	85.411	0.0022	85.417	0.0020	83.136	0.0025	84.799	0.0019	85.282	0.0033
97.985	0.0024	97.746	0.0040	97.290	0.0026	93.936	0.0025	96.057	0.0031	97.989	0.0036
98.317	0.0035	97.891	0.0089	97.716	0.0029	94.431	0.0020	96.754	0.0044	98.253	0.0040
109.551	0.0120	102.312	0.0225	106.921	0.0062	104.302	0.0090	98.434	0.0140	101.338	0.0094
116.503	0.0076	114.856	0.0024	115.243	0.0033	111.449	0.0030	113.794	0.0032	115.182	0.0024
117.305	0.0117	116.173	0.0031	116.259	0.0052	112.365	0.0026	114.559	0.0029	116.151	0.0028

Table 4: Damping values for all blades at all obtained natural frequencies

ACCELEROMETER LOCATION	BLADE X COORDINATE (Inches)	BLADE Y COORDINATE (Inches)	BLADE Z COORDINATE (Inches)	APPROXIMATE RADIAL STATION (Inches)
1	0.0	0.0	0.0	43.0
2	0.0	19.0	0.0	43.0
3	28.4	0.0	0.0	71.4
4	28.4	19.0	0.0	71.4
5	56.9	0.0	0.0	99.9
6	56.9	19.0	0.0	99.9
7	85.3	0.0	0.0	128.3
8	85.3	19.0	0.0	128.3
9	113.8	0.0	0.0	156.8
10	113.8	19.0	0.0	156.8
11	142.2	0.0	0.0	185.2
12	142.2	19.0	0.0	185.2
13	170.7	0.0	0.0	213.7
14	170.7	19.0	0.0	213.7
15	199.1	0.0	0.0	242.1
16	199.1	19.0	0.0	242.1
17	227.6	0.0	0.0	270.6
18	227.6	19.0	0.0	270.6
19	256.0	0.0	0.0	299.0
20	256.0	19.0	0.0	299.0
21	278.0	0.0	0.0	321.0
22	278.0	19.0	0.0	321.0

Table 5: Coordinates of accelerometer measurement points (see also Figure 3)

APPENDICES

APPENDIX A

STATISTICAL EVALUATION

With only three blades in the unrepaired population it is difficult to get statistically meaningful results, but some form of statistical analysis was necessary in order to interpret the experimental results. The first step in this process was to compute the mean and standard deviation of the natural frequencies for the unrepaired blades. The mean value of the natural frequencies was computed using:

$$f_m = \frac{1}{n} \sum_{i=1}^{n} f_i$$

where f_m is the mean of the natural frequencies, f_i are the individual natural frequencies for each blade, and n is the total number of blades. The standard deviation was found using the formula for the unbiased or sample standard deviation for small sets of data as follows:

$$\sigma = \left[\frac{\sum_{i=1}^{3} (f_i - f_m)^2}{n-1} \right]^{\frac{1}{2}}$$

The values of the mean natural frequencies and standard deviations are listed in the first two columns of Tables 2 and 3. The deviations from the mean for each blade, both in absolute Hz and as a percentage of the mean value, were computed and compared. Table 2 shows this comparison for the repaired blades while Table 3 gives the comparison for the unrepaired blades.

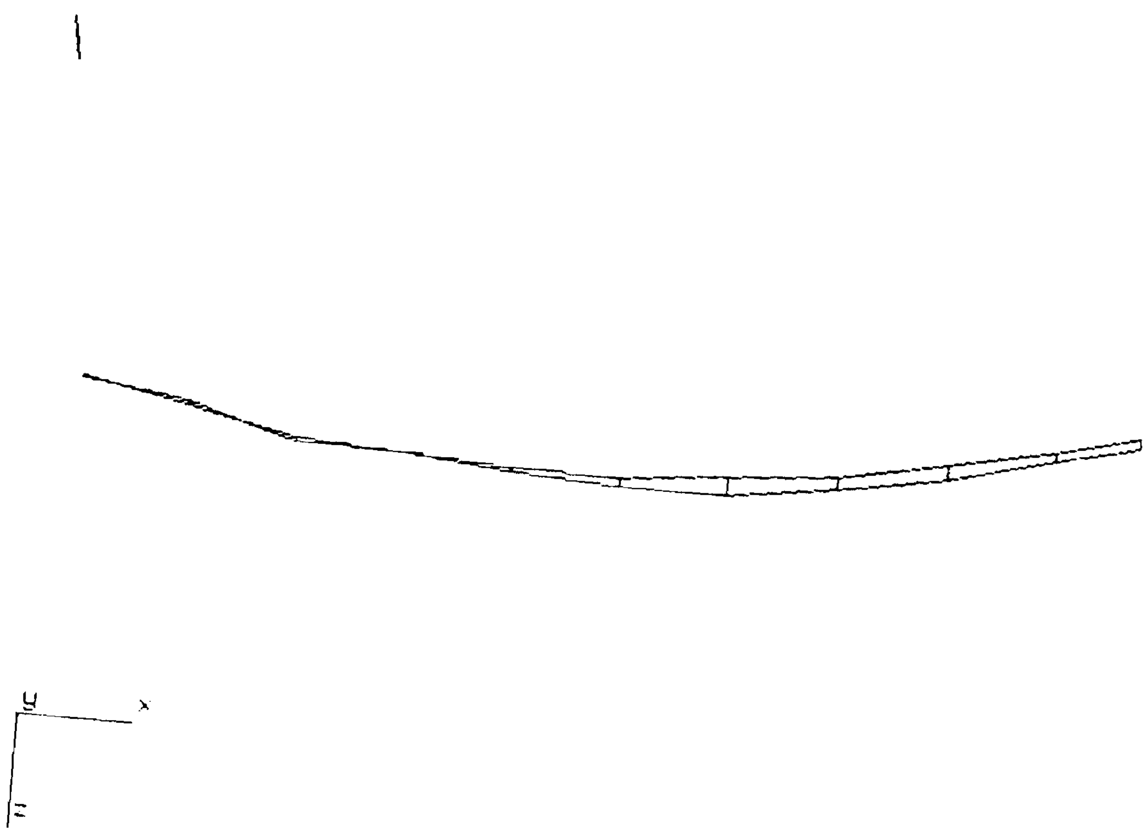
APPENDIX B

MODE SHAPE PLOTS

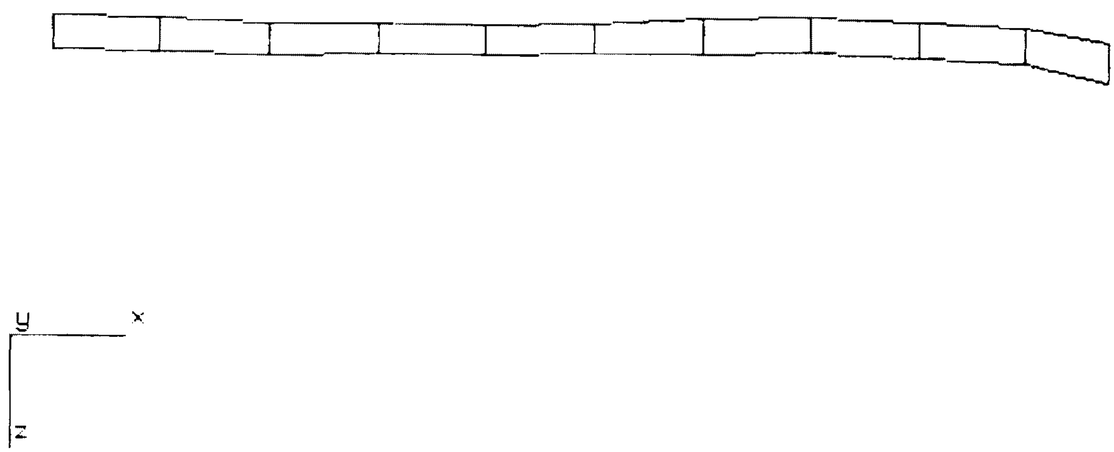
BLADE SN A007-01637

Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

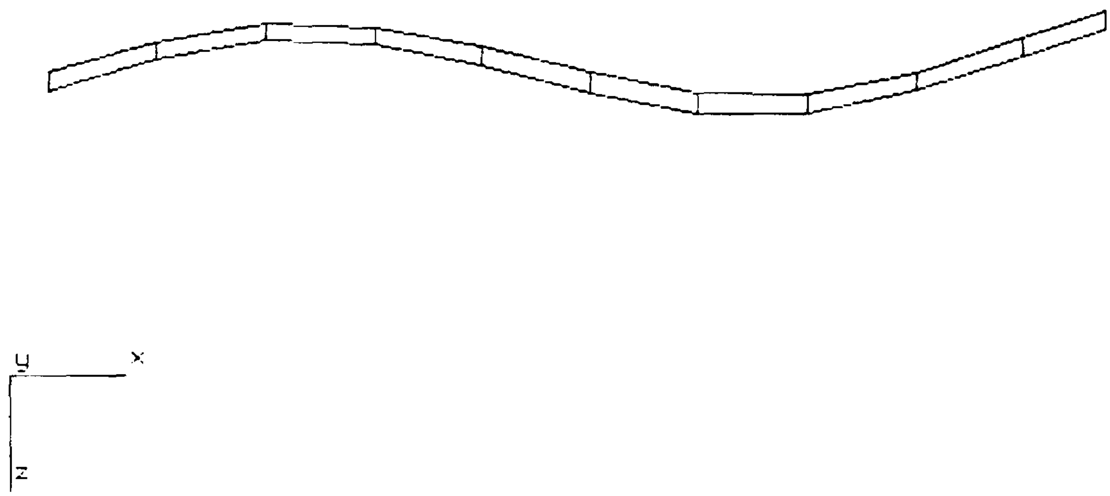
It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.



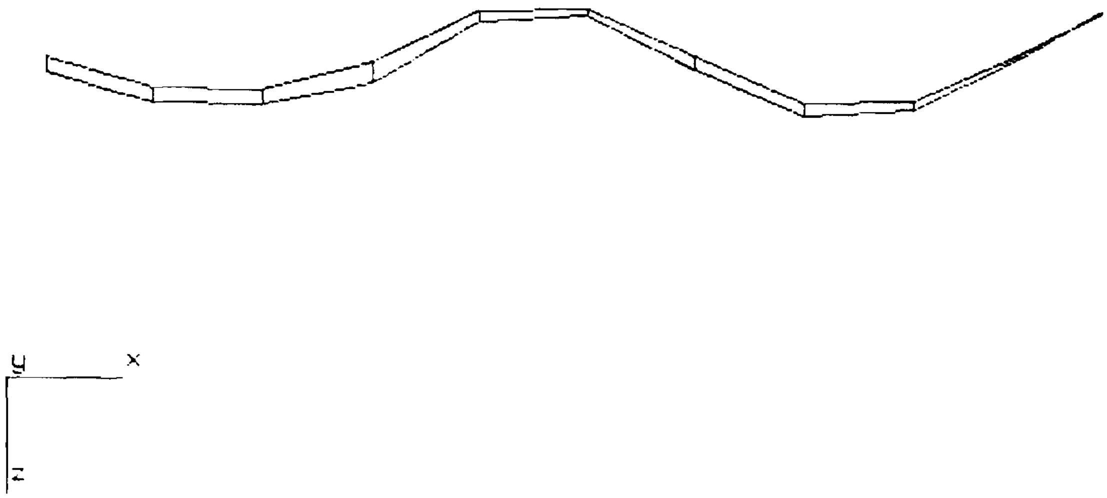
4.510 Hz

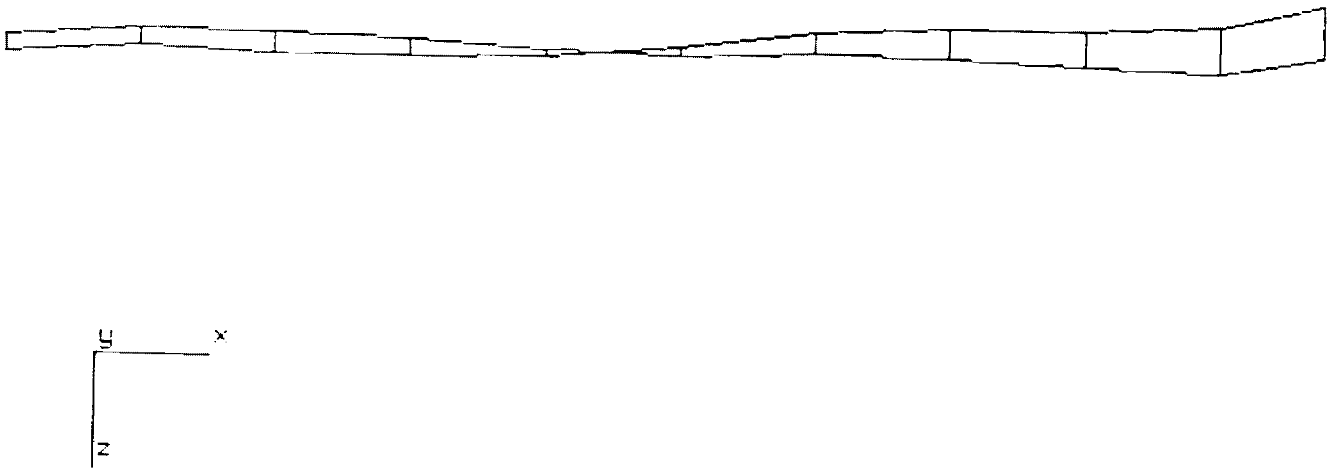


11.088 Hz

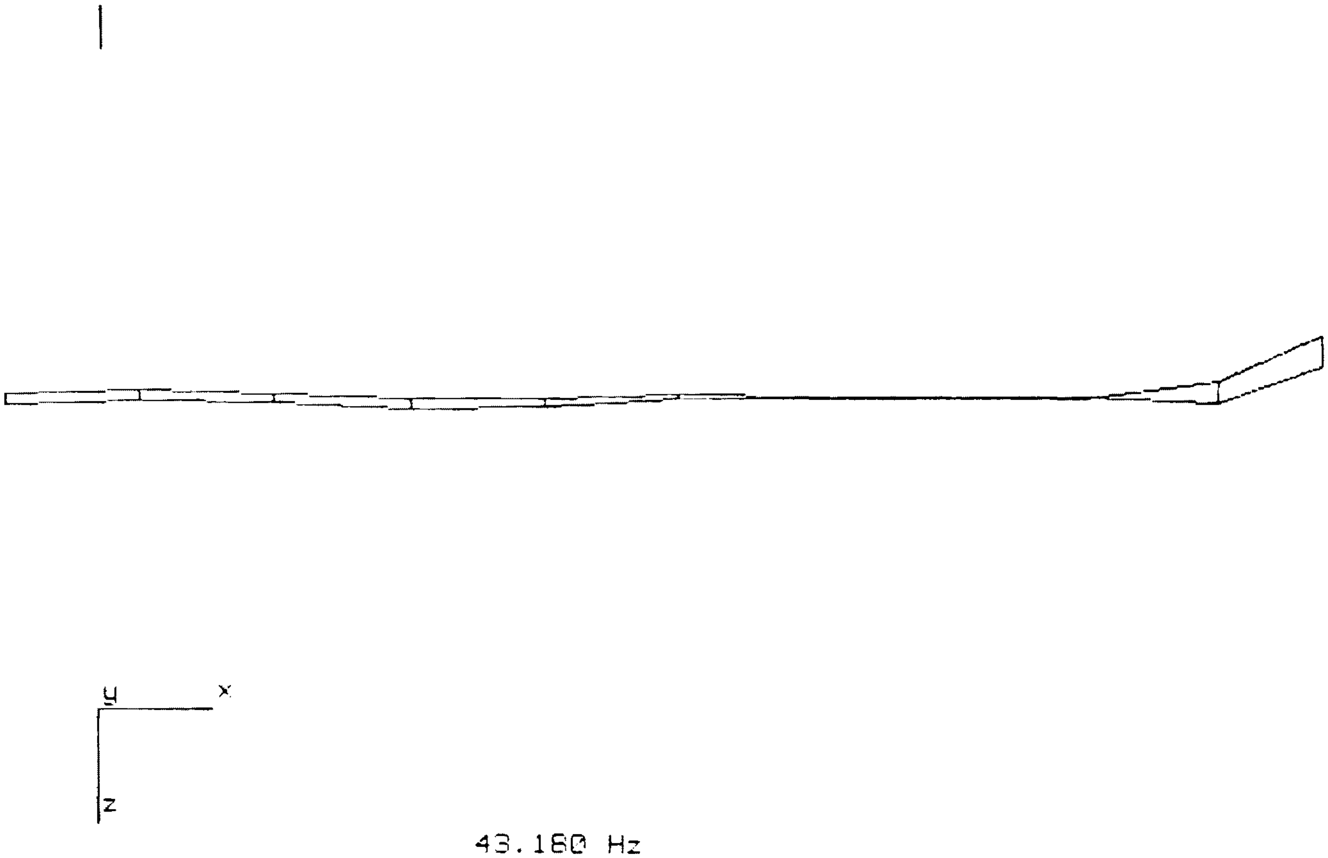


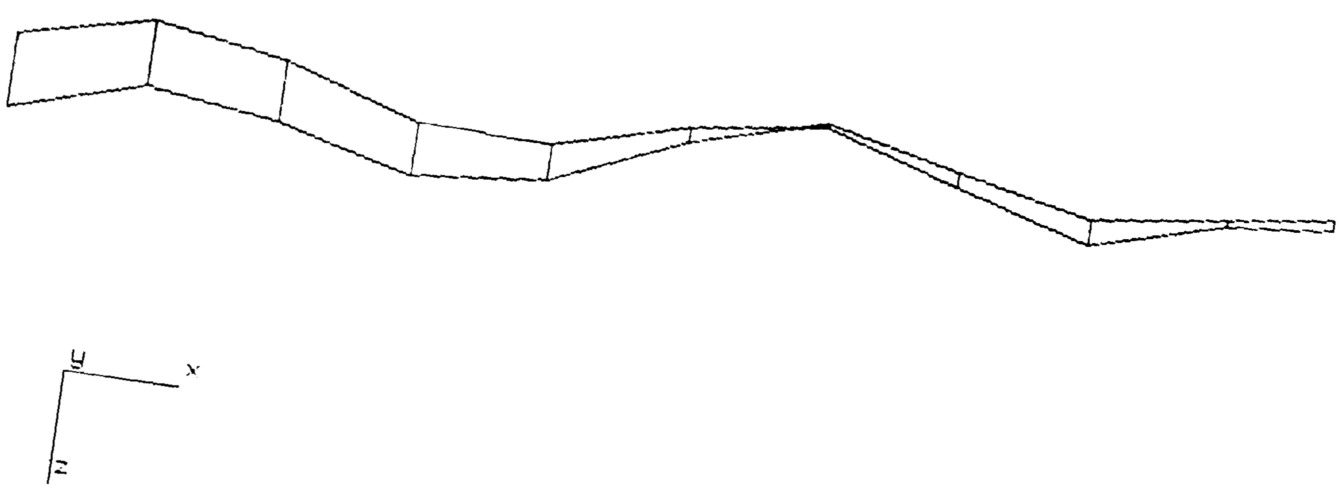
13.255 Hz


x

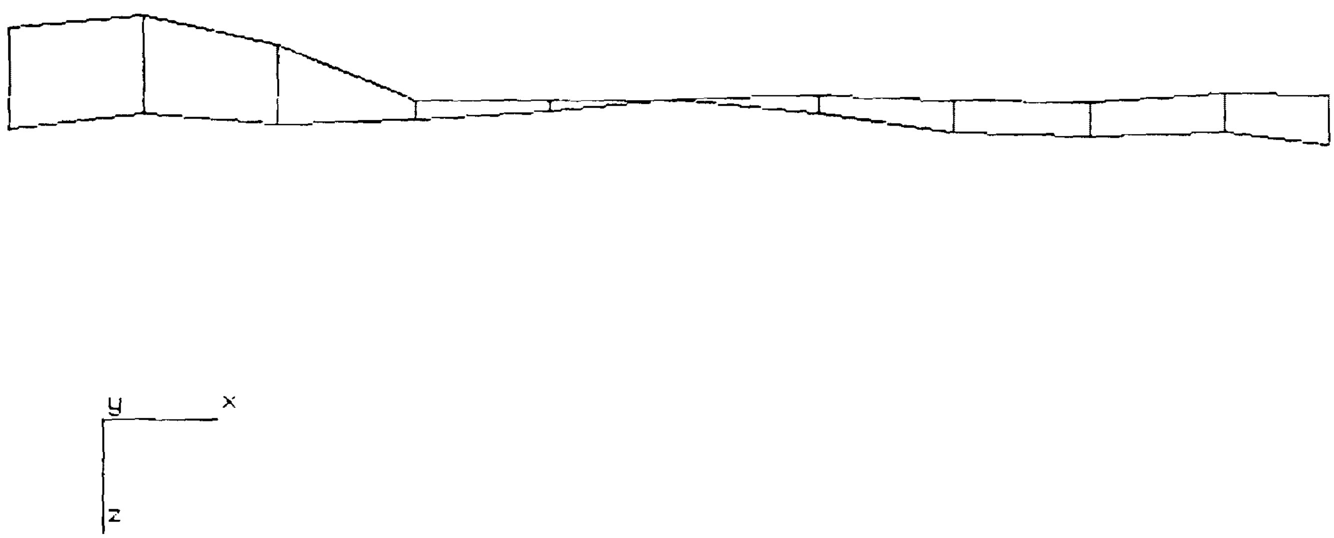


38.170 Hz

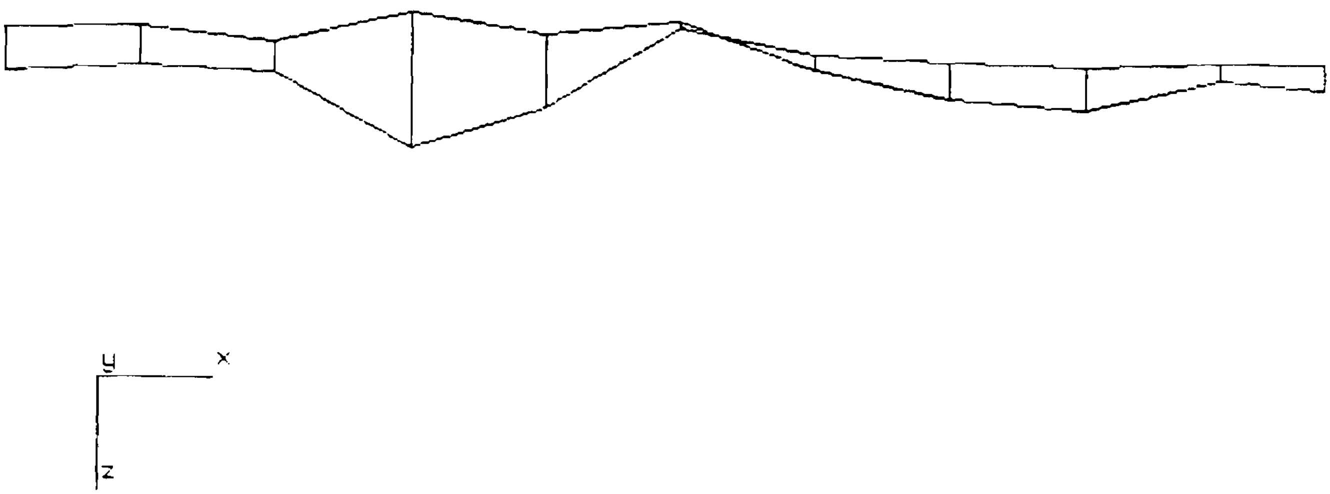

y
x
z
43.180 Hz



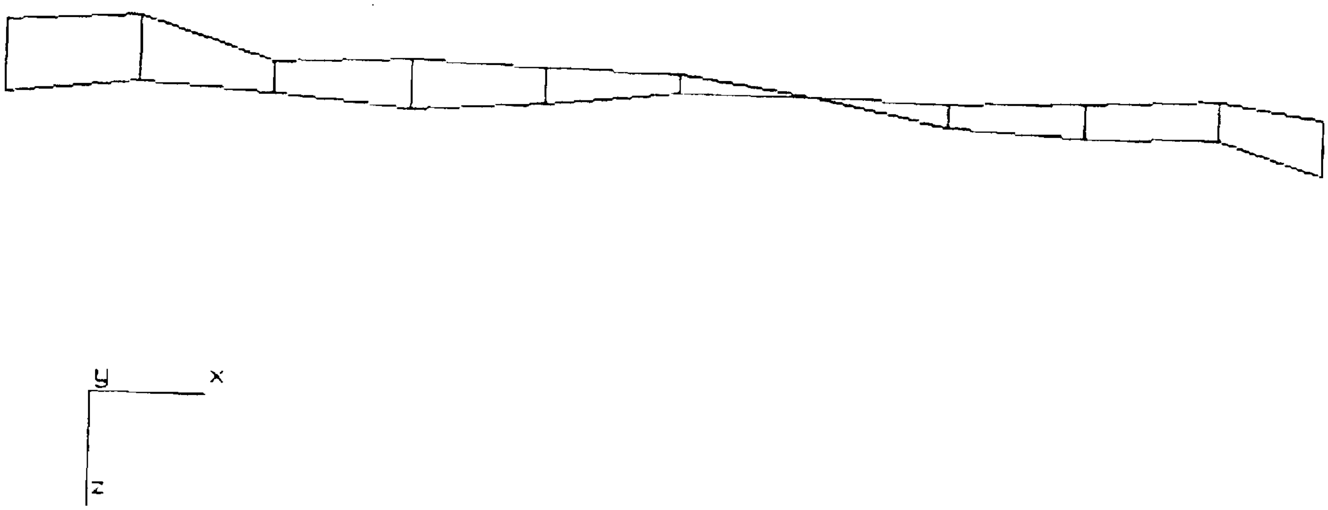
43.528 Hz



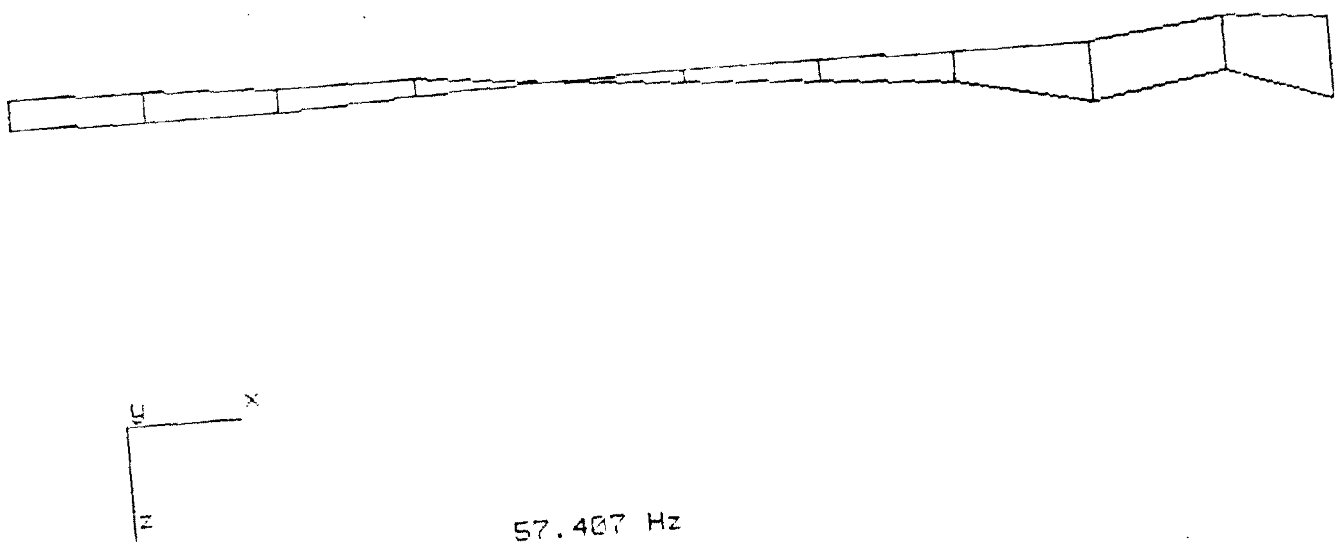
46.880 Hz



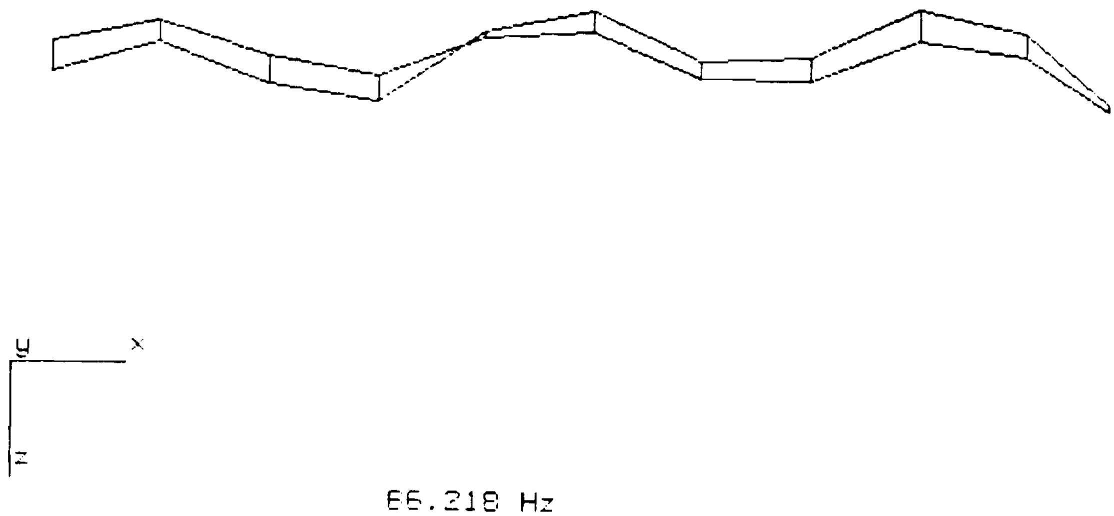
48.114 Hz

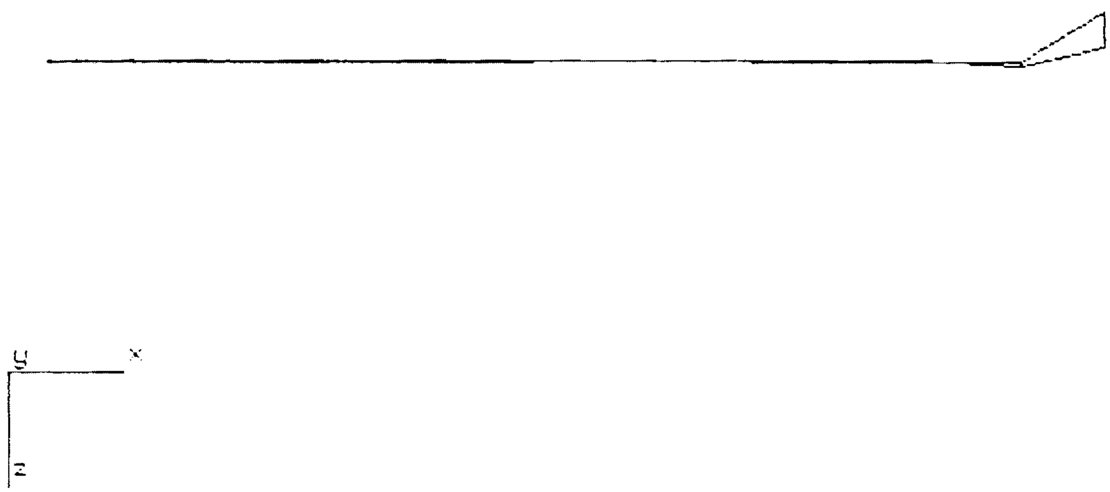


55.266 Hz

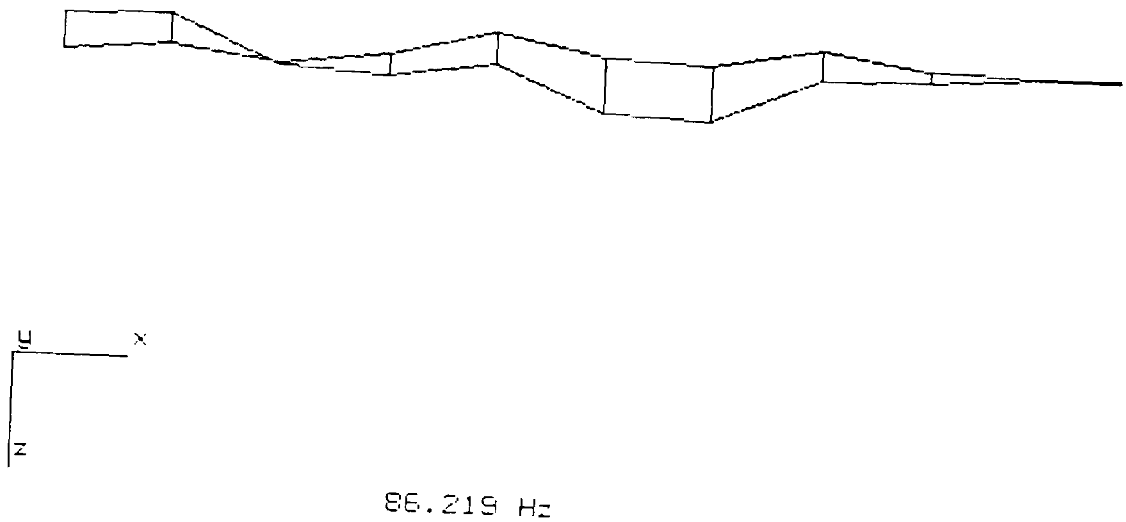


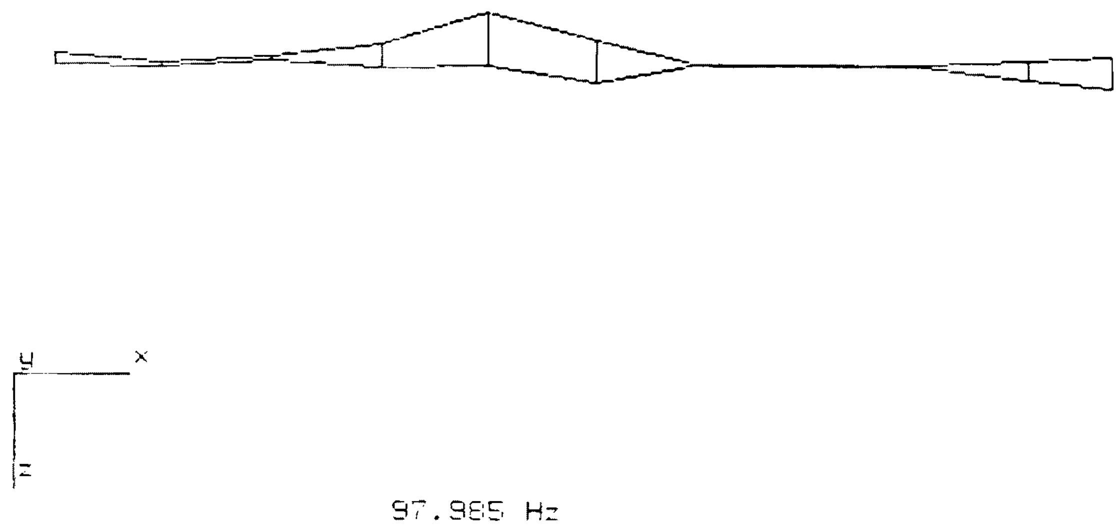
57.407 Hz

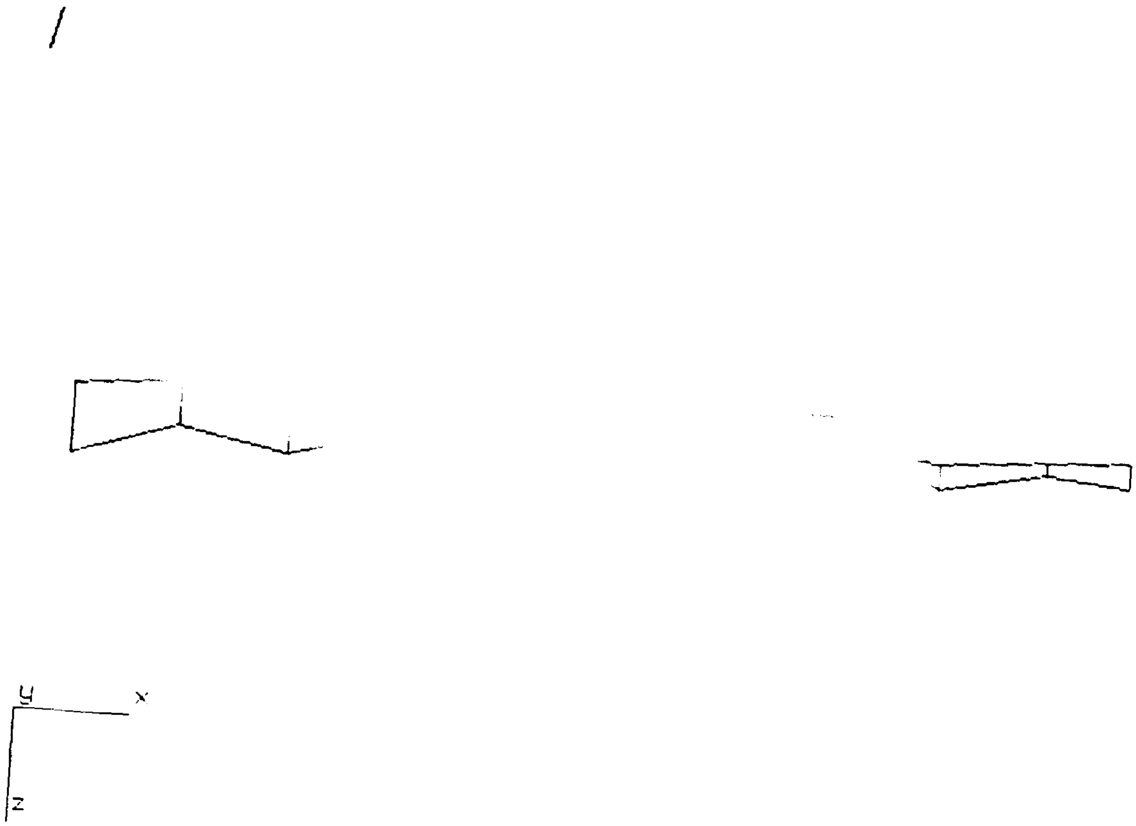

y
x
z
66.218 Hz



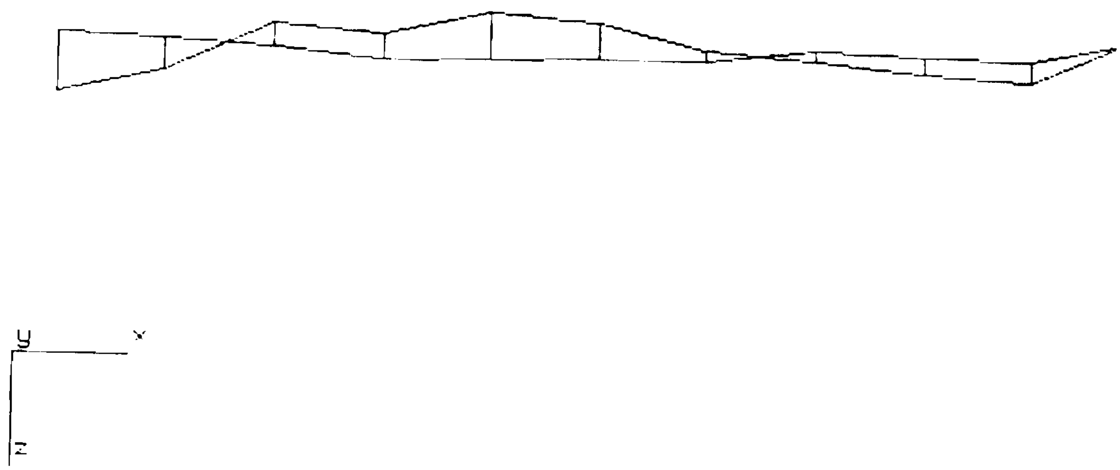
85.441 Hz


y
x
z
86.219 Hz

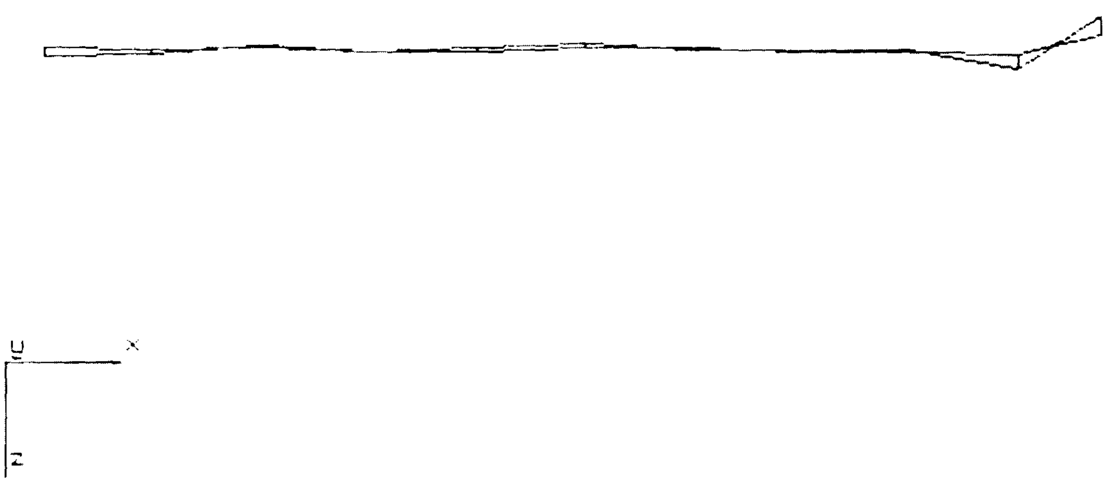

y
x
z
97.985 Hz



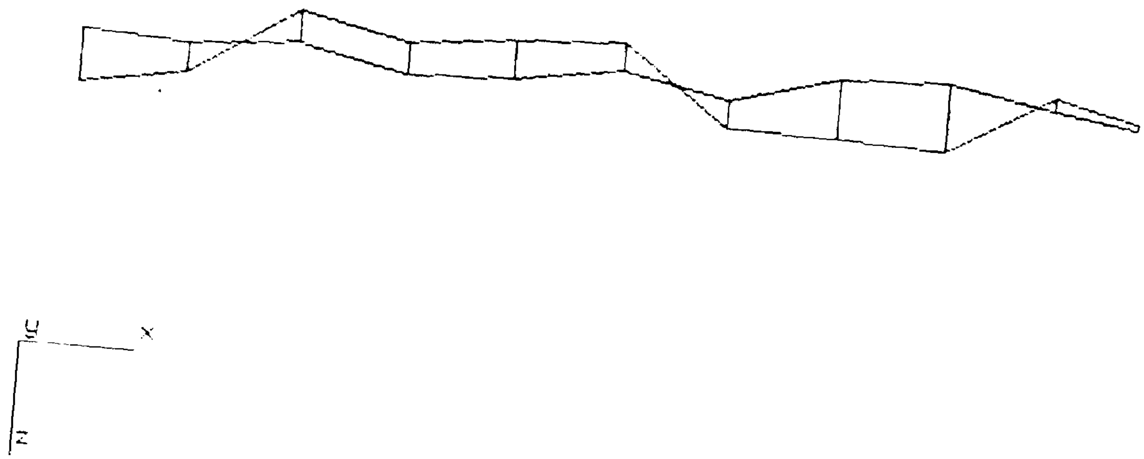
98.317 Hz



109.551 Hz



118.503 Hz



117.305 Hz

APPENDIX C

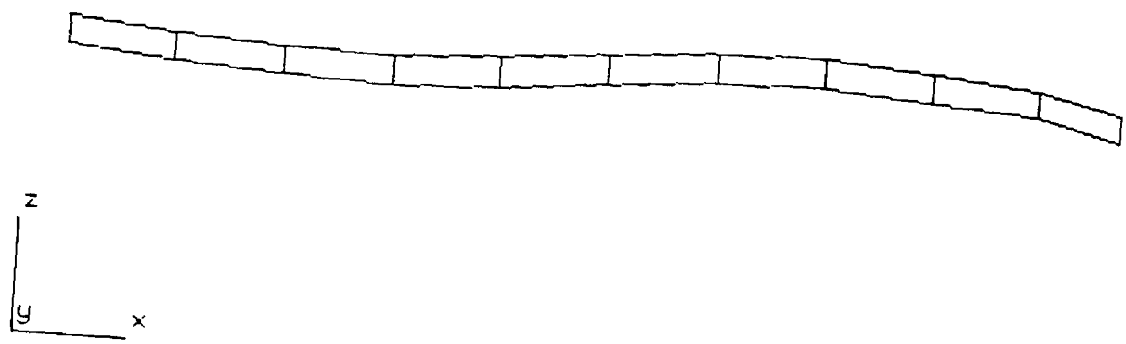
MODE SHAPE PLOTS

BLADE SN A007-00855

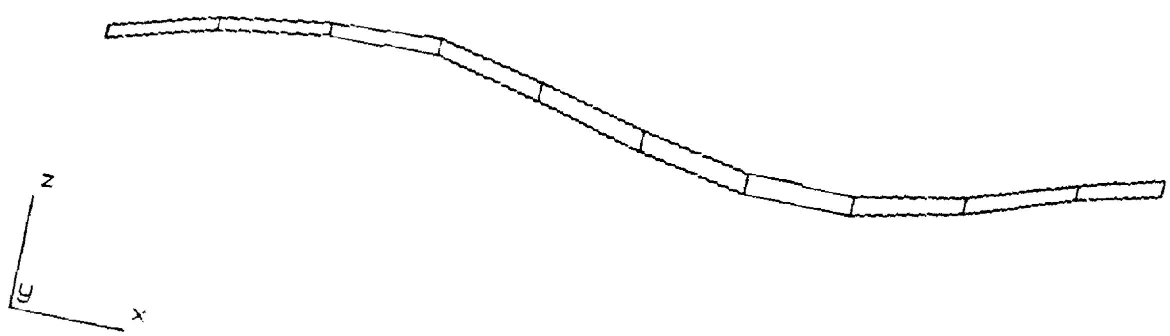
Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.

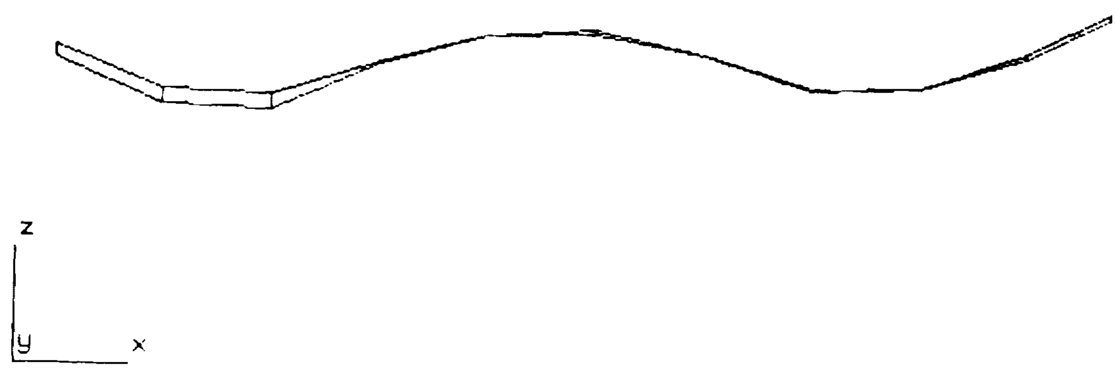
4.365 Hz



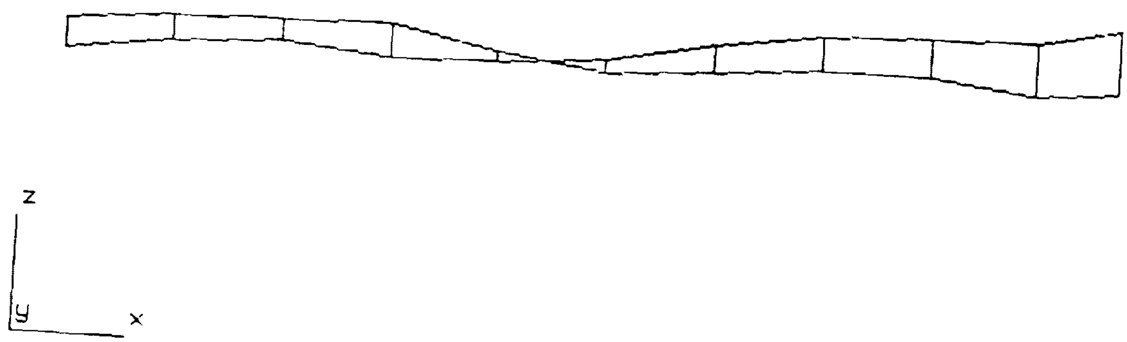
11.234 Hz



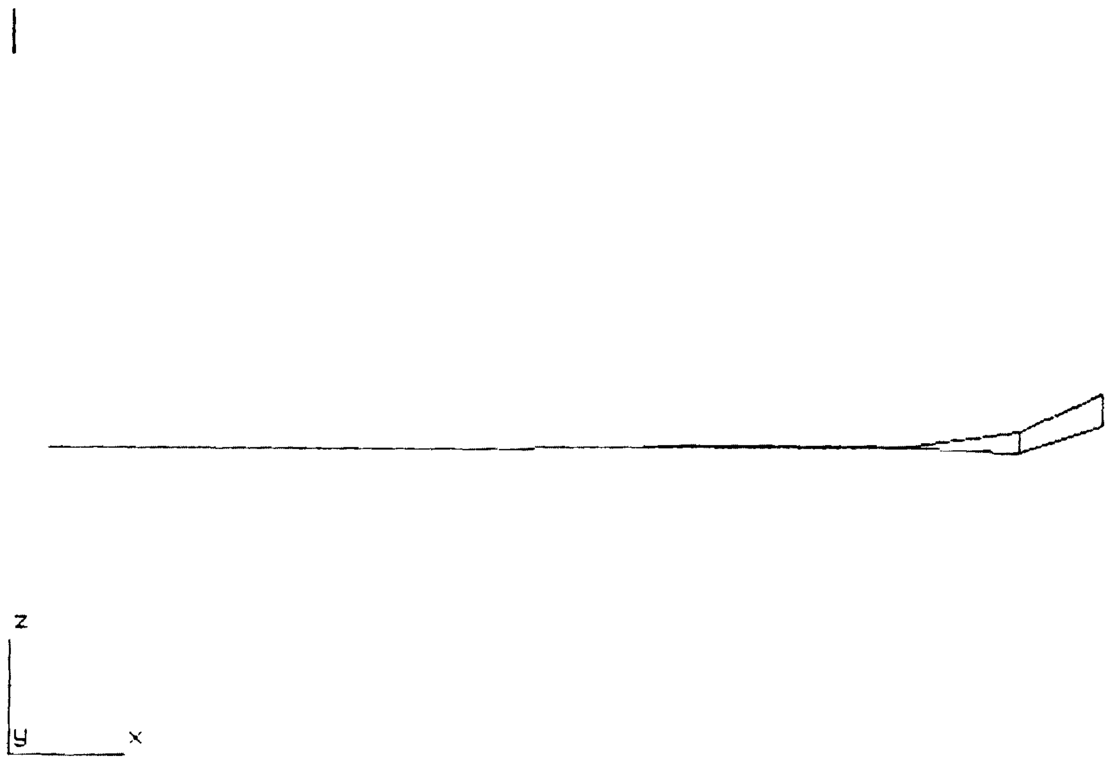
13.139 Hz



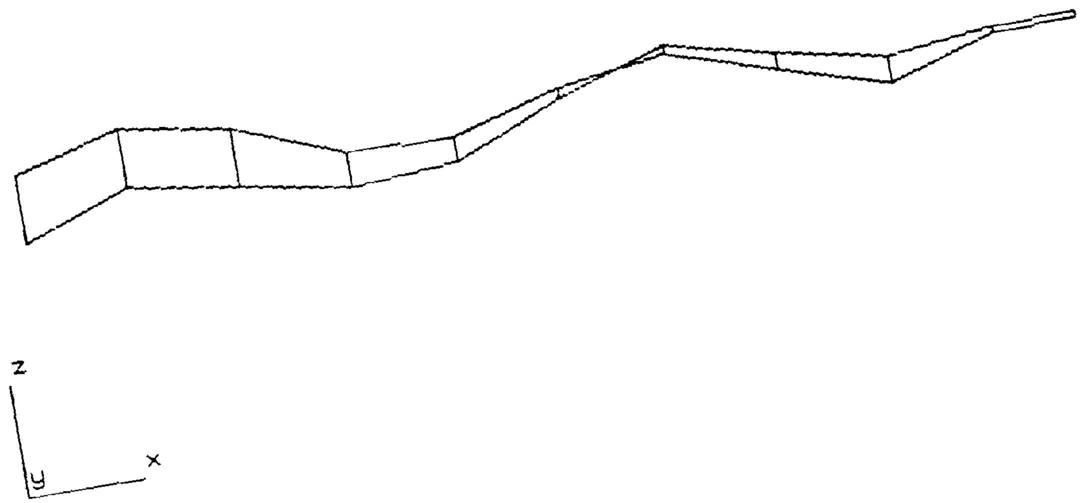
26.191 Hz


z
y
x

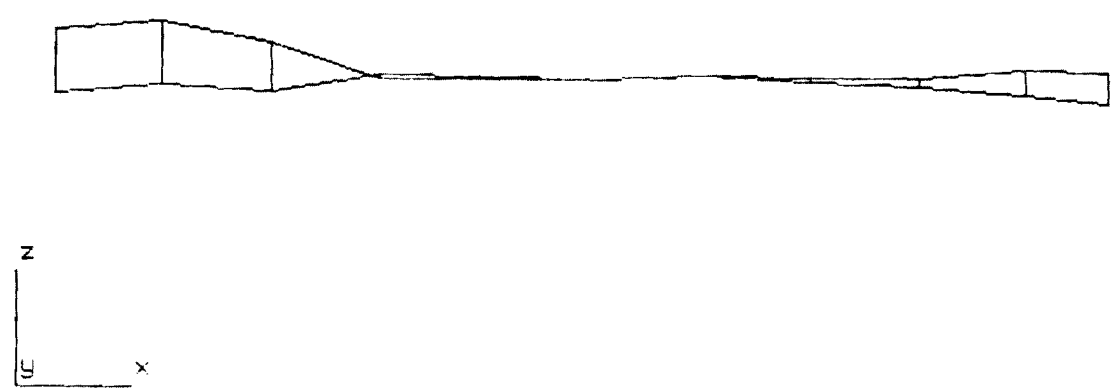
[illegible]



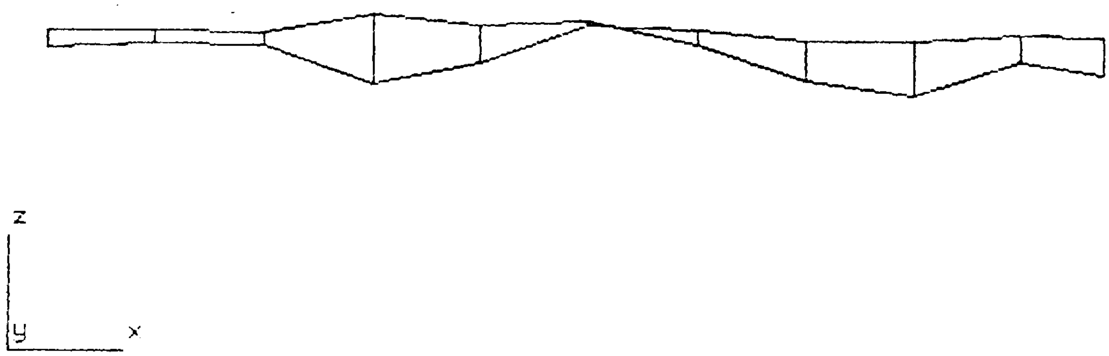
42.945 Hz



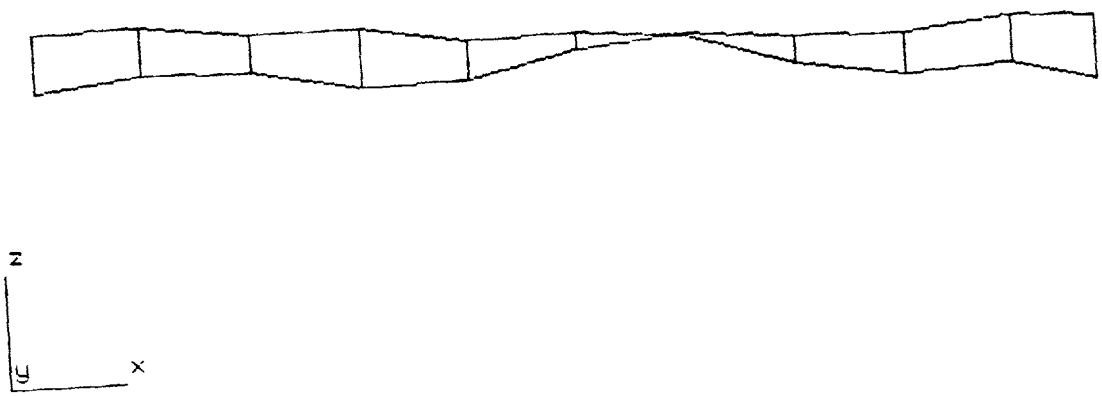
43.398 Hz



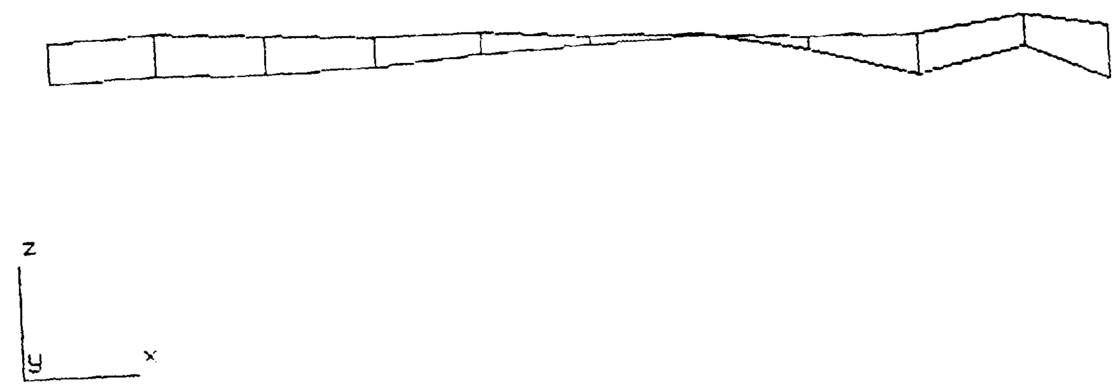
46.230 Hz



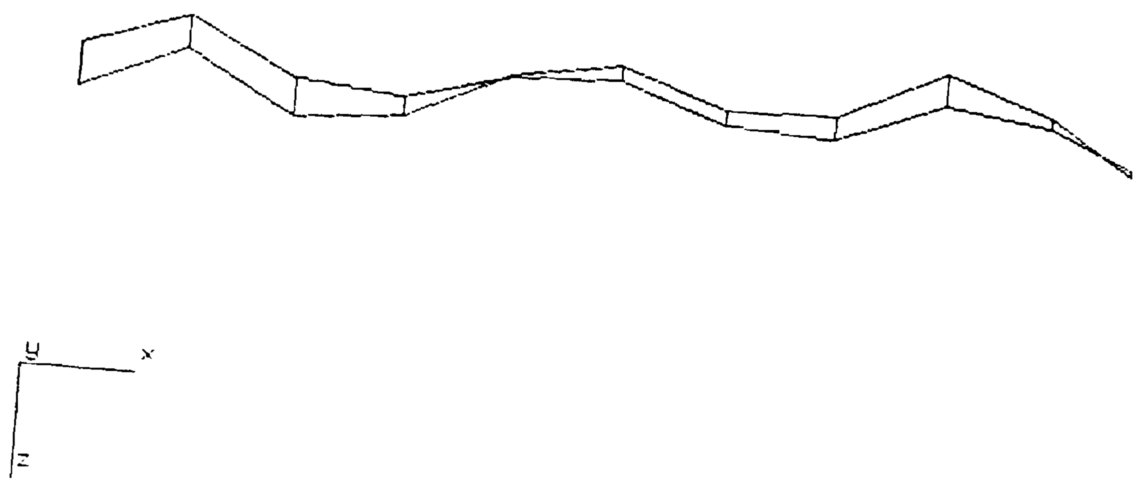
46.538 Hz



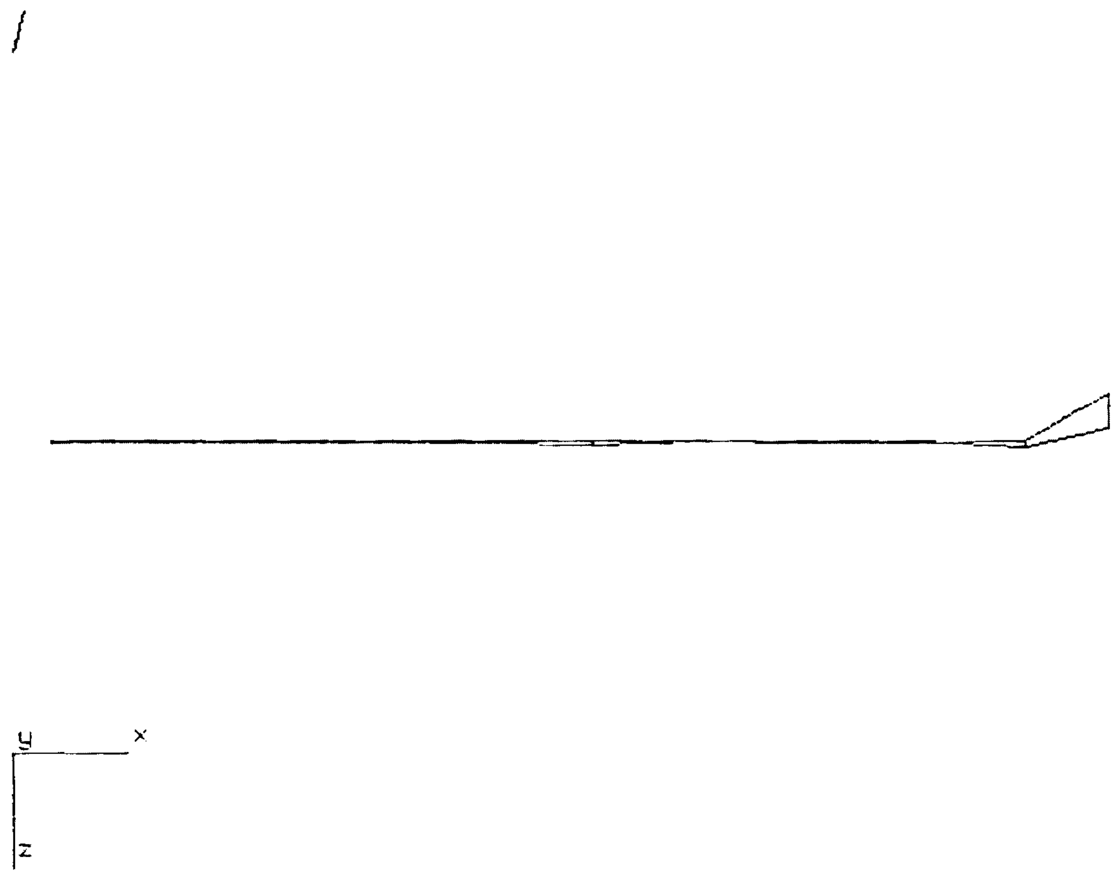
54.904 Hz



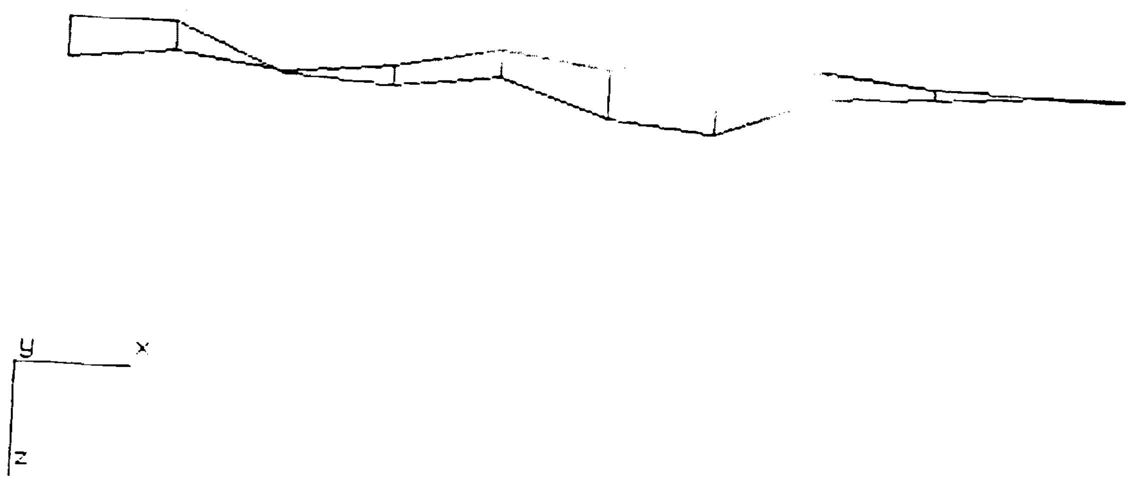
60.157 Hz



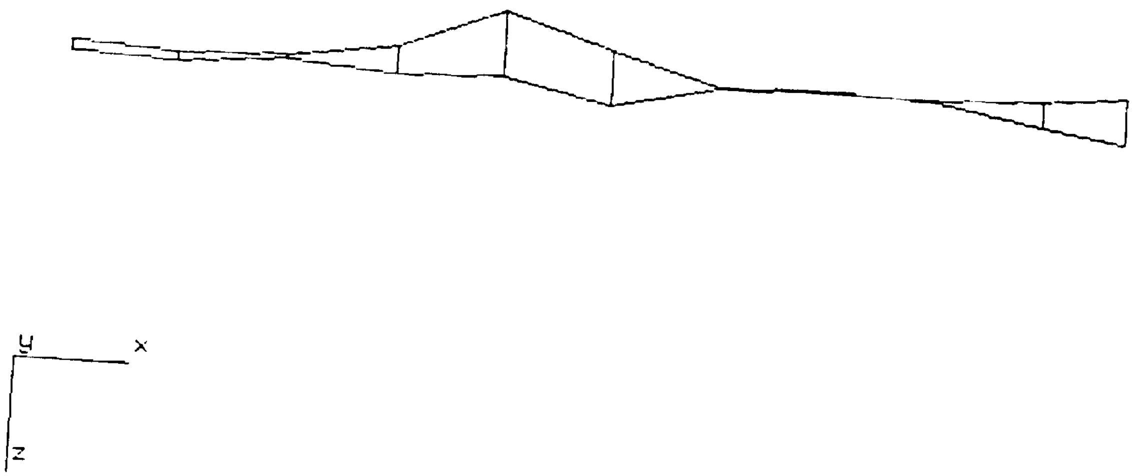
65.769 Hz



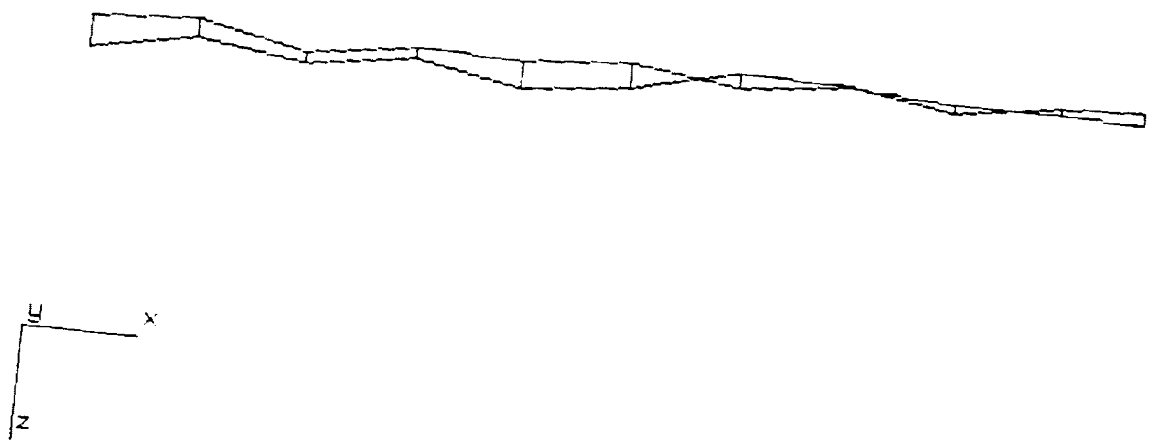
84.535 Hz



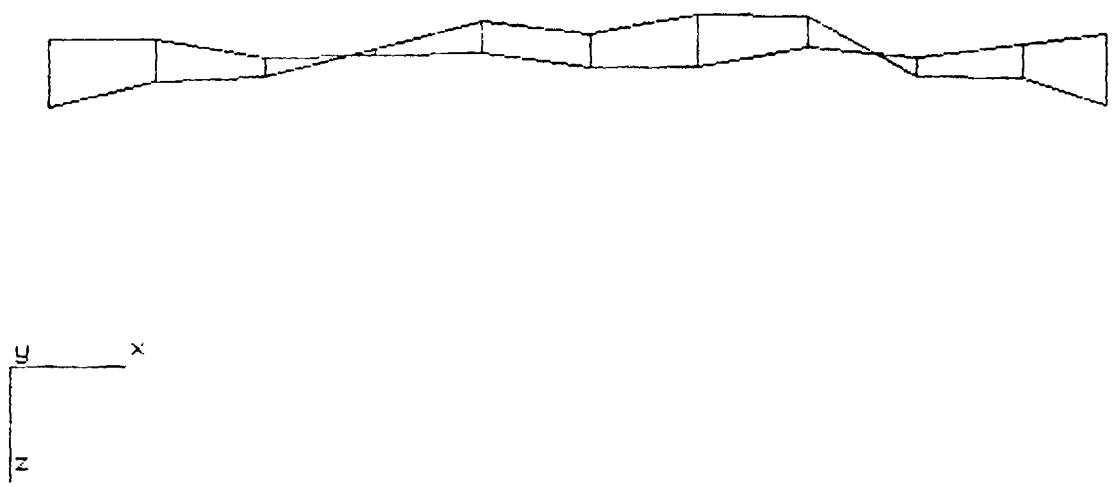
85.411 Hz



97.746 Hz

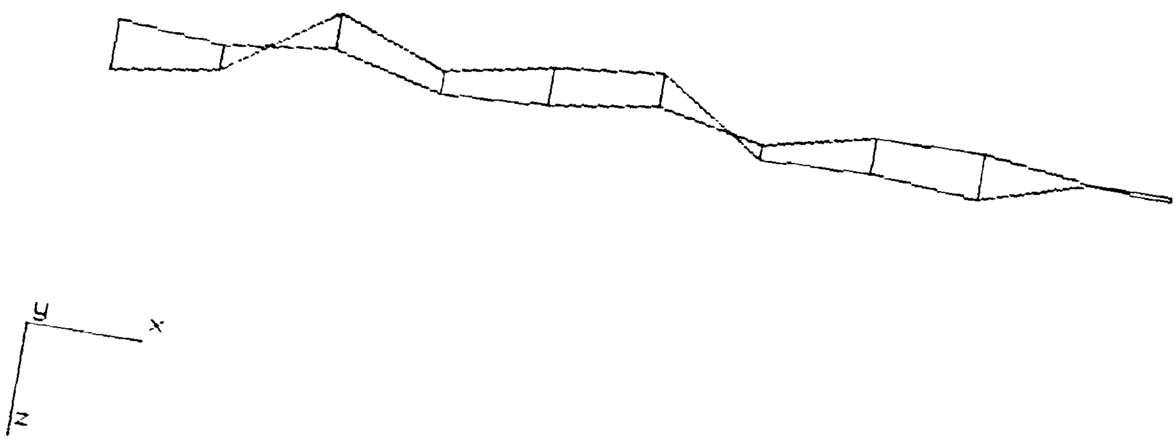


97.891 Hz



102.312 Hz

114.856 Hz



116.173 Hz

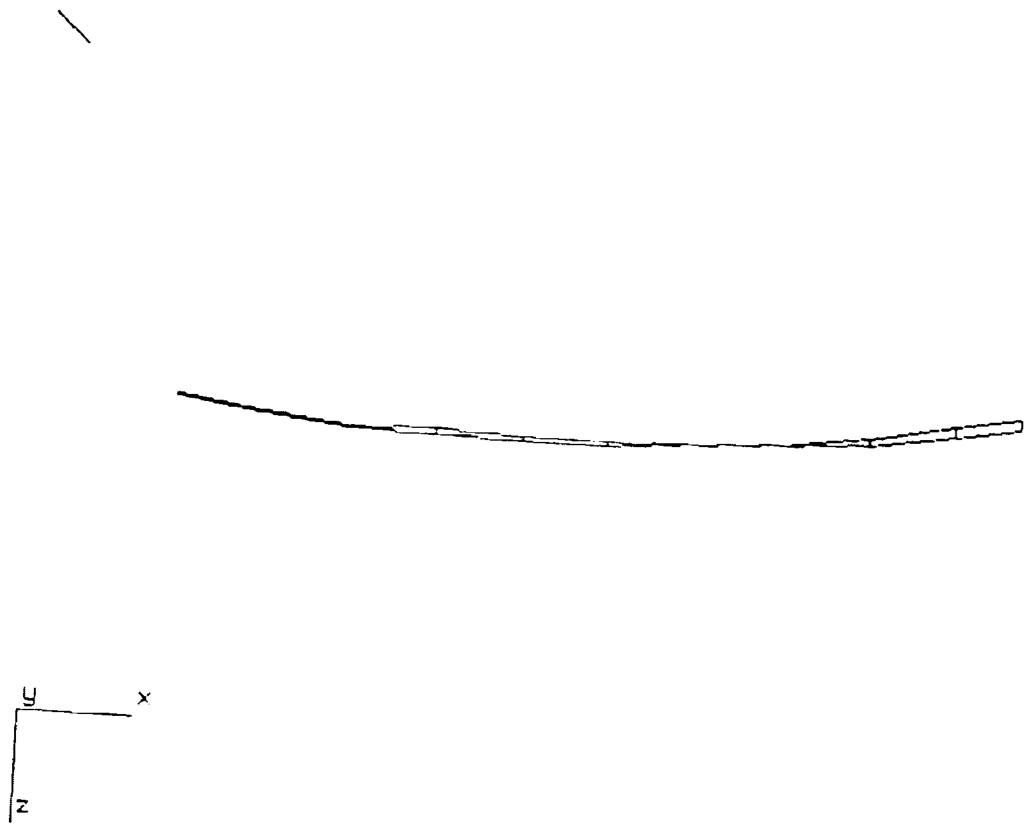
APPENDIX D

MODE SHAPE PLOTS

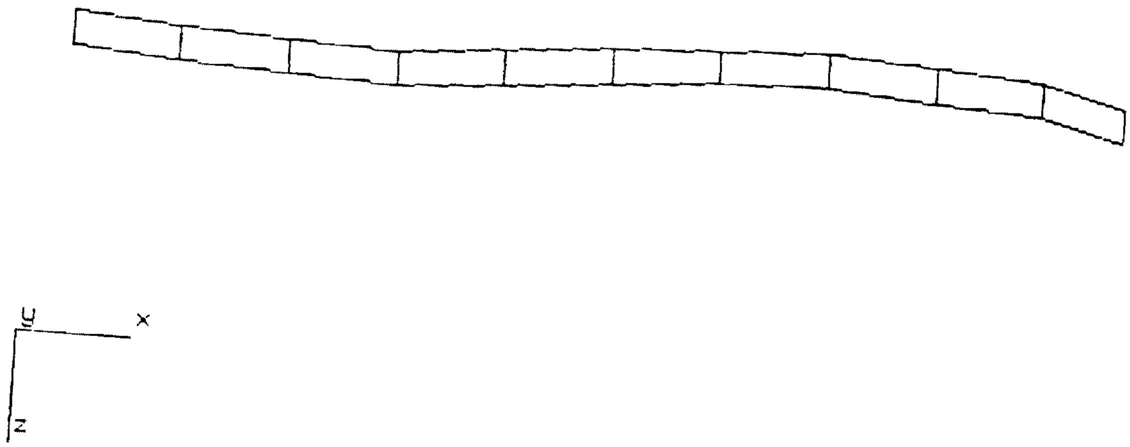
BLADE SN A007-00885

Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

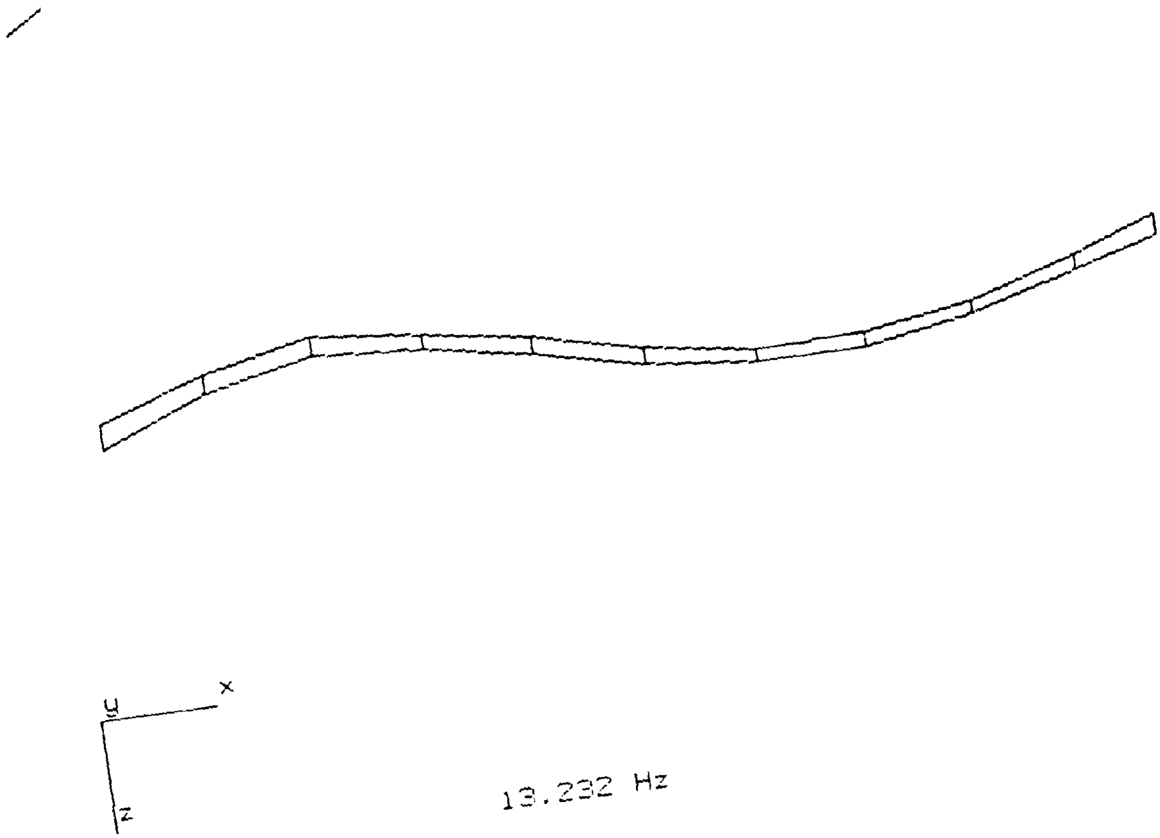
It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.

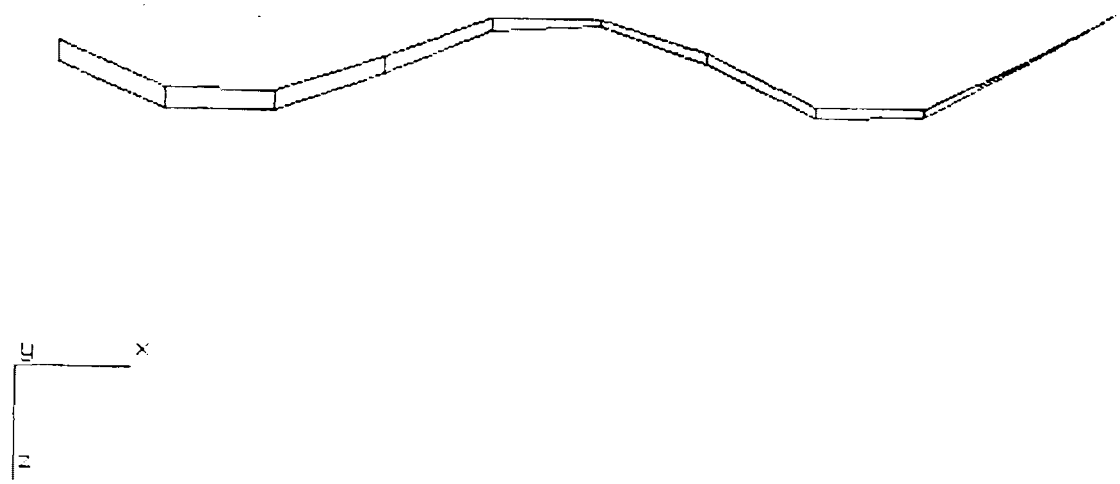


4.403 Hz

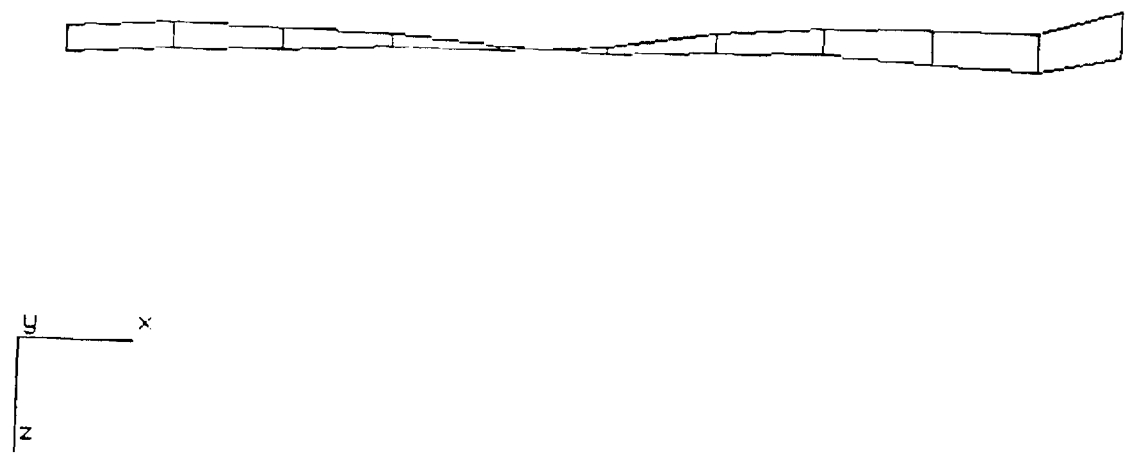


11.580 Hz

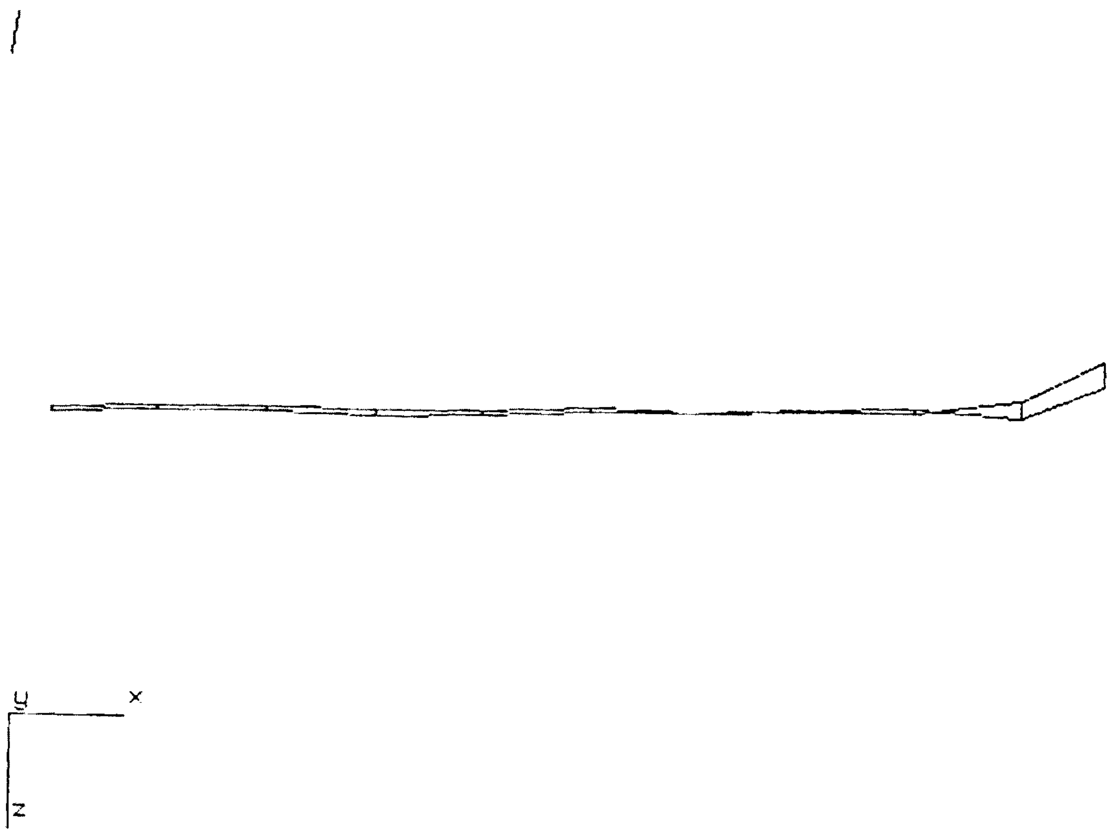

y
x
z
13.232 Hz



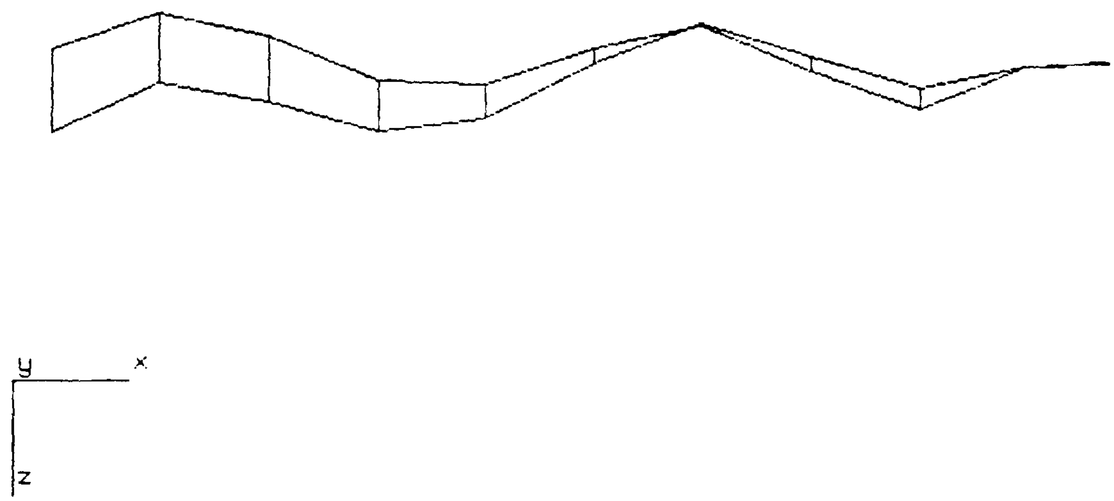
26.148 Hz



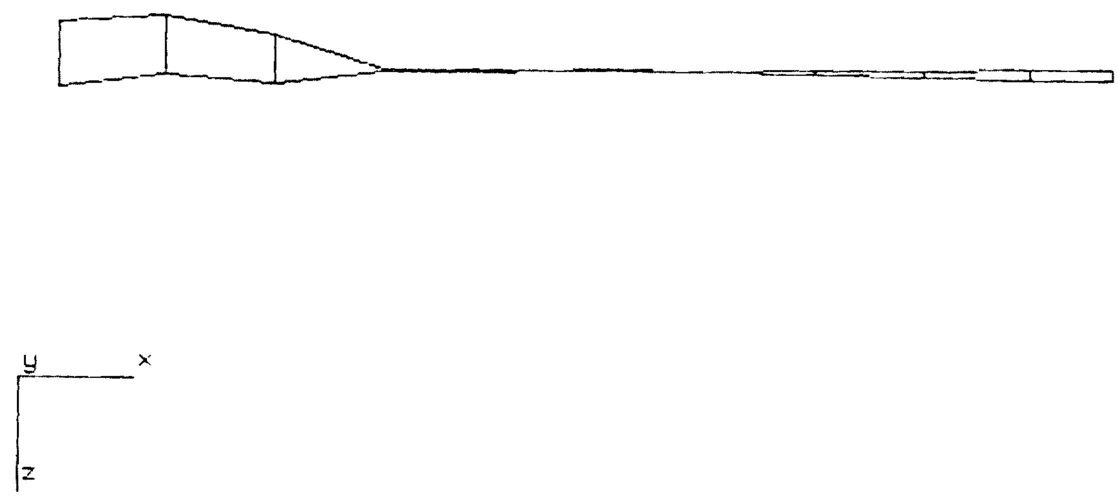
38..113 Hz



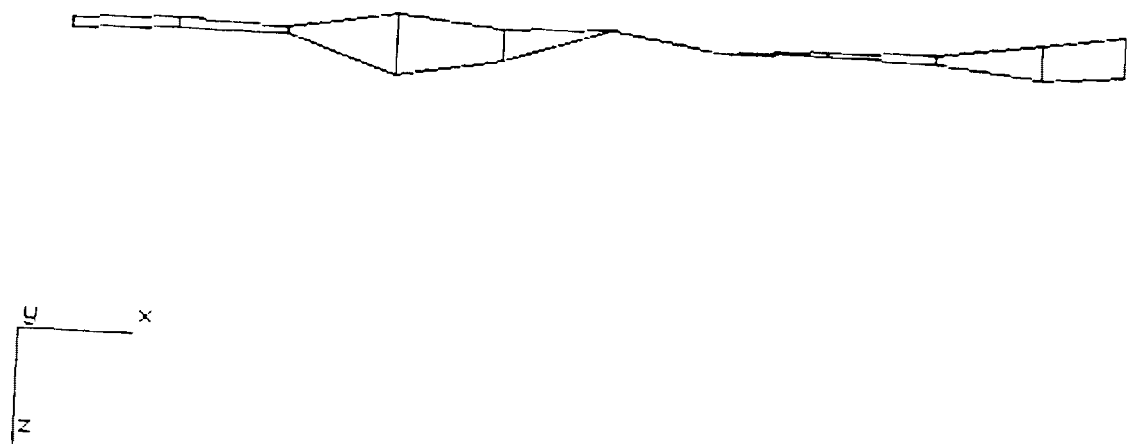
42.857 Hz



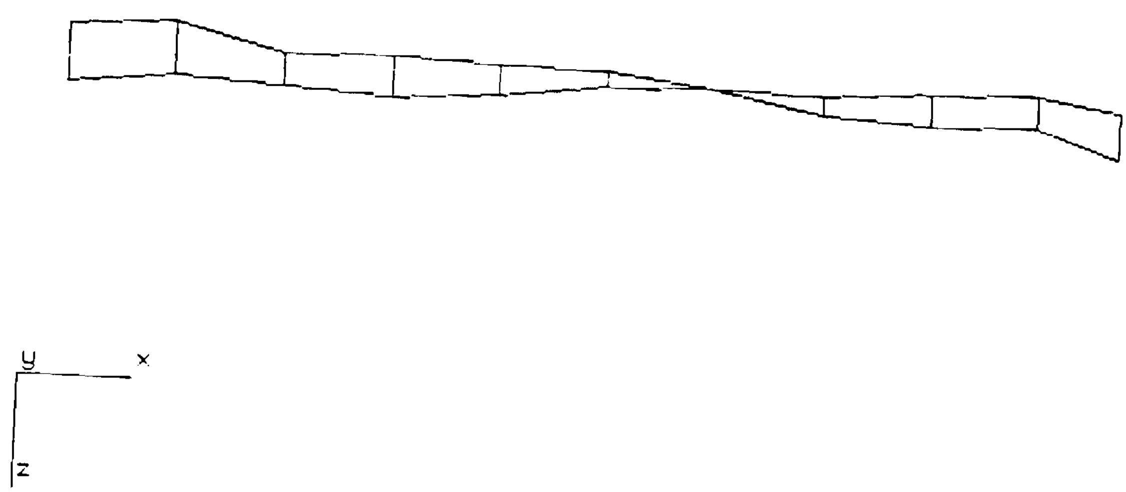
43.150 Hz



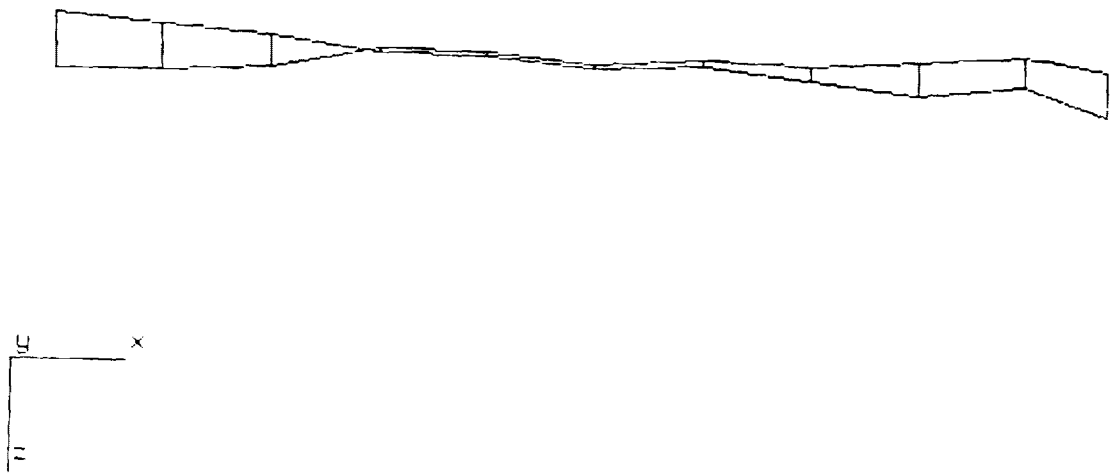
46.503 Hz



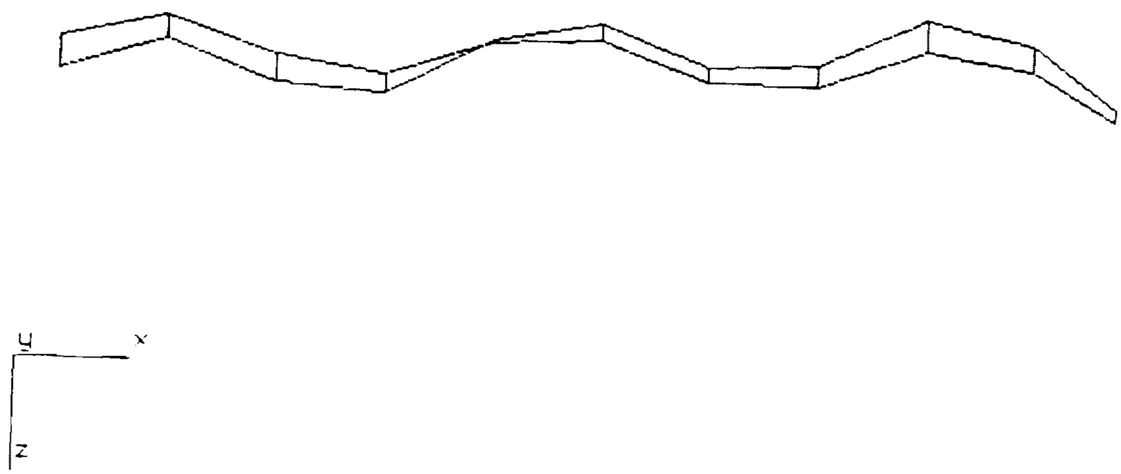
47.418 Hz



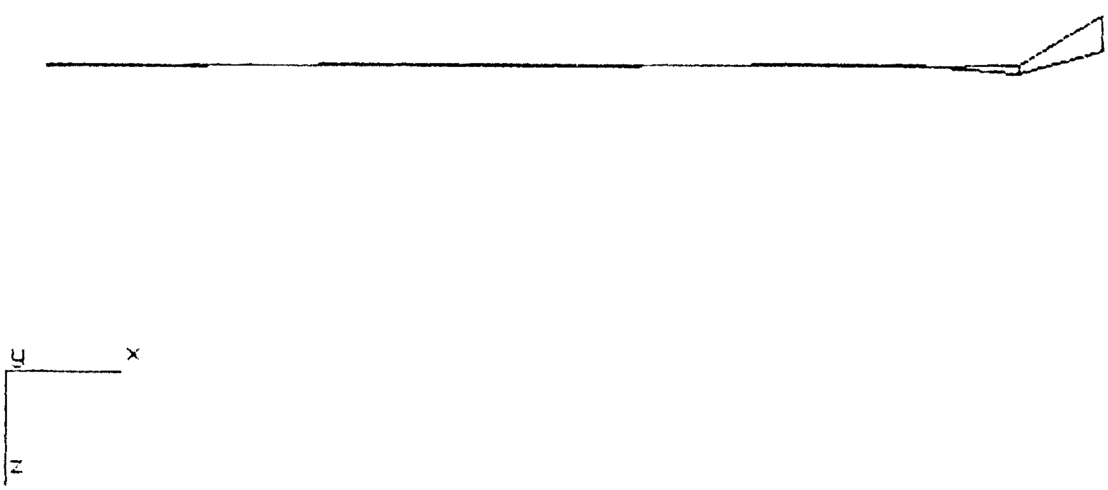
54.625 Hz



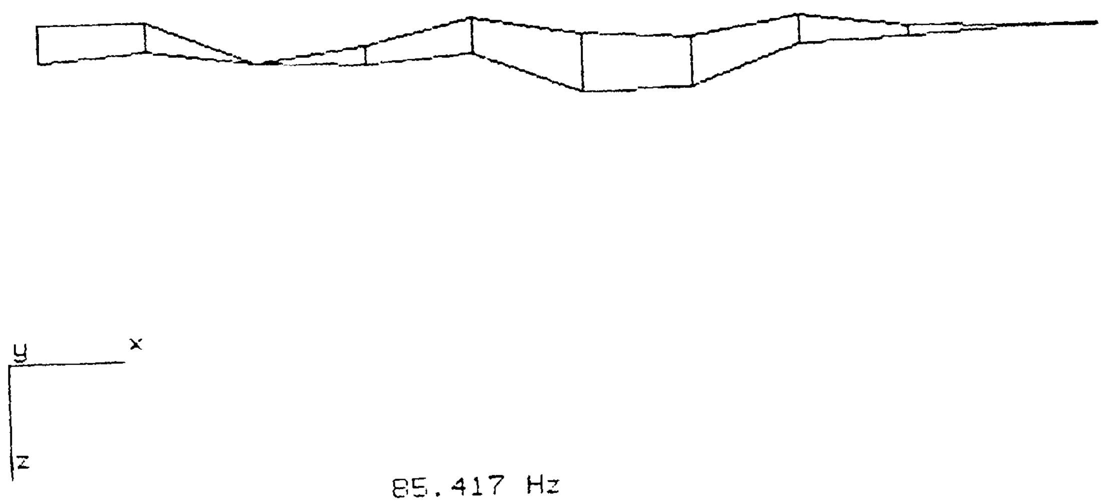
55.131 Hz



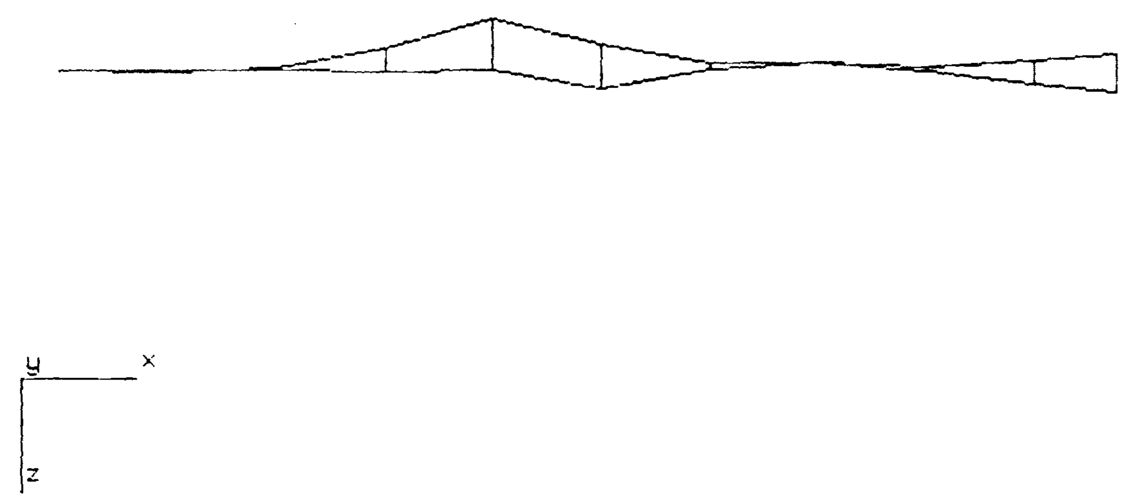
65.704 Hz



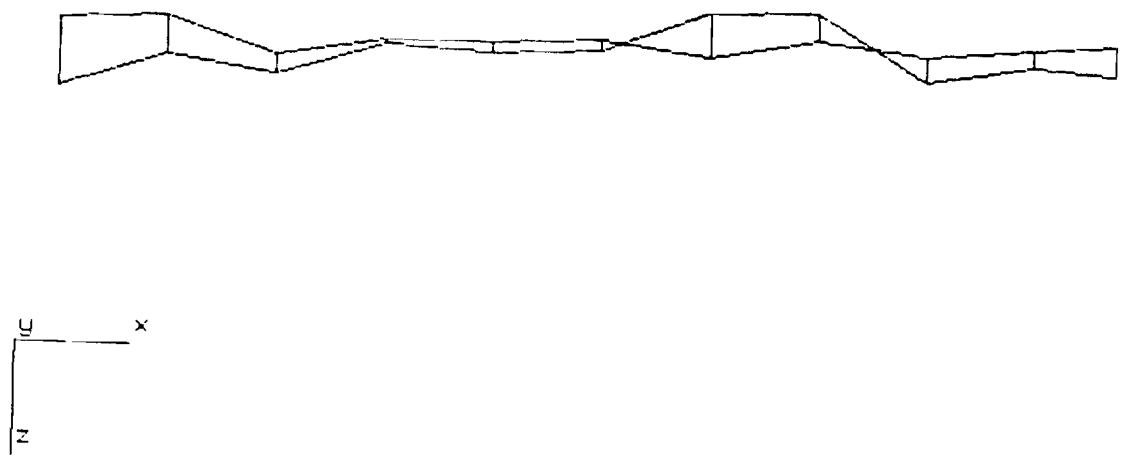
64.625 Hz



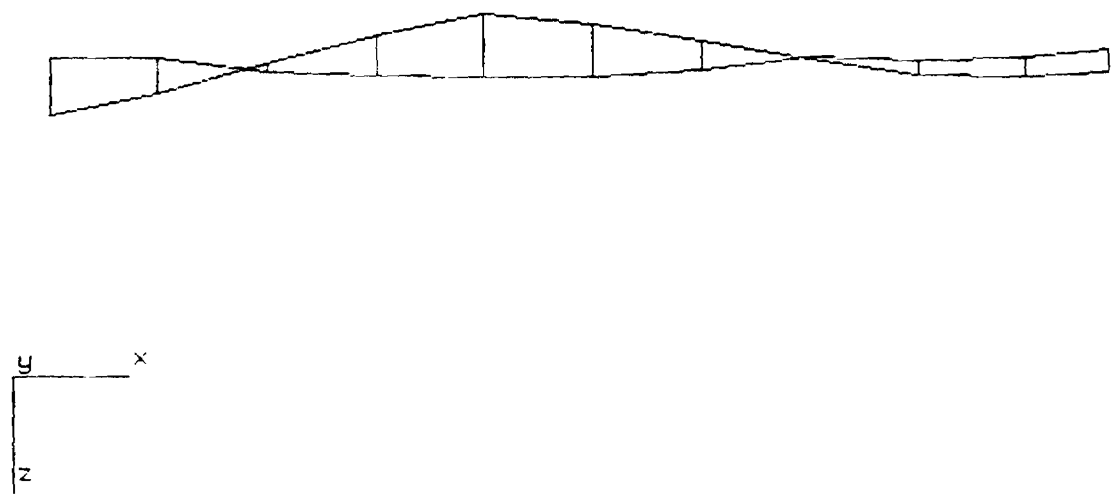
85.417 Hz



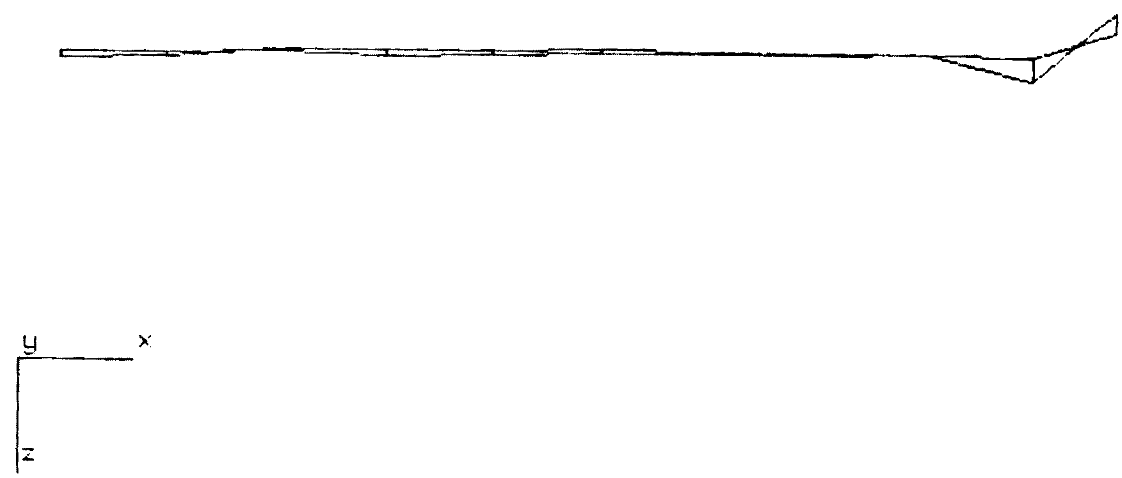
97.290 Hz



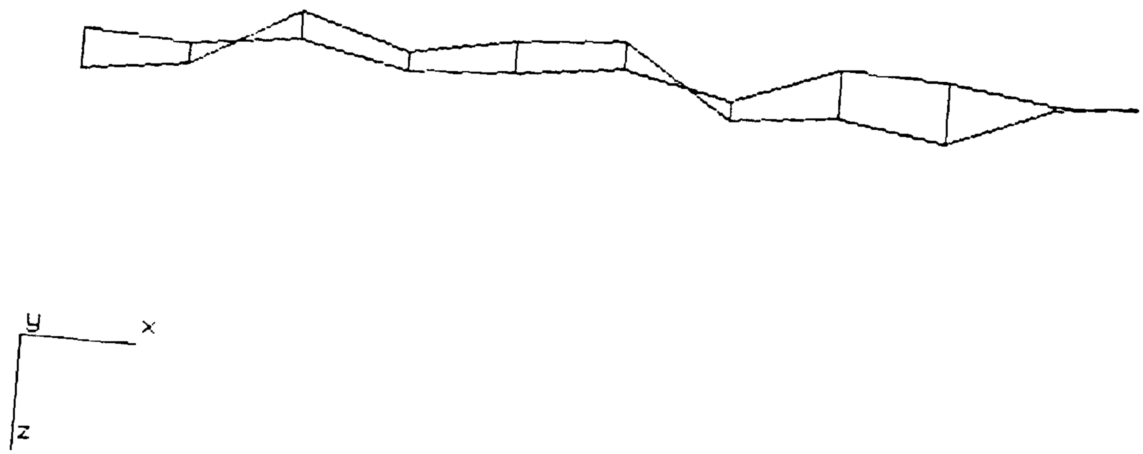
97.716 Hz



106.921 Hz



115.243 Hz



116.259 Hz

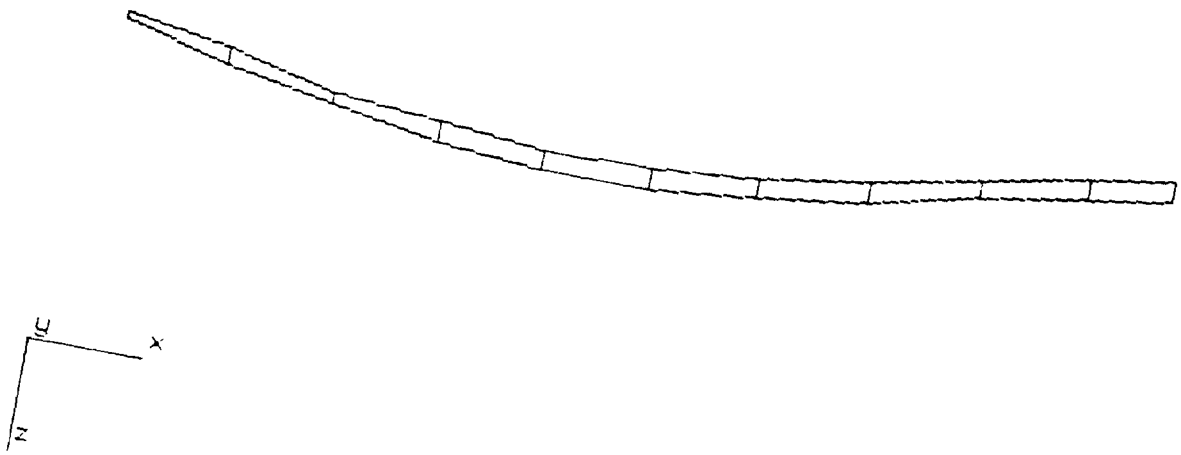
APPENDIX E

MODE SHAPE PLOTS

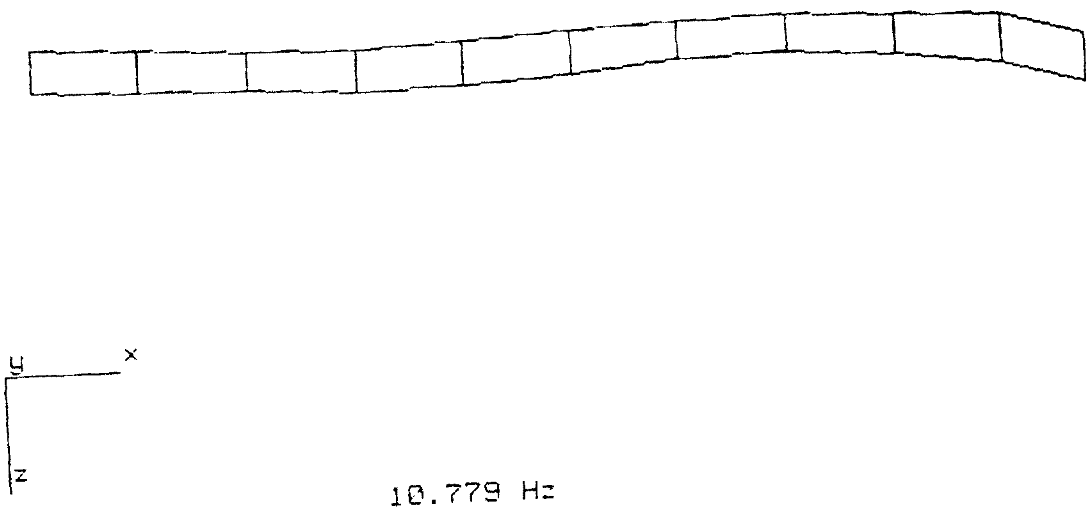
BLADE SN A007-03068

Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

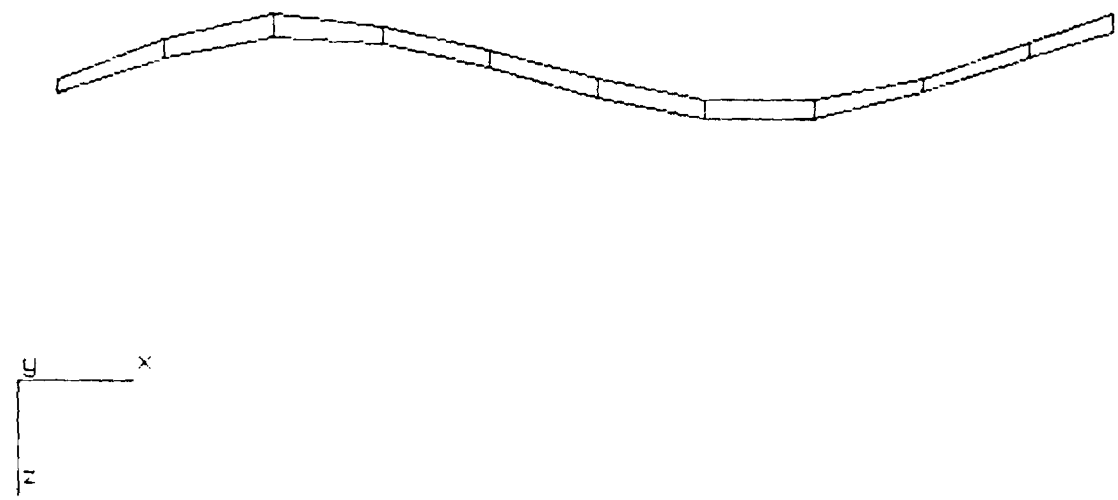
It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.



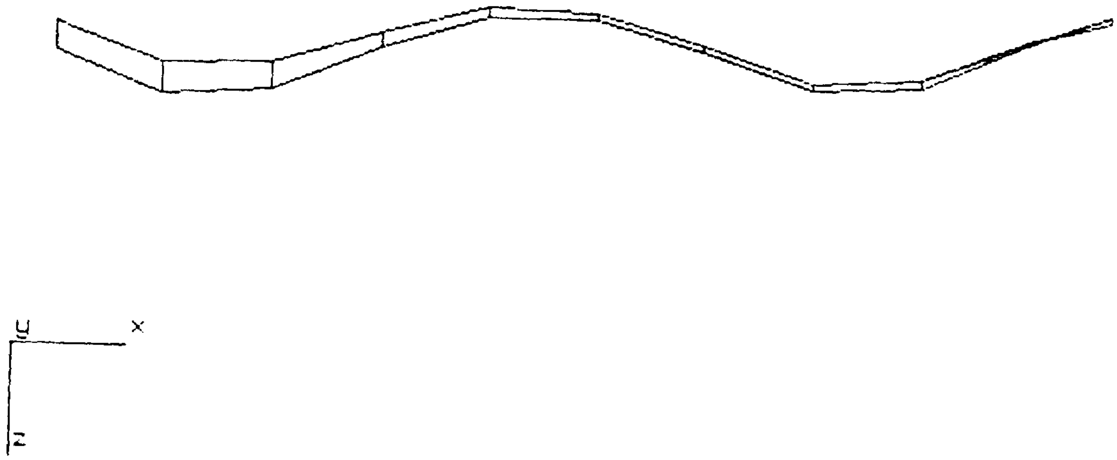
4.508 Hz



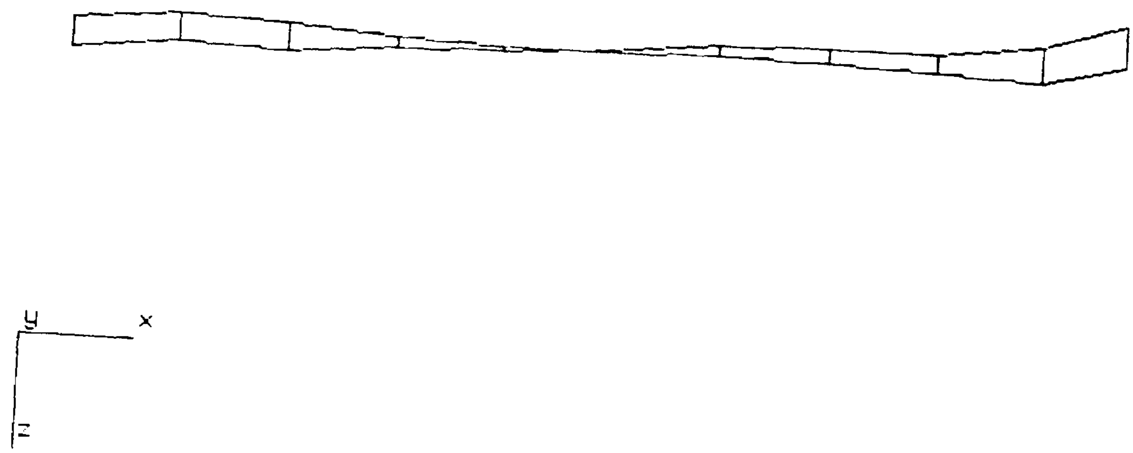
10.779 Hz



12.881 Hz

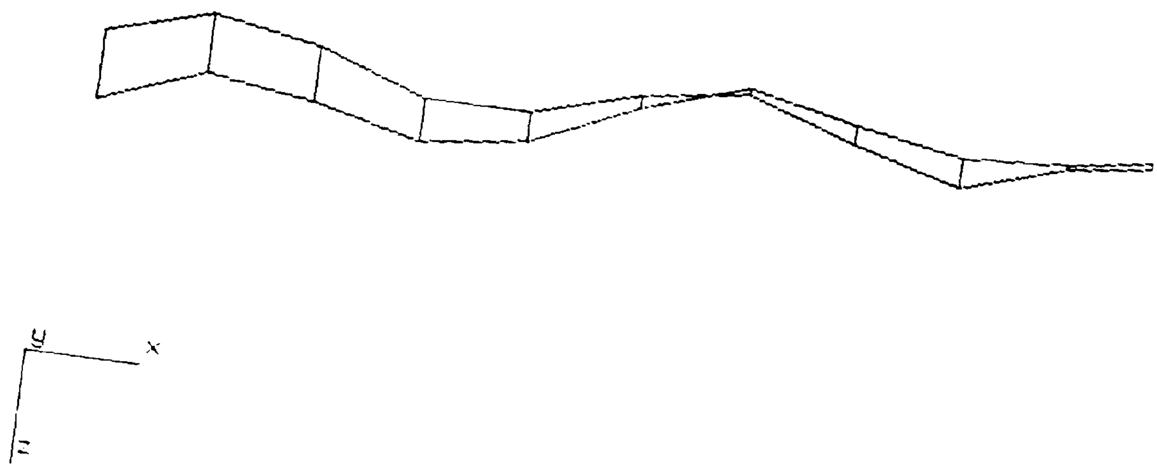


25.

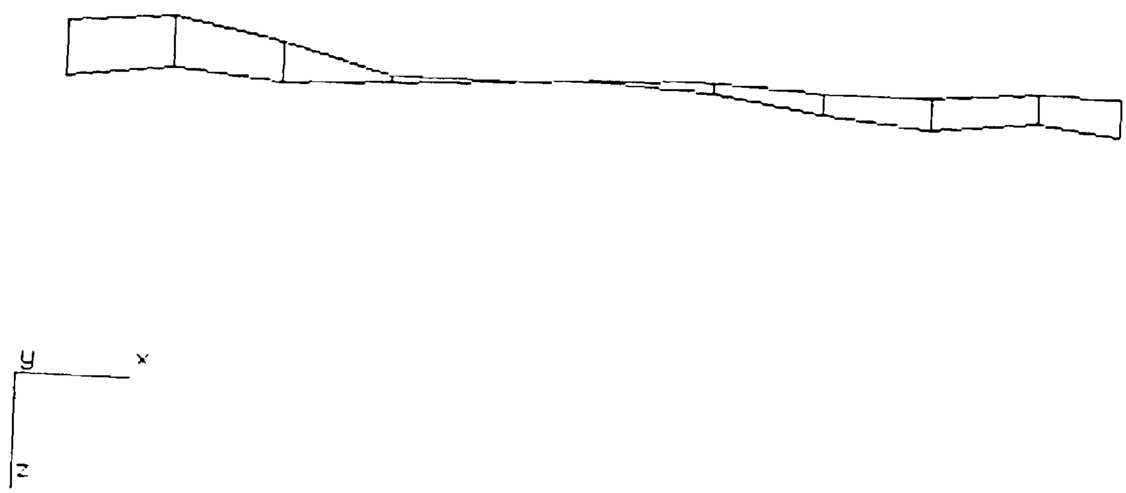


39.390 Hz

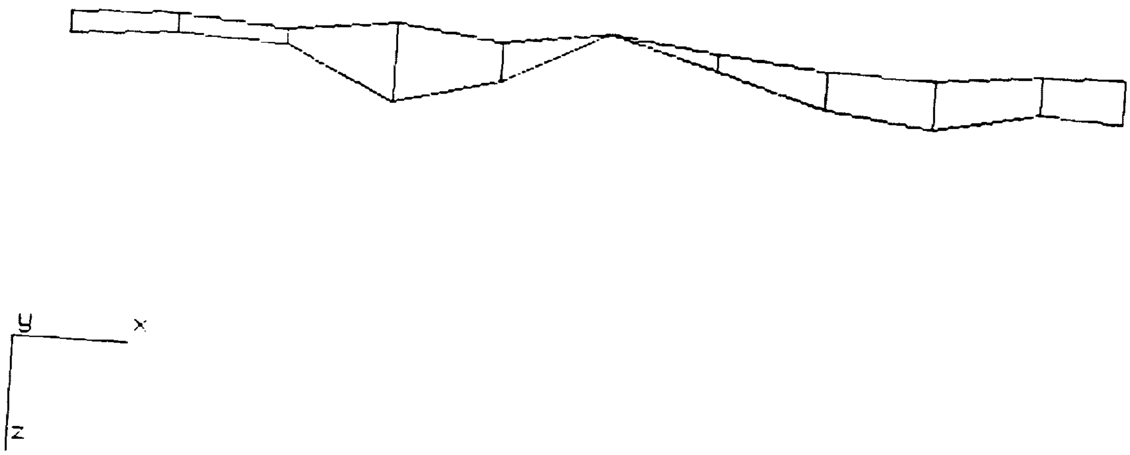
41.511 Hz



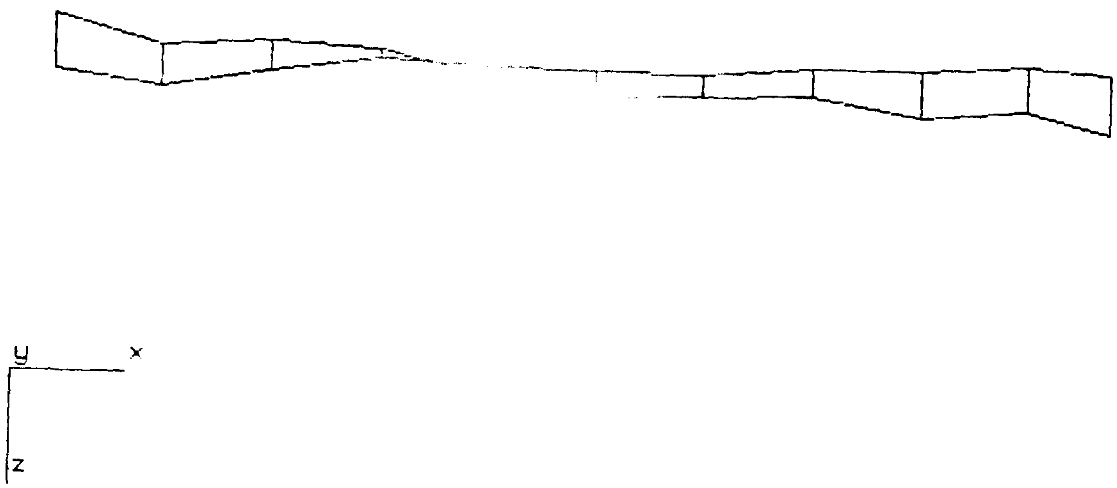
42.158 Hz



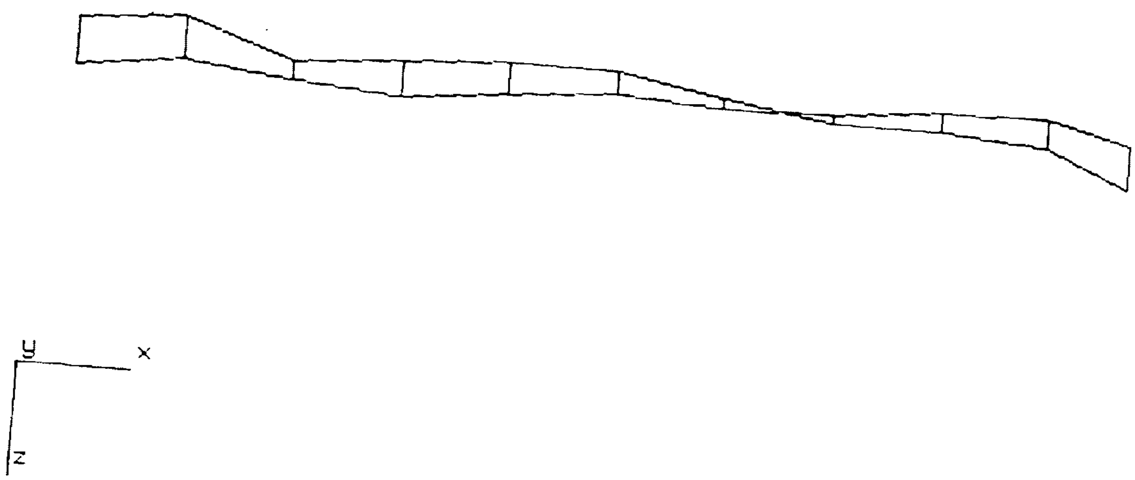
44.720 Hz



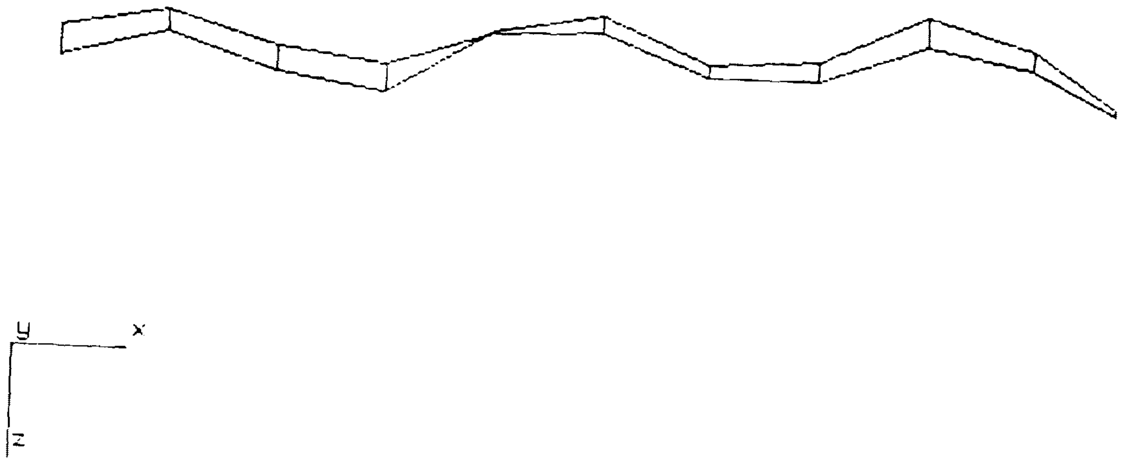
45.790 Hz



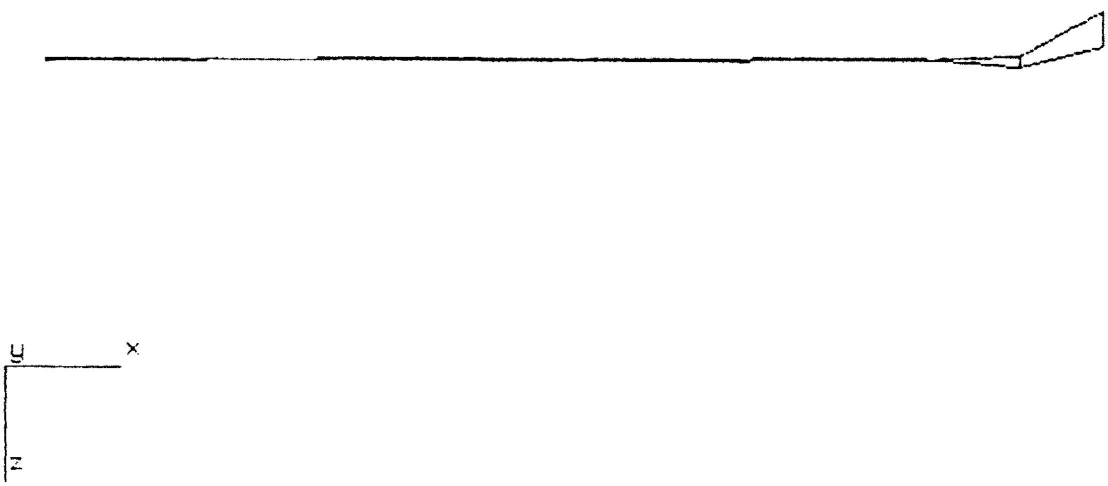
53.194 Hz



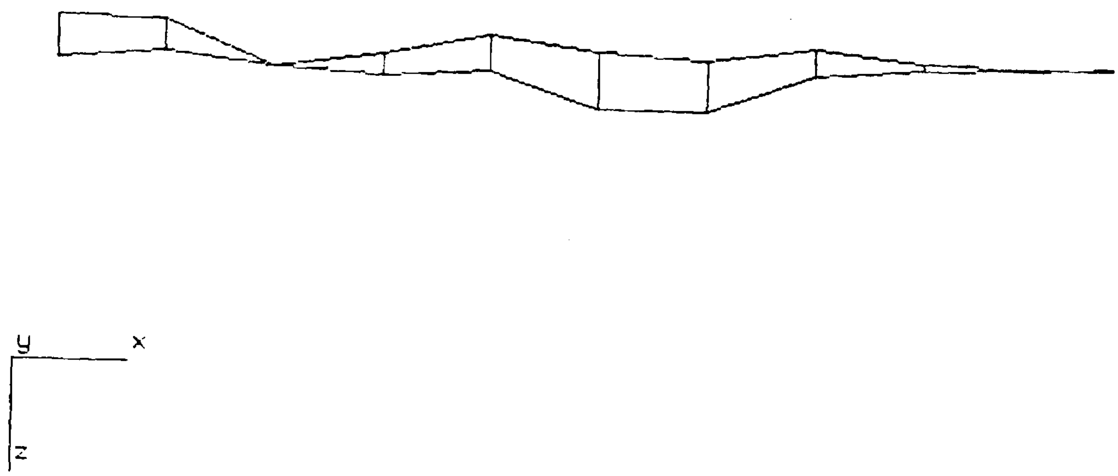
57.759 Hz



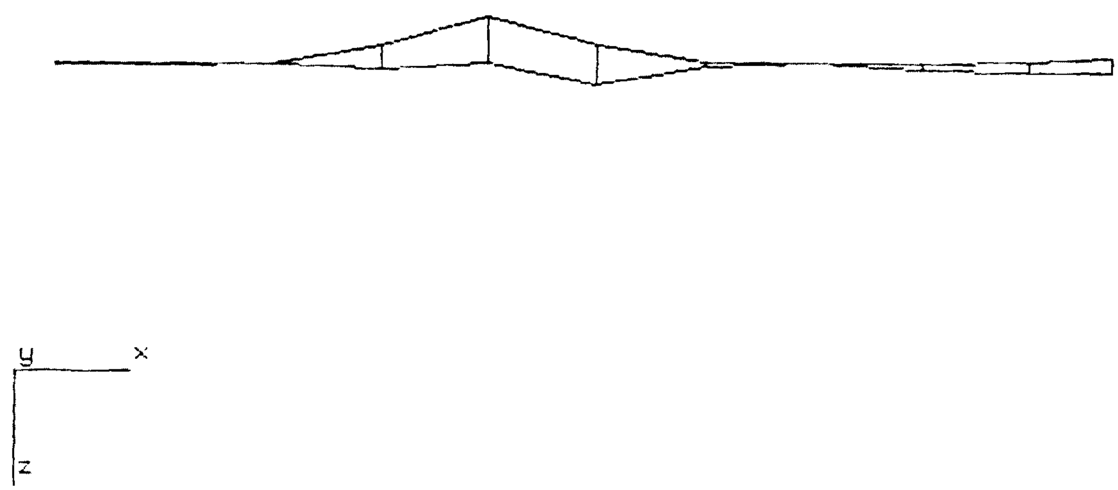
64.446 Hz



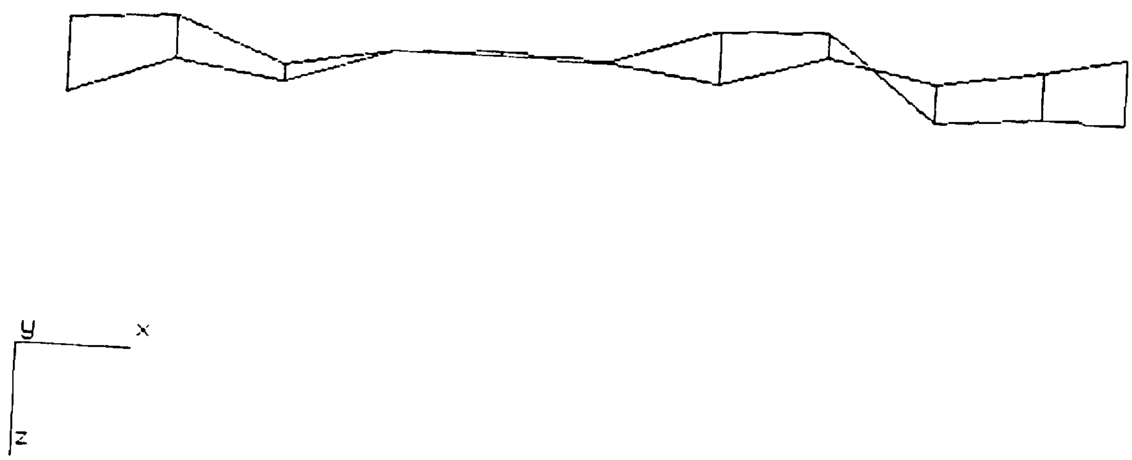
82.375 Hz



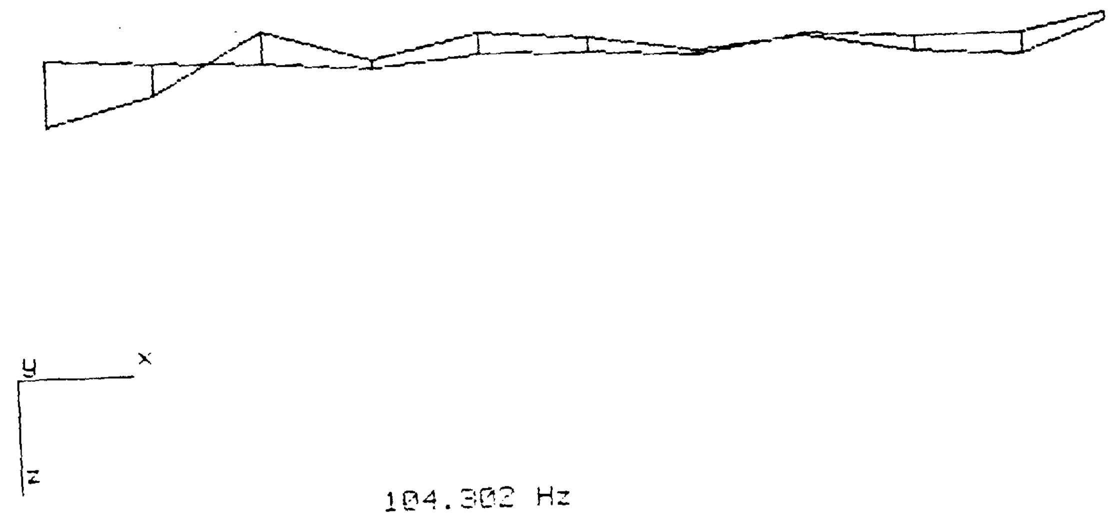
83.136 Hz

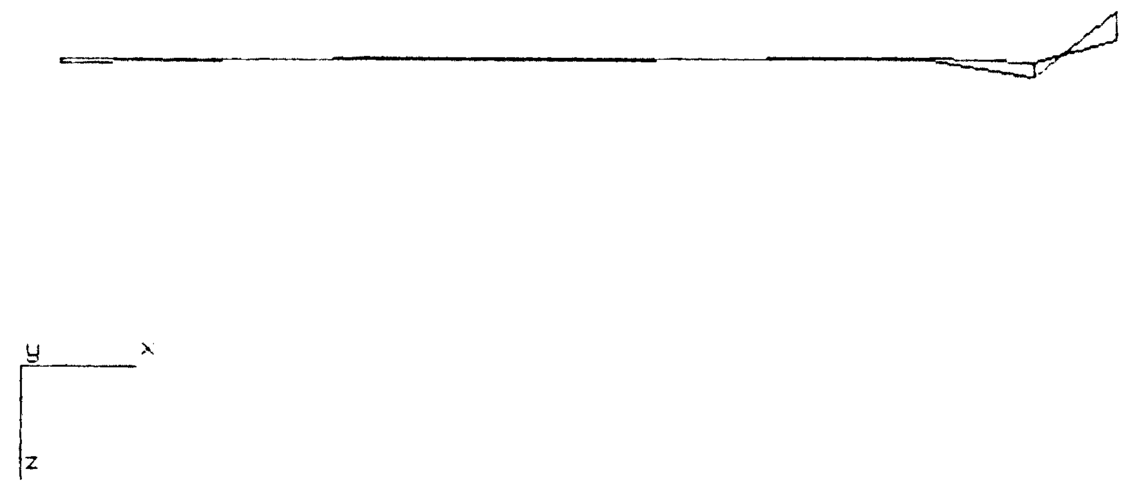


93.936 Hz

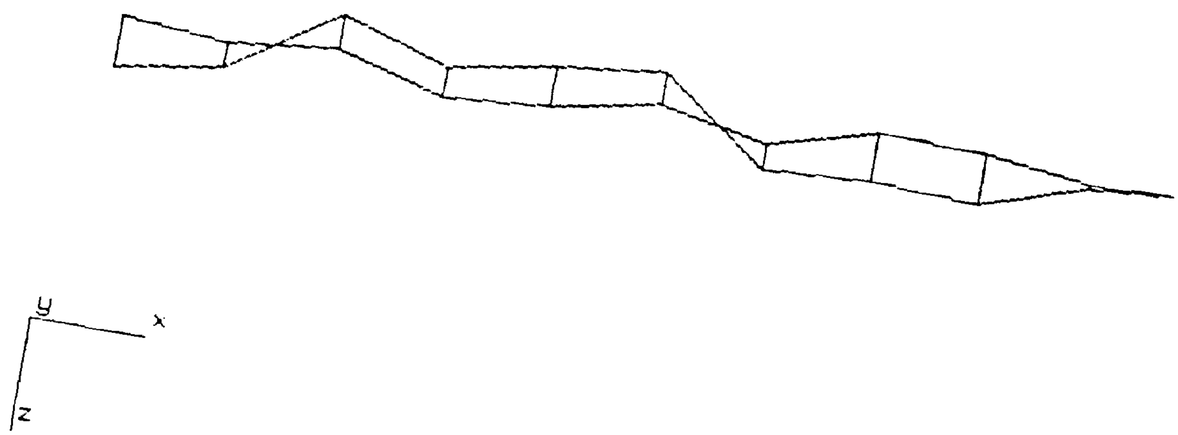


94.431 Hz


y
x
z
104.302 Hz



111.449 Hz



112.365 Hz

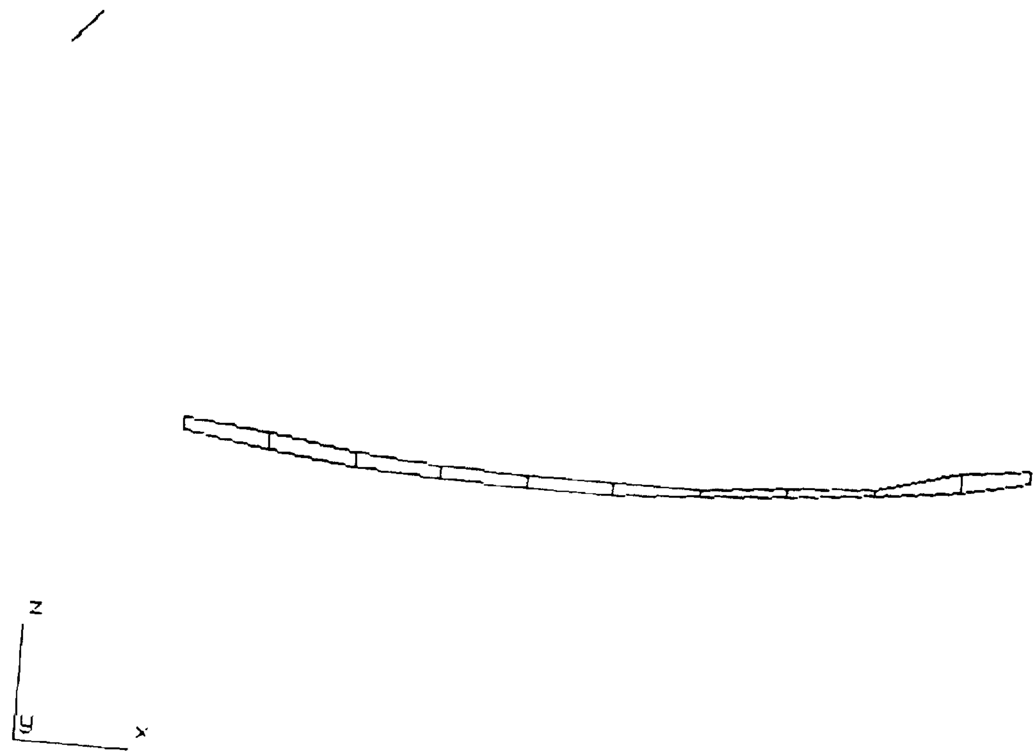
APPENDIX F

MODE SHAPE PLOTS

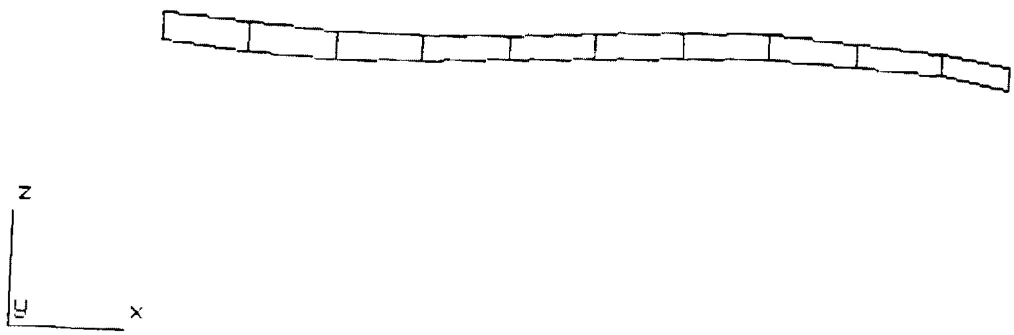
BLADE SN A007-02773

Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

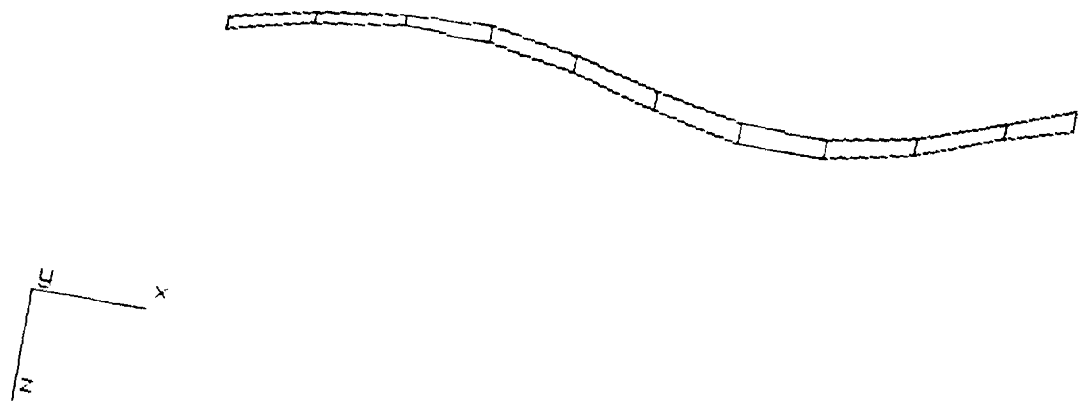
It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.



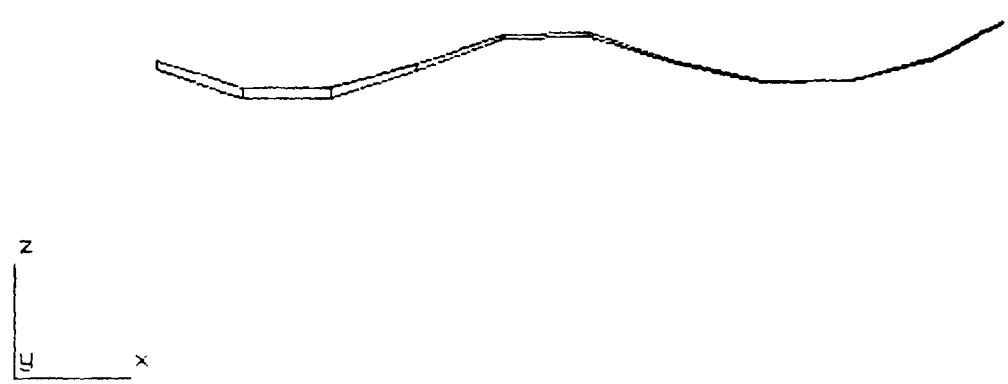
4.473 Hz



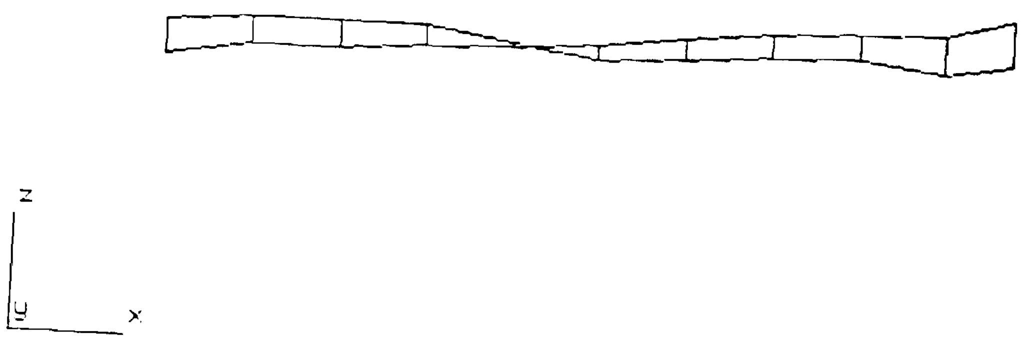
10.844 Hz



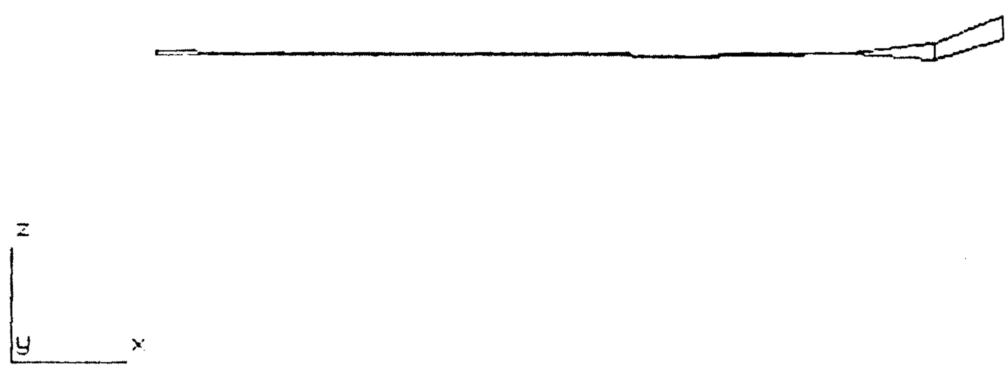
13.072 Hz



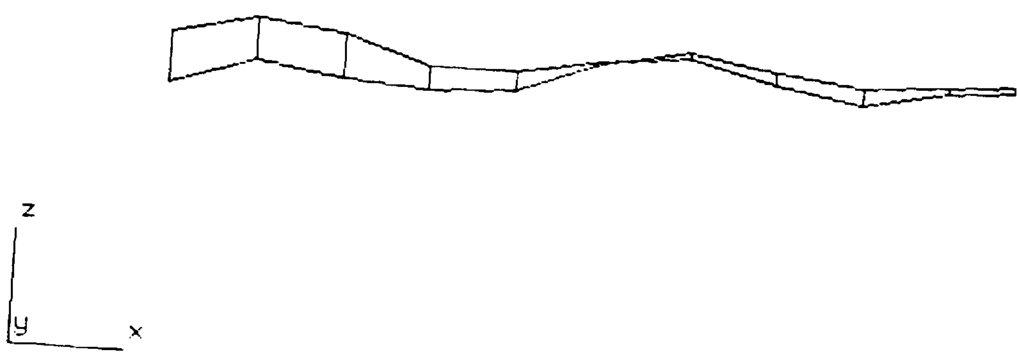
25.863 Hz



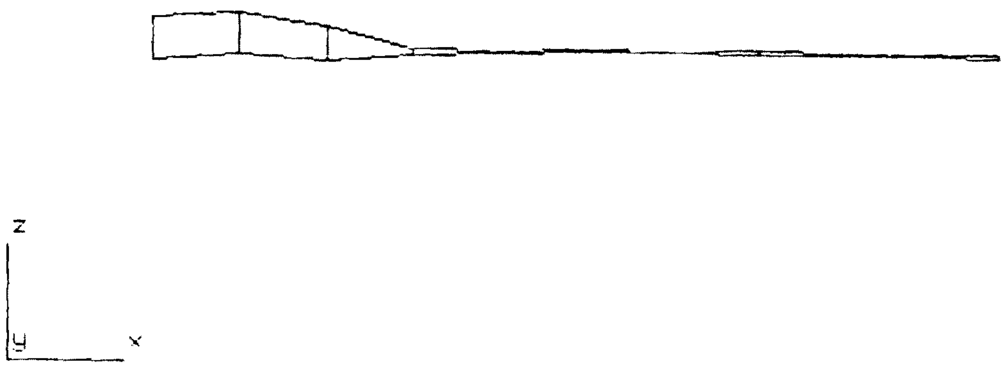
36.524 Hz



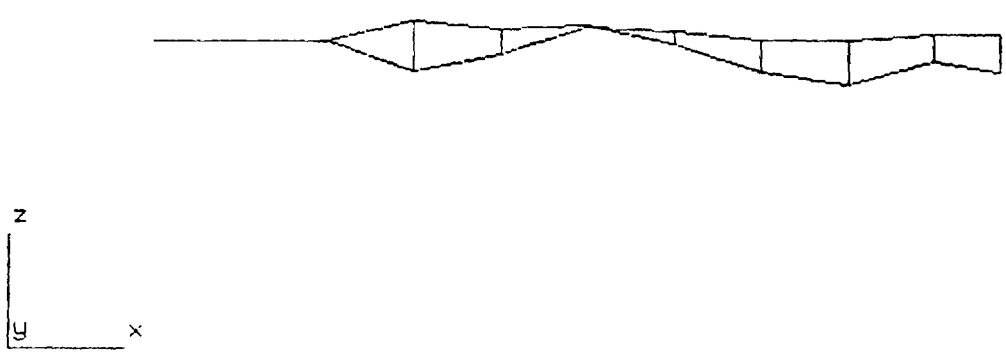
42.373 Hz



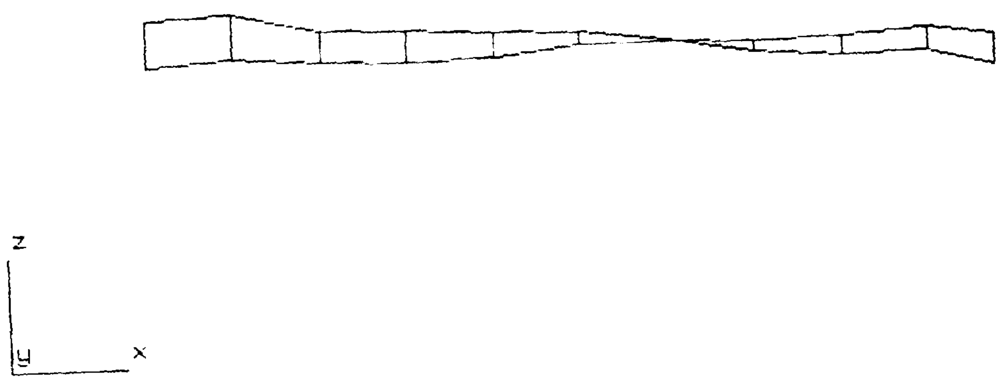
42.665 Hz



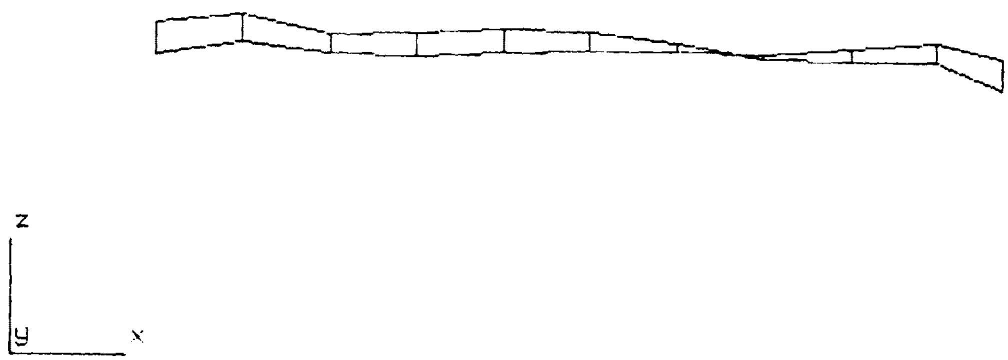
45.695 Hz



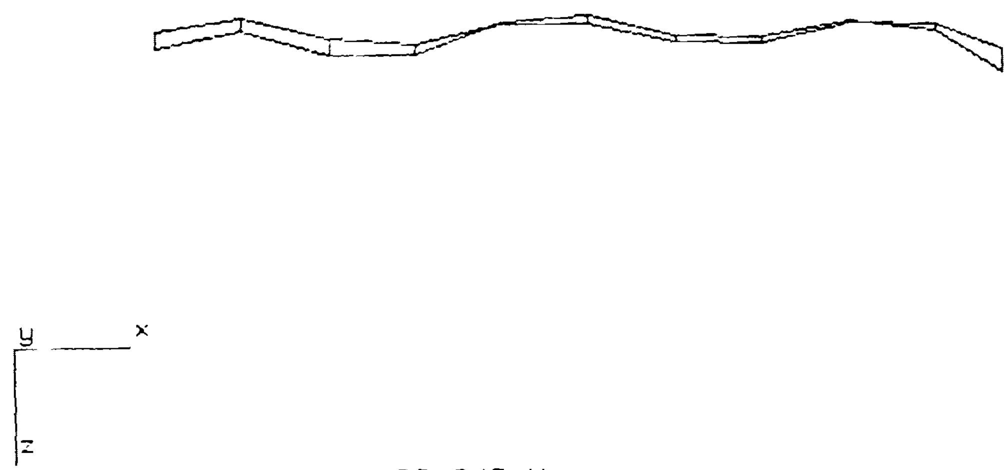
46.009 Hz



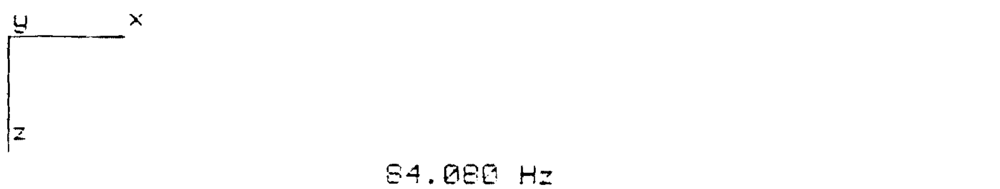
52.451 Hz

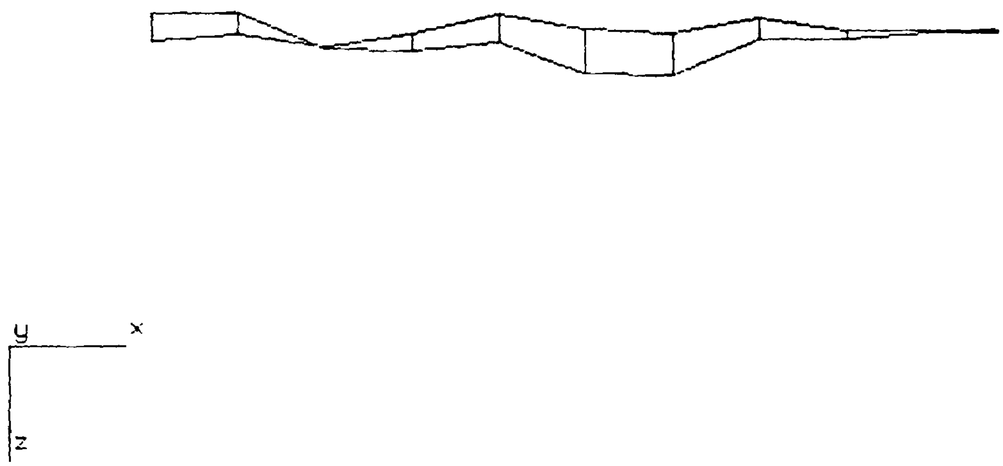


57.430 Hz

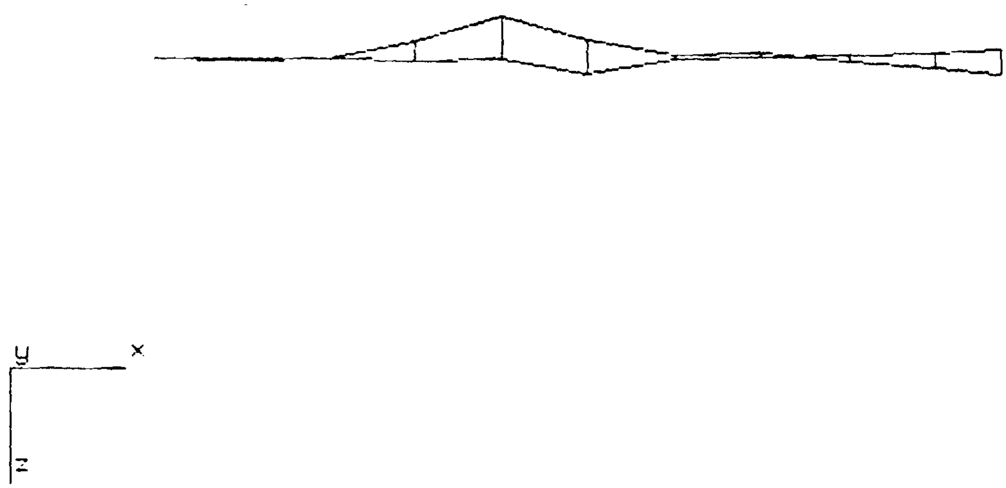


66.248 Hz

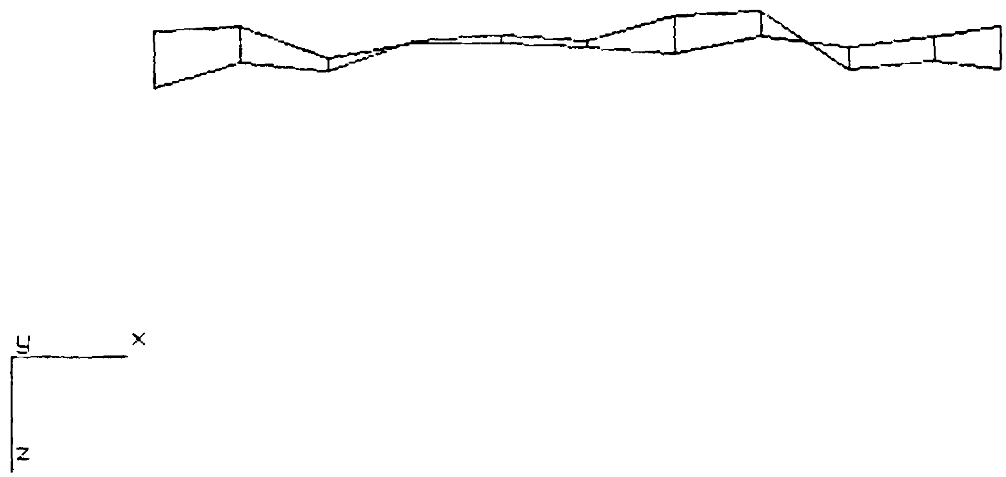

y
x
z
64.080 Hz



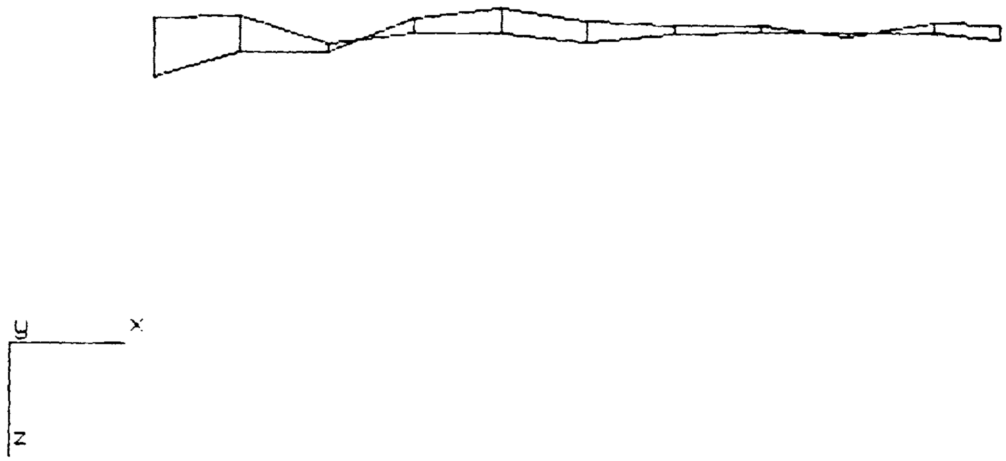
84.799 Hz



96.057 Hz



96.754 Hz



98.434 Hz

113.794 Hz

114.559 Hz

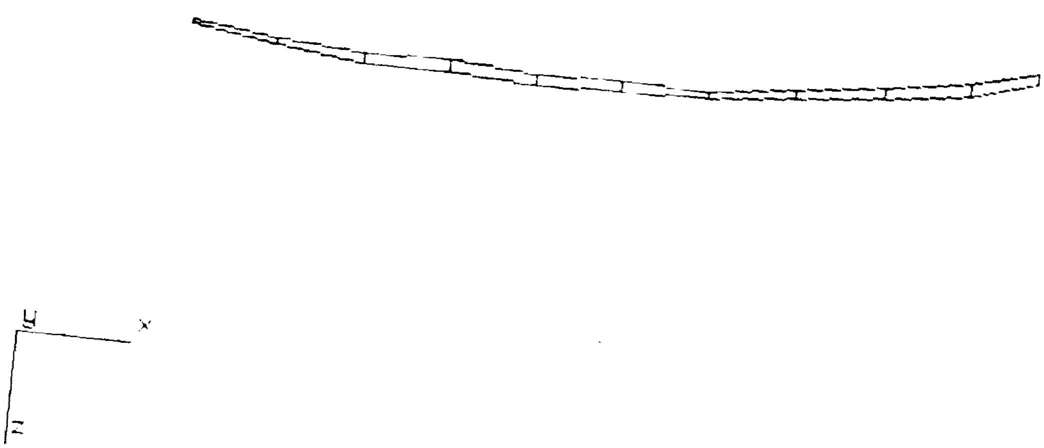
APPENDIX G

MODE SHAPE PLOTS

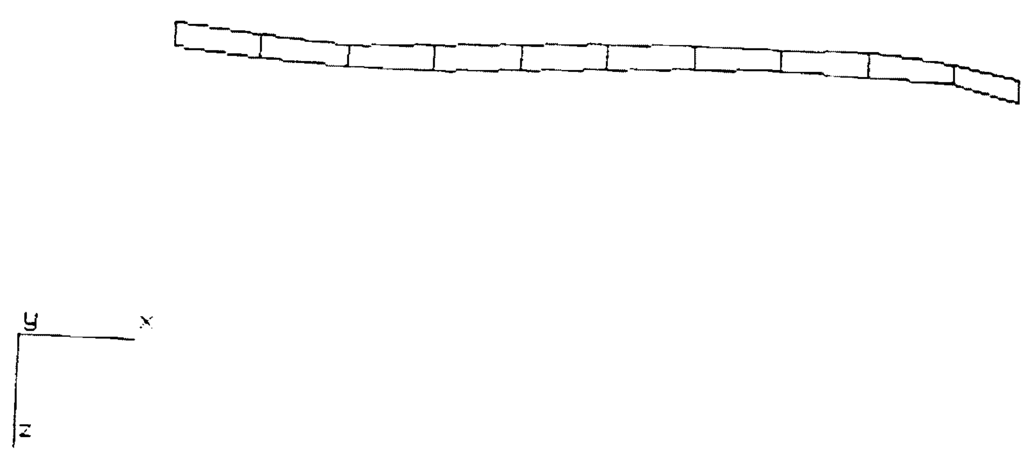
BLADE SN A007-00680

Following pages show mode shape deflection patterns at each natural frequency as determined by the Modal-Plus software package. All plots show an edgewise view of the blade with the hub at the left side and the tip at the right as indicated by the provided coordinate system (see Figure 2 for coordinate system orientation). The plots show the animated mode shapes frozen at maximum deflection.

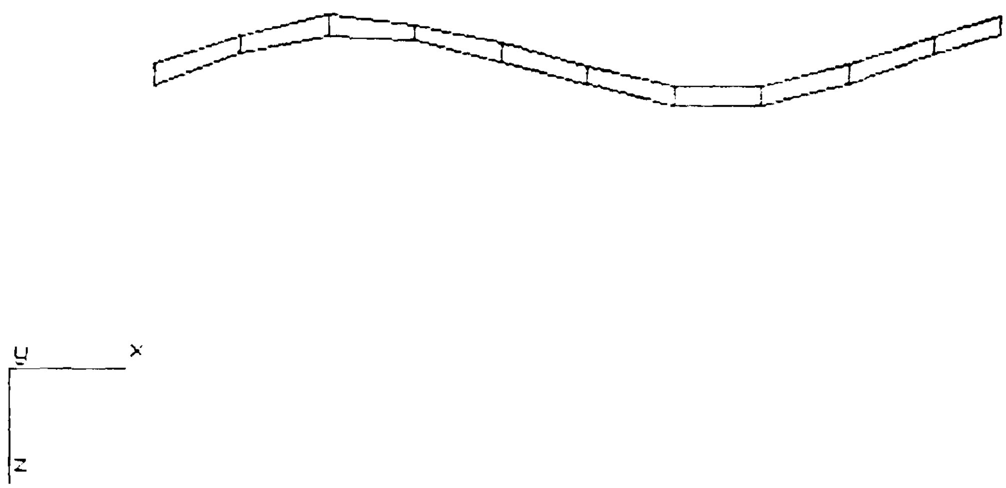
It is important to point out that each of the provided mode shapes is normalized to a maximum deflection amplitude of unity. Therefore, no amplitude comparison can be drawn between different modes.



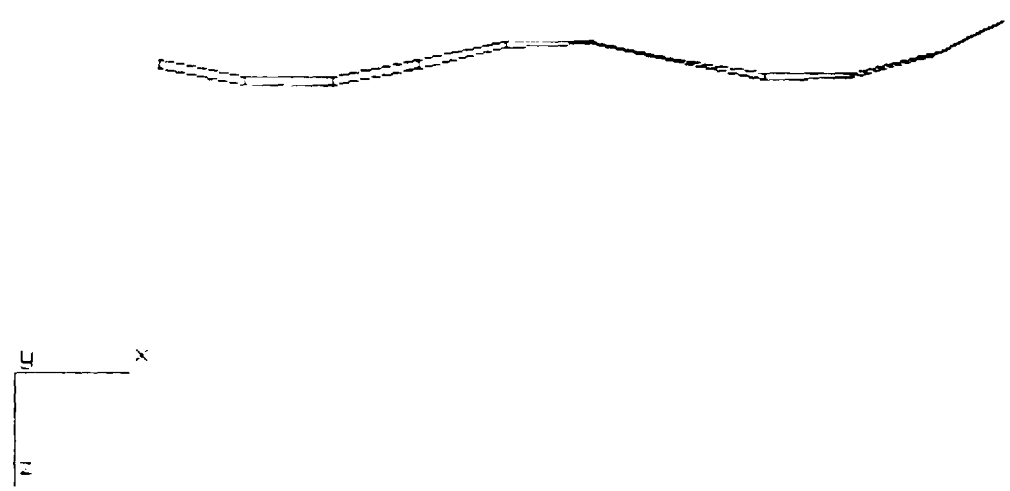
4.393 Hz



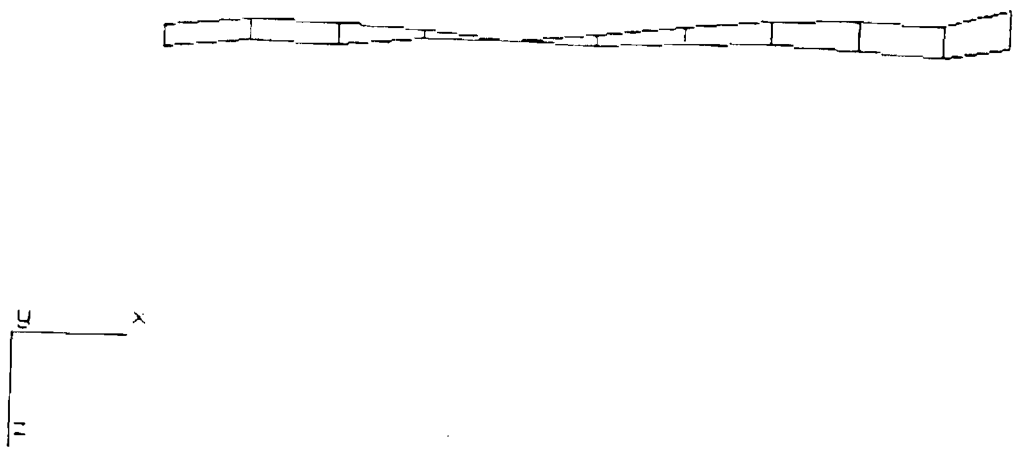
11.858 Hz



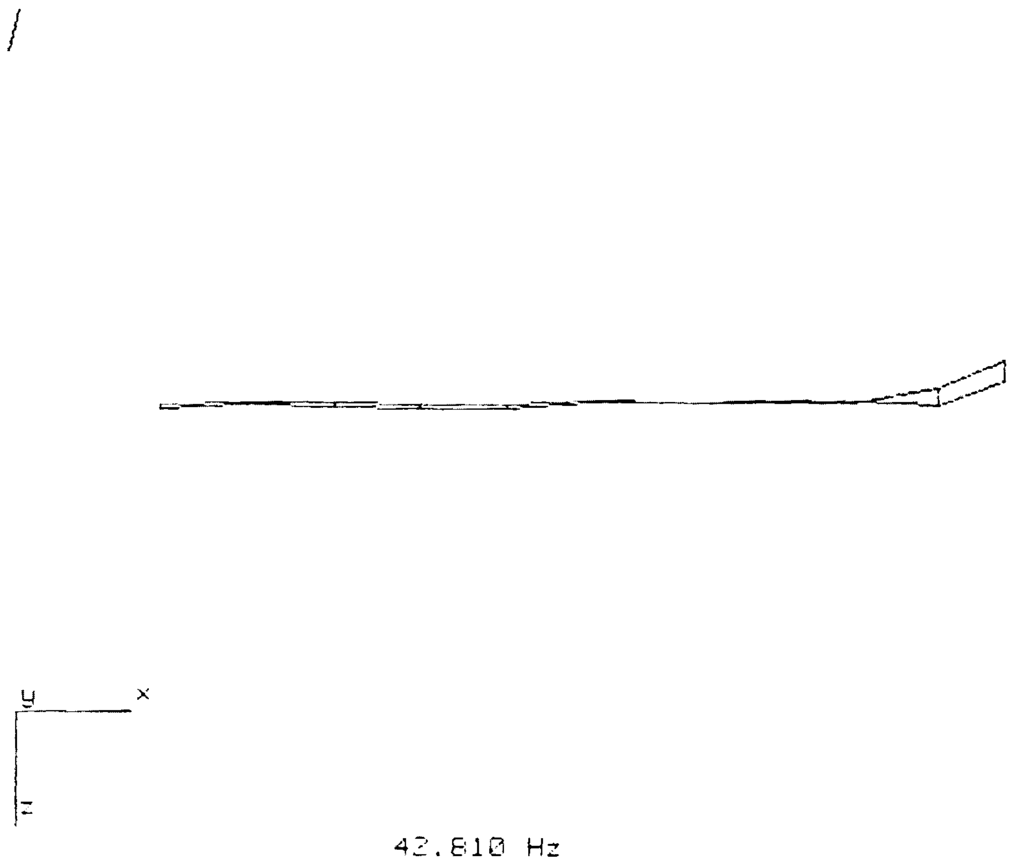
13.282 Hz

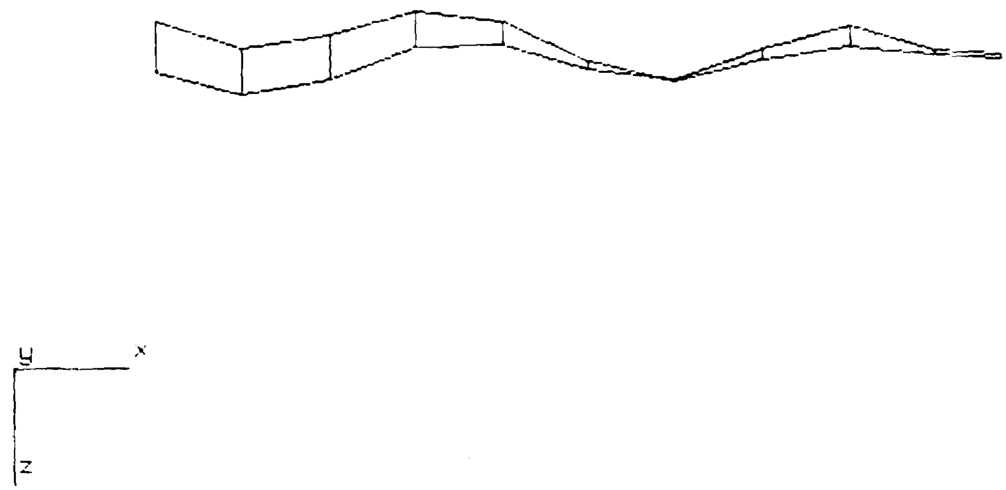


26.250 Hz

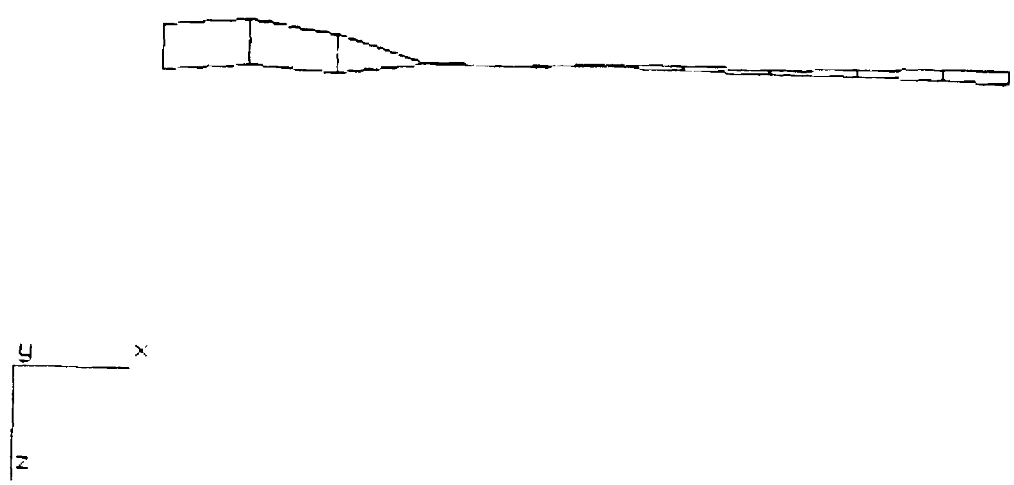


37.947 Hz

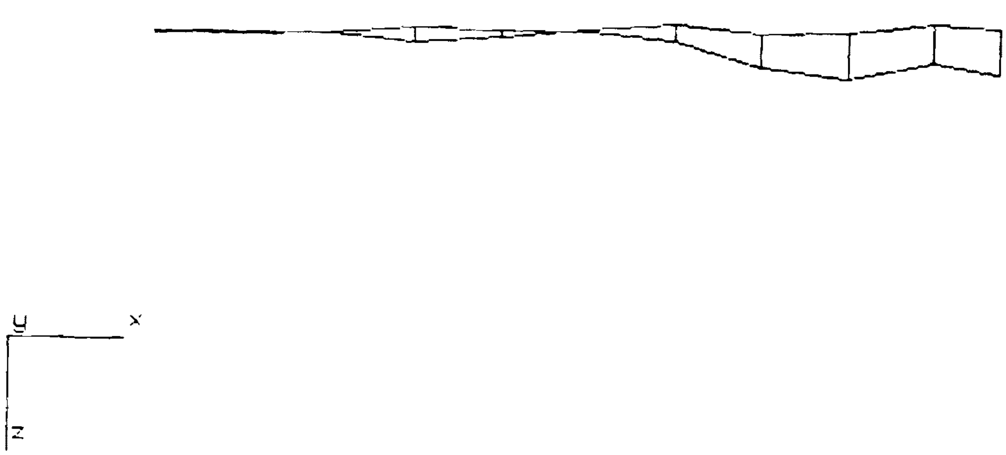

y
x
z
42.810 Hz



43.131 Hz

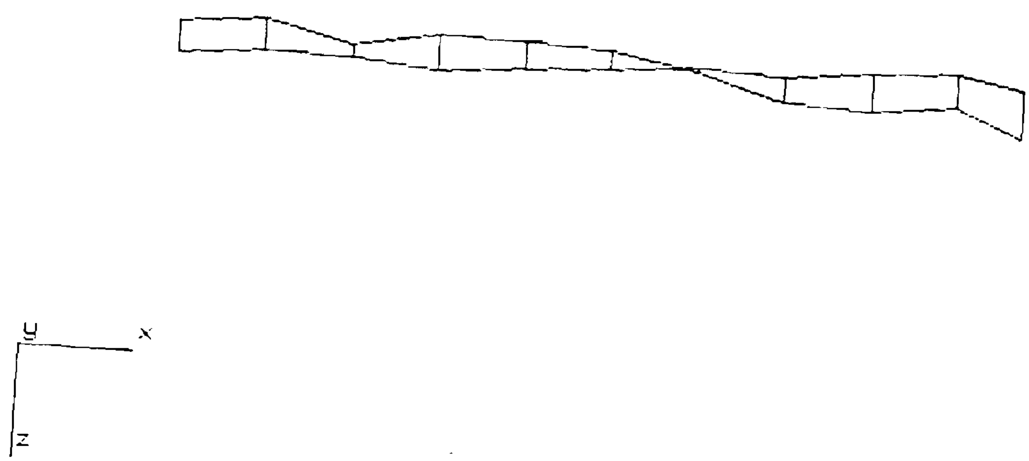


46.729 Hz

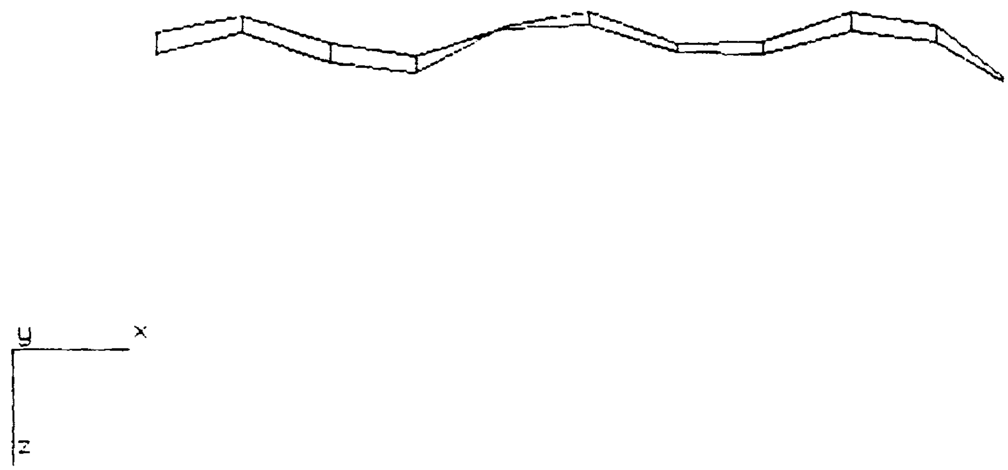


47.108 Hz

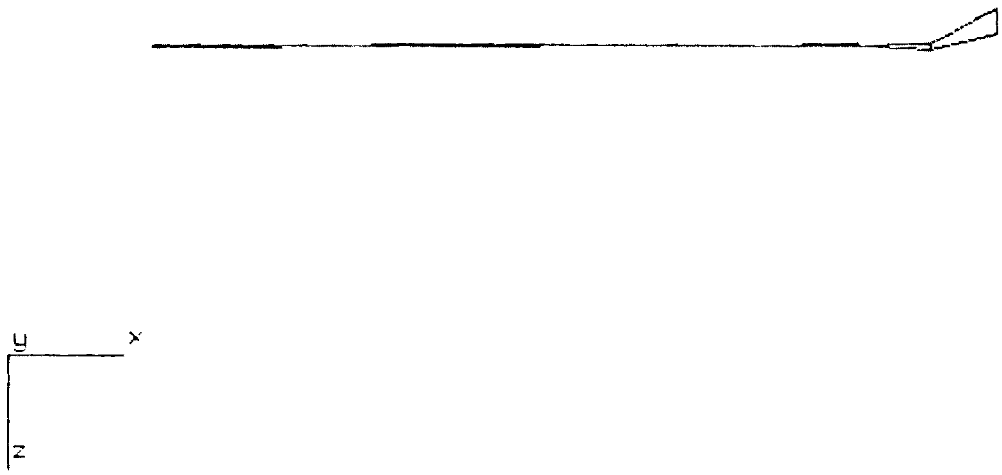
53.862 Hz



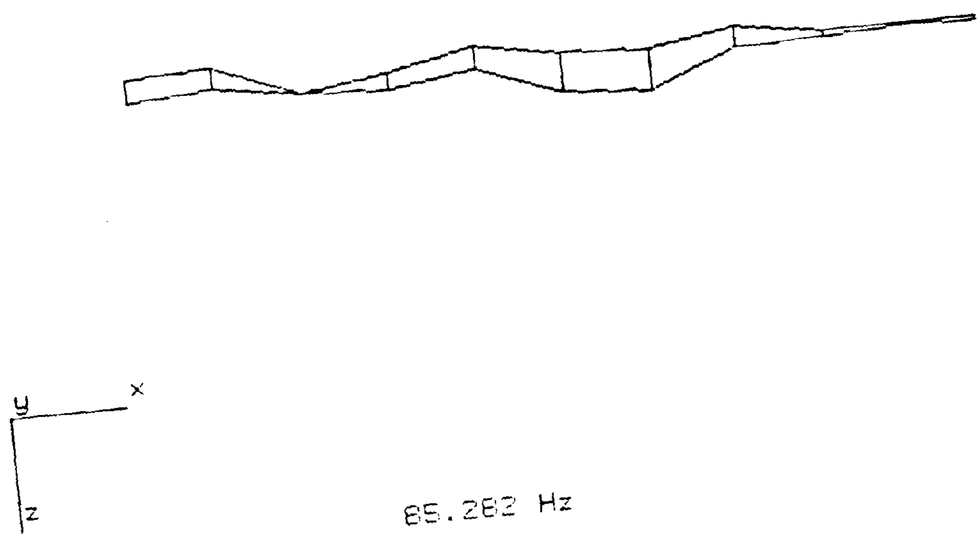
54.779 Hz

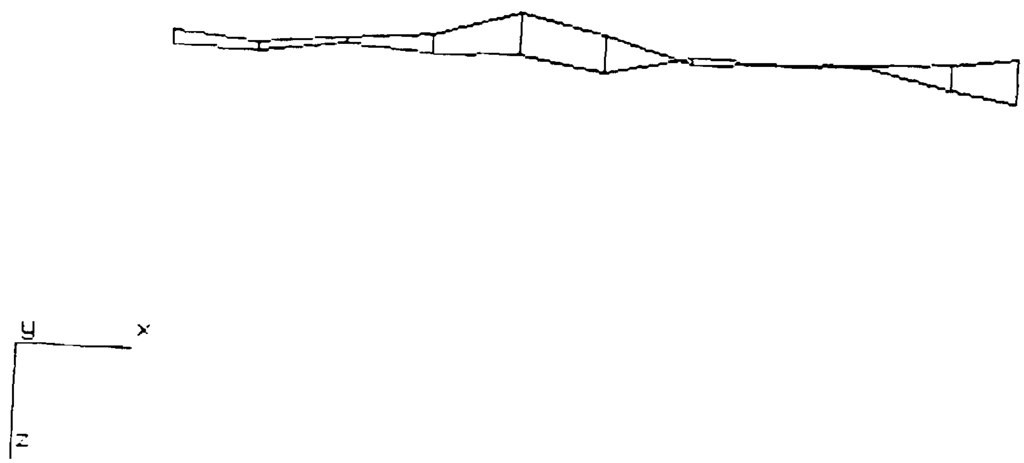


65.517 Hz

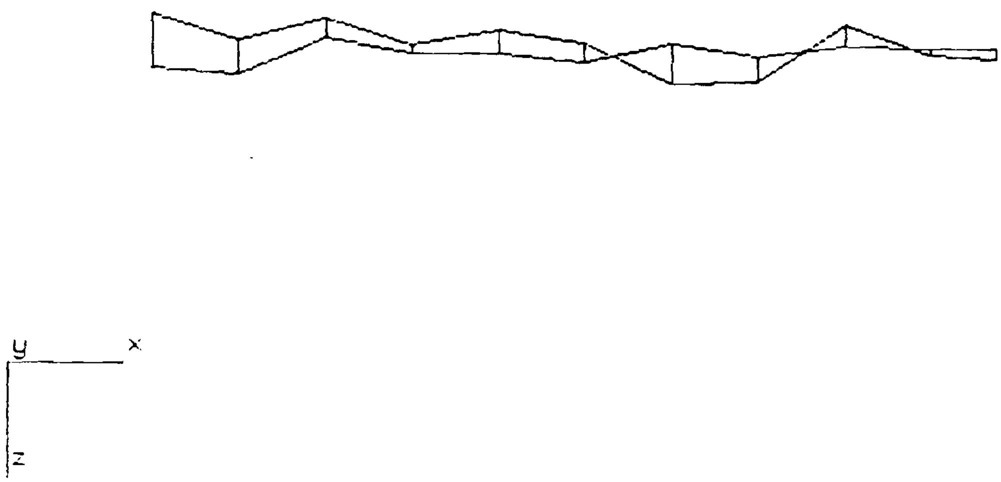


84.541 Hz

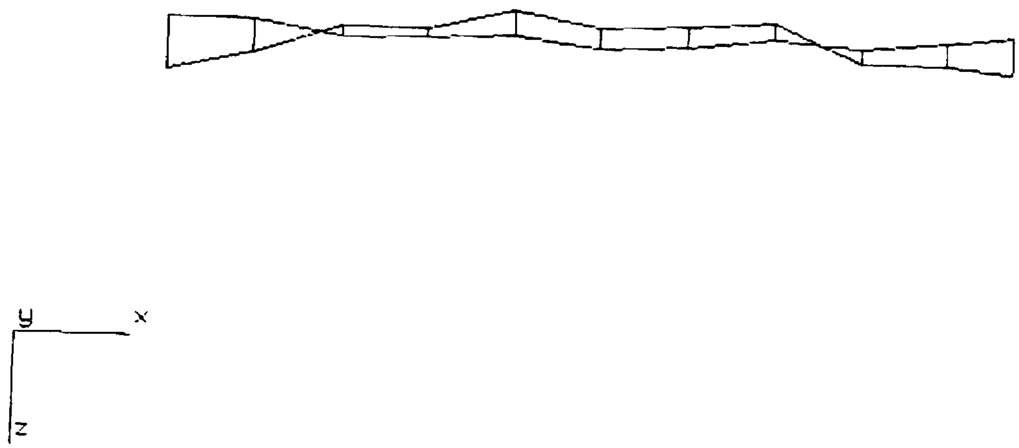

y
x
z
85.282 Hz



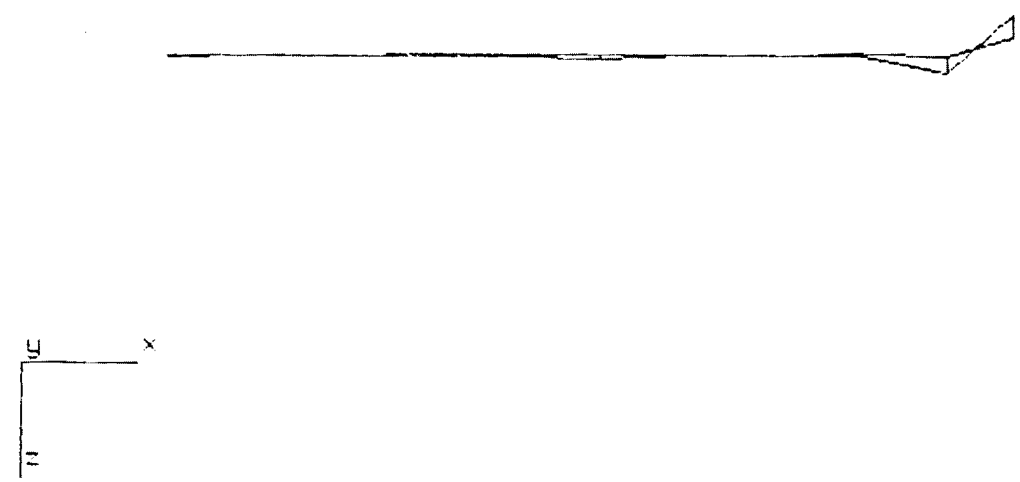
97.989 Hz



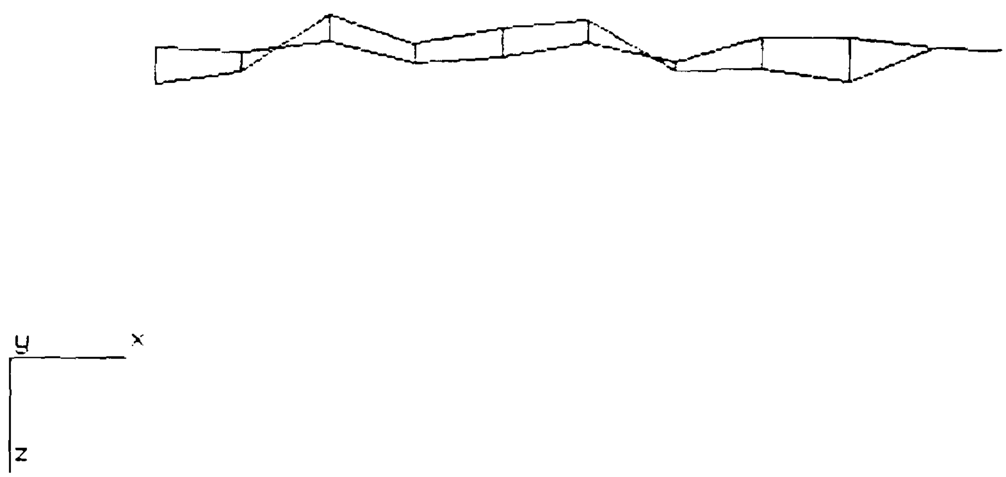
96.253 Hz



101.338 Hz



115.182 Hz



116.151 Hz

APPENDIX H

TEST EQUIPMENT LIST

and

ACCELEROMETER CALIBRATION CERTIFICATES

EQUIPMENT	MANUFACTURER	MODEL	SERIAL NUMBER
FAST FOURIER ANALYZER	GENRAD	2515	2932-1074
POWER SUPPLY	PCB	483 B 07	157
PRINTER	HP	2932A	2450 A 14124
SHAKER	MB DYNAMICS	50	14353
ACCELEROMETER	PCB	308 B 14	24840
ACCELEROMETER	PCB	308 B 14	24931
ACCELEROMETER	PCB	308 B 14	24932
ACCELEROMETER	PCB	308 B 14	24933
ACCELEROMETER	PCB	308 B 14	25027
ACCELEROMETER	PCB	308 B 14	25028
LOAD CELL	PCB	208 A 02	4417

TEST EQUIPMENT LIST

ICP CALIBRATION DATA

PCB

Model 208A02

S/N 4417

Cal Range 0-100 lbs

Sens* 51.5 mV/ lb.

Linearity* <1.0 %FS

* By comparison with reference standard per ISA S37.10. Zero Based best straight line.

Input TC 500 sec

Rise Time 10 µ sec

Nat'l Freq 70 kHz

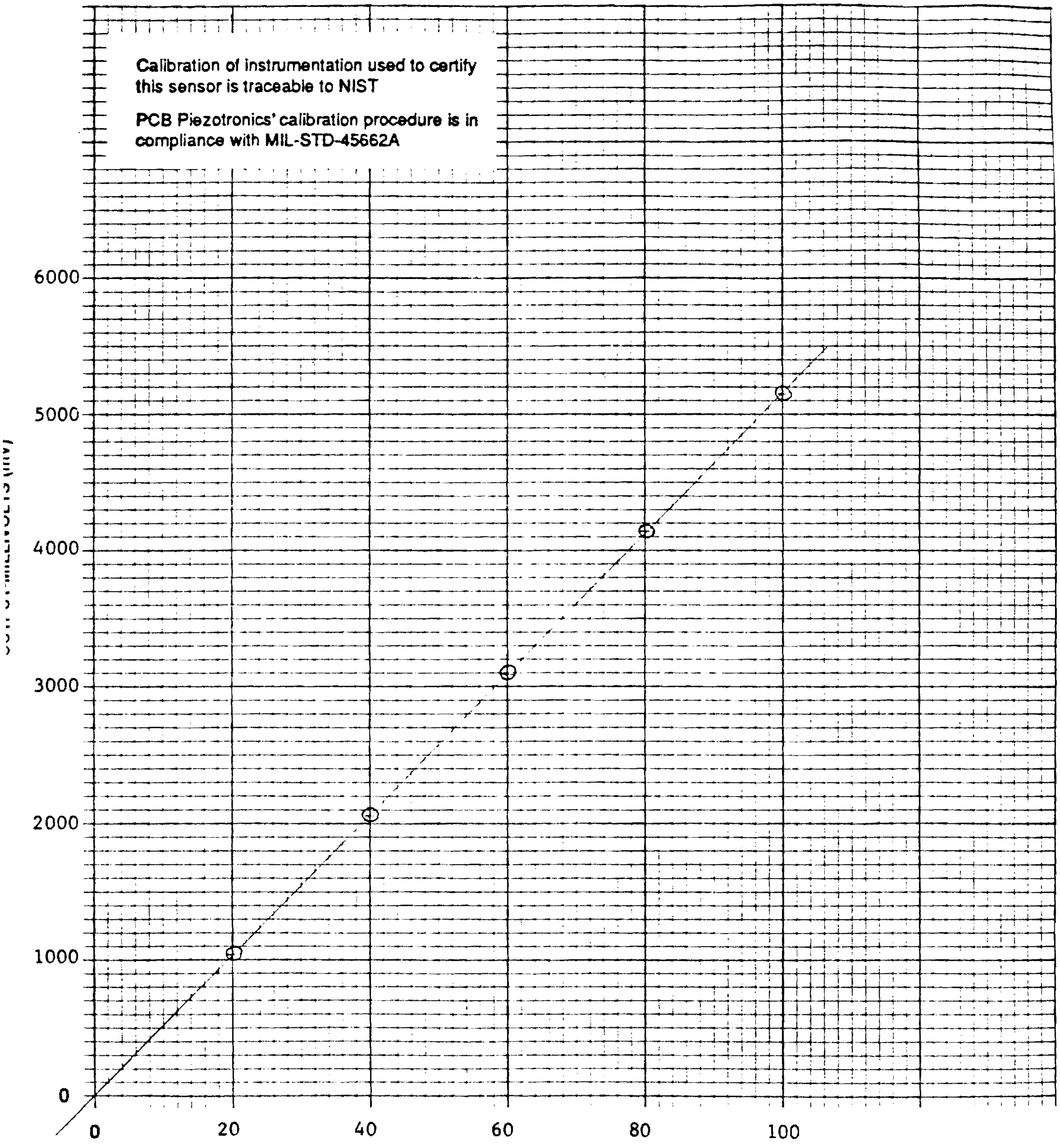
Output Imp <100 ohms

By P. Linehan

Date 10/11/91

Calibration of instrumentation used to certify this sensor is traceable to NIST

PCB Piezotronics' calibration procedure is in compliance with MIL-STD-45662A



INPUT lbs.

ICP-CD787

PCB PIEZOTRONICS, INC.
3425 Walden Avenue, Depew NY 14043
Tel 716-684 0001 TWX 710-263 1371

Customer ____________

PO Number ____________

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 24840

PO No. ______ **Customer** ______

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.6	mV/g
Transverse Sensitivity	0.8	%
Resonant Frequency	35	kHz
Time Constant	0.8	s
Output Bias Level	11.8	V

KEY SPECIFICATIONS

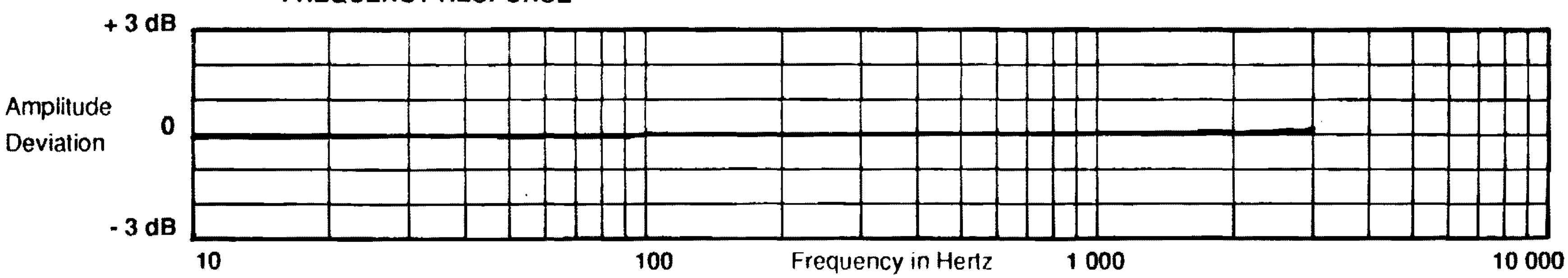
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms^{-2} = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	-.9	-1.0	-.3	-.8	0.0	0.0	.2	.4	1.9			

FREQUENCY RESPONSE



Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2495 USA
716-684-0001

Date 10/11/91

Calibrated by ______

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 24931

PO No. ______ Customer ______

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.2	mV/g
Transverse Sensitivity	2.6	%
Resonant Frequency	33.5	kHz
Time Constant	0.7	s
Output Bias Level	11.5	V

KEY SPECIFICATIONS

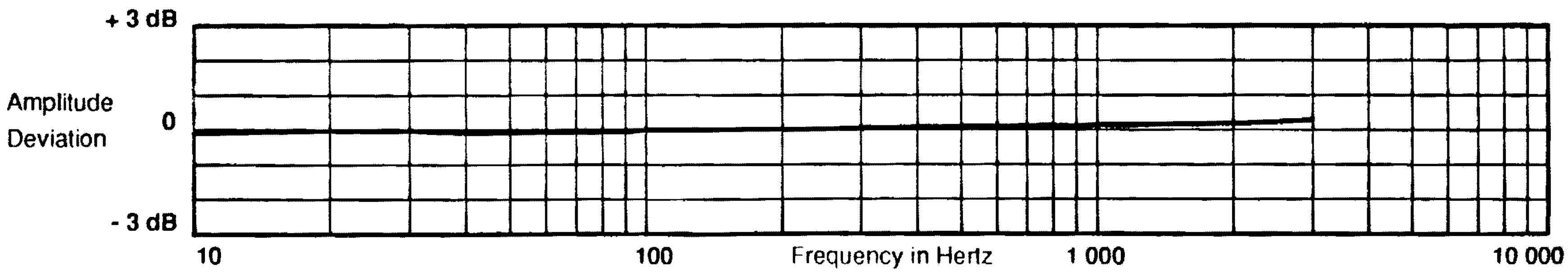
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms^{-2} = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	-.9	-.2	-.4	-.9	0.0	.8	1.2	1.7	3.6			

FREQUENCY RESPONSE



PCB® Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2495 USA
716-684-0001

Date 10/11/91

Calibrated by ______

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 24932

PO No. ______________ Customer ______________________

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.2	mV/g
Transverse Sensitivity	4.7	%
Resonant Frequency	34.5	kHz
Time Constant	0.6	s
Output Bias Level	11.4	V

KEY SPECIFICATIONS

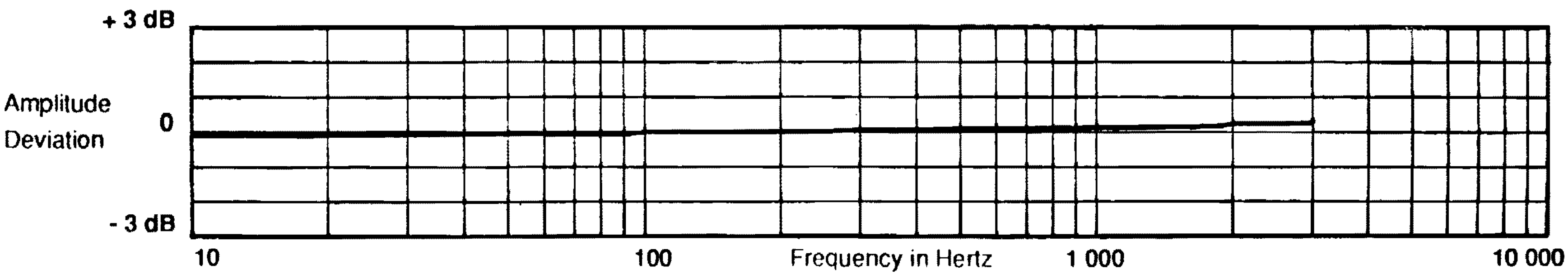
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms^{-2} = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	-1.1	-1.3	-.8	-.9	0.0	.8	1.2	1.7	3.5			

FREQUENCY RESPONSE



PCB Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2495 USA
716-684-0001

Date 10/11/91

Calibrated by ______

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 24933

PO No. ______ Customer ______

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.2	mV/g
Transverse Sensitivity	5.0	%
Resonant Frequency	33	kHz
Time Constant	0.8	s
Output Bias Level	11.3	V

KEY SPECIFICATIONS

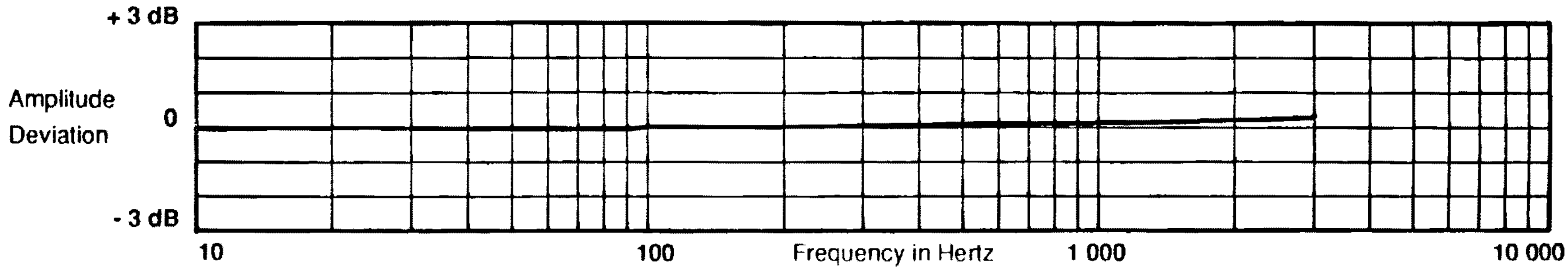
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms $^{-2}$ = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	-.6	-.2	-.5	-.8	0.0	.7	1.1	1.6	3.6			

FREQUENCY RESPONSE



Piezotronics, Inc. 3425 Walden Avenue Depew, NY 14043-2495 USA
716-684-0001

Date 10/11/91

Calibrated by ______

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 25027

PO No. ______ Customer ______

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.5	mV/g
Transverse Sensitivity	1.4	%
Resonant Frequency	34.5	kHz
Time Constant	0.8	s
Output Bias Level	11.8	V

KEY SPECIFICATIONS

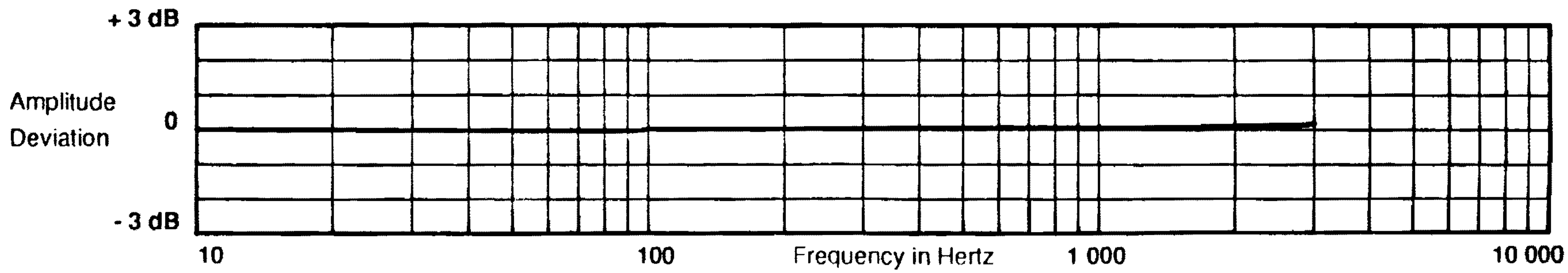
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms $^{-2}$ = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	-.1	0.0	-.5	-.7	0.0	.3	.4	.5	2.0			

FREQUENCY RESPONSE



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716-684-0001

Date 10/11/91

Calibrated by ______

Calibration Certificate

Per ISA-RP37.2

Model No. 308B14

Serial No. 25028

PO No. ______ Customer ______

Calibration traceable to NIST thru Project No. 732/245191-90

ICP® ACCELEROMETER
with built-in electronics

Calibration procedure is in compliance with MIL-STD-45662A and traceable to NIST.

CALIBRATION DATA

Voltage Sensitivity	100.8	mV/g
Transverse Sensitivity	4.0	%
Resonant Frequency	37	kHz
Time Constant	0.6	s
Output Bias Level	11.8	V

KEY SPECIFICATIONS

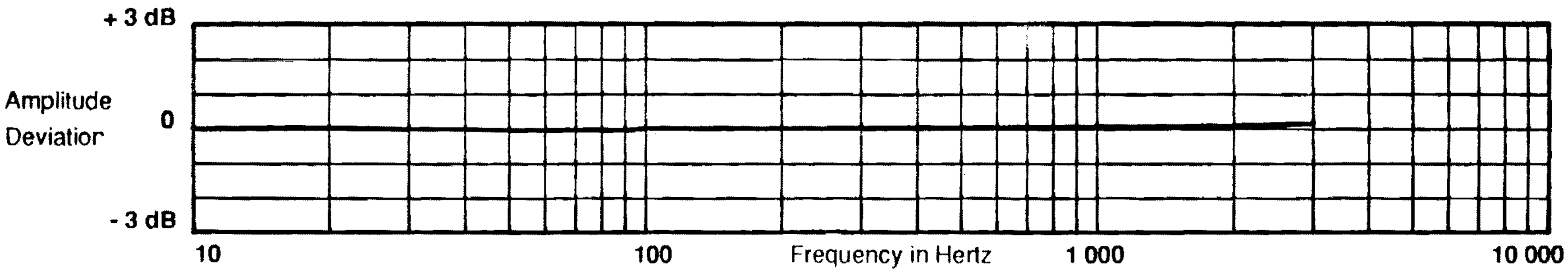
Range	50	± g
Resolution	0.001	g
Temp. Range	-100/+250	°F

METRIC CONVERSIONS:
ms $^{-2}$ = 0.102 g
°C = 5/9 x (°F -32)

Reference Freq.

Frequency Hz	10	15	30	50	100	300	500	1000	3000			
Amplitude Deviation %	0.0	.3	-.4	-.6	0.0	.4	.5	.6	1.9			

FREQUENCY RESPONSE



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