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Ground Vibration Test and Flutter Analysis of Air Sampling Probe

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SUMMARY

The Dryden Flight Research Facility of NASA Ames Research Center conducted a ground vibration test and a flutter analysis of an air sampling probe that was to be mounted on a Convair 990 airplane. The probe was a steel, wing-shaped structure used to gather atmospheric data. The ground vibration test was conducted to update the finite-element model used in the flutter analysis. The analysis predicted flutter speeds well outside the operating flight envelope of the Convair 990 airplane.

INTRODUCTION

A Convair 990 airplane was modified by mounting an atmospheric air sampling probe through existing window openings. To determine if the probe was free from flutter throughout the Convair 990 flight envelope, a ground vibration test (GVT) and predictive flutter analysis were performed on the probe and its supporting structure. The GVT was conducted to measure the modal frequencies and shapes of the probe. The GVT results were used to update the finite-element model used in the flutter analysis. The flutter analysis was performed to predict the probe flutter mechanism and flutter speed.

NOMENCLATURE

FAST	flutter analysis system
GVT	ground vibration test
NASTRAN	NASA structural analysis

DESCRIPTION OF PROBE AND MOUNTING

The Convair 990 air sampling probe was a wing-shaped structure with a steel spar and steel skins and a foam core. The probe measured 20 in long by 9.5 in wide at the root and 4.3 in wide at the tip, with a symmetric airfoil cross section. Seven air sampling tubes extended through the leading edge of the probe. The probe was mounted in a window opening (fig. 1). The aluminum probe support structure was attached to the aircraft ring frames at four locations. An aluminum plate replaced the window. An aluminum bracket secured the plate at the top and bottom of the window frame. The plate was glued to the probe in the center, as shown in figure 2.

ANALYSIS DESCRIPTION

A finite-element model of the Convair 990 probe was created. The probe was modeled as a simple beam structure with the mass distributed off the elastic axis. The mass and area moments of inertia were calculated at several locations along the span of the probe and the support structure. The support structure that attaches the probe to the aircraft was also modeled. A vibration analysis was performed on the finite-element model using the NASA structural analysis program (refs. 1 and 2). To correlate with GVT results, the window plate was also modeled with freedom of movement in all directions. The boundary conditions were the same for both the GVT and the analysis; the support structure was fixed at the four corners.

Two different programs were used to perform the flutter analysis: the NASA structural analysis (NASTRAN) and the flutter analysis system (FAST), described in references 3 and 4, respectively. Two reasons for using these different programs to perform the flutter analysis were (1) to cross-check each program and to indicate possible discrepancies in the results, and (2) to gain the experience in flutter analysis using these programs. The NASTRAN analysis used the doublet-lattice aerodynamic theory; the FAST method incorporated a subsonic kernel function lifting-surface aerodynamic theory.

The flutter analysis program in NASTRAN is a continuation of the vibration analysis. The aerodynamic model of the probe (fig. 3) was fitted to the structural points with a beam spline. The first seven elastic probe modes were used in calculating the generalized air forces. The aerodynamic matrix was calculated for a few selected Mach numbers and reduced frequencies and interpolated for others. With the K-method (ref. 2) of flutter analysis, NASTRAN was used to compute the frequency and damping estimates for each specified set of parameters: density ratio, Mach number, and reduced frequency.

The FAST program is an automated procedure for computing flutter eigenvalues. The vibration mode shapes of the first seven elastic probe modes from the NASTRAN vibration analysis were used to calculate the generalized forces in FAST at the specified collocation points shown in figure 4. A nonsymmetric surface spline was used to interpolate the vibration mode shapes and deflections to the collocation points. The aerodynamic forces were interpolated with respect to reduced frequency using a tabulated cubic spline. The flutter solution was then obtained from an eigenvalue routine that takes advantage of the parametric nature of the velocity-damping solution.

GVT TEST PROCEDURES

The probe was mounted in the support structure used on the aircraft and was attached, by means of C-clamps, at the four corner connection points to two aluminum stands (figure 5). The stands were bolted to the floor and weighted with 125 lb of lead shot. The window was not constrained at either end and was allowed to move freely.

An instrumented impact hammer was used to excite the structure. The probe response to excitation was monitored by a piezoelectric accelerometer. The data measurement points are shown in figure 6. A piezoelectric accelerometer was affixed to the probe with double-sided tape at the trailing edge. The hammer was then used to excite the structure five times at each data measurement point (fig. 6); the responses were averaged and recorded by a minicomputer-based structural analysis system (ref. 5).

A structural analysis system was used to analyze the data over a bandwidth of 50 to 2000 Hz. A frequency-response function was generated for each measurement location. Subsequently, a frequency-response function was chosen that contained the modes of interest. The computer fitted a multi-degree-of-freedom curve to the frequency-response function and generated an estimate of frequency, amplitude, damping, and phase. To obtain a good curve fit for all modes, many transfer functions had to be examined. Using the estimated parameters from the curve fit (frequency, amplitude, damping, and phase), the modal coefficients were computed for each mode using the amplitude and phase of the measured response at the selected resonance frequency.

GVT RESULTS

The modes of vibration that were measured are listed in table 1 showing frequency, damping, and phase for each mode. Twelve modes were identified in the direction perpendicular to the probe wing planform. The probe was also excited in the chordwise direction to identify the first forward and aft wing bending mode (24.5 Hz) that was the lowest mode predicted by analysis. Although no data were recorded or analyzed for this mode, the mode was identified visually and noted during the test.

ANALYSIS RESULTS

A comparison of measured and calculated frequencies is listed in table 2. The corresponding mode shapes from the GVT and the vibration analysis are presented in the appendix. Several modes predicted by the analysis were not found during the GVT. The forward and aft wing bending modes were not identified because the probe was not excited in the forward and aft directions except to identify the first mode. The missing plate modes were not identified because of the weak response measured at the trailing edge tip of the probe due to plate excitation. The remaining analytically predicted modes and frequencies compared well with the measured GVT results with only small differences.

The finite-element model was then modified by constraining the ends of the plate from movement to represent the probe as installed on the Convair 990 airplane. The vibration analysis was repeated using the modified model, and the results were input to the flutter analysis.

The velocity-damping plots from the NASTRAN and FAST flutter analysis for the standard cruise condition of Mach 0.4 at 21,000 ft are shown in figures 7 and 8, respectively. The lowest flutter speed predicted by both methods was approximately 4100 knots with the 1026.0-Hz mode (the first probe torsion) becoming unstable. Because the flutter speed was extremely high, a matched point solution was not obtained. For a matched point solution, the density, Mach number, and velocity are consistent with actual physical conditions standard atmosphere conditions. In the preliminary analyses, the forward and aft wing bending mode at 40 Hz did not effect the flutter results; hence, it was not used in the final analysis.

CONCLUSIONS

A ground vibration test and flutter analyses were conducted on a Convair 990 air sampling probe. The finite-element model used in the flutter analyses was tuned using the ground vibration test results. The flutter analyses demonstrated that the probe had flutter speeds well outside the flight envelope of the Convair 990 airplane. In general, probes of design and construction similar to the probe analyzed should have equally high flutter speeds.

National Aeronautics and Space Administration
Ames Research Center
Dryden Flight Research Facility
Edwards, California, June 5, 1985

REFERENCES

1. The NASTRAN® User's Manual NASA SP-222(06), 1983.

2. The NASTRAN® Theoretical Manual. NASA SP-221(06), 1981.

3. Desmarais, Robert N., and Bennett, Robert M.: User's Guide for a Modular Flutter Analysis Software System (FAST Version 1.0). NASA TM-78770, 1978.

4. Desmarais, Robert N. and Bennett, Robert M.: An Automated Procedure for Computing Flutter Eigenvalues. J. Aircraft, vol. 11, Feb. 1974, pp. 75-80.

5. Kehoe, Michael W.: F-8 Refueling Boom Ground Vibration Test. NASA TM-84914, 1985.

APPENDIX — MODE SHAPE DATA

The mode shapes (figs. 9 to 32) were normalized to the maximum deflection. Each mode shape is usually displayed showing a comparison between experimental and analytical results. In some instances (for example, figs. 9 and 12 to 14), a mode was not identified in the GVT due to reasons discussed previously. Also, the support structure was modeled as a single beam in the analysis, while the responses at the leading and trailing edges were measured during the GVT. Therefore, the modeling of the support structure for the GVT differed from the modeling for the NASTRAN analysis.

TABLE 1. — GROUND VIBRATION TEST RESULTS

Mode number	Frequency, Hz	Damping, g	Phase, rad
1	64.0	0.021	-1.47
2	136.4	0.076	1.65
3	267.5	0.060	1.58
4	304.0	0.043	-2.45
5	425.0	0.018	1.88
6	507.4	0.078	1.54
7	882.9	0.042	-1.41
8	963.8	0.004	1.56
9	1133.1	0.005	-1.45
10	1422.7	0.006	-1.63
11	1524.4	0.003	-1.73
12	1803.2	0.002	1.51

TABLE 2. — COMPARISON OF RESULTS OF NASTRAN VIBRATION AND GVT ANALYSES

Mode	Vibration analysis frequency, Hz	GVT frequency, Hz	Description
1	40.0	24.5	First forward and aft wing bending
2	67.6	64.0	First wing bending
3	118.7	136.4	Plate roll
4	140.7	a	Support and wing bending
5	184.0	a	Wing and forward and aft support bending
6	284.8	a	Forward and aft support bending
7	288.8	267.5	First torsion (support twist)
8	306.9	304.0	First plate bending
9	434.7	425.0	Second wing bending
10	445.3	507.4	First plate torsion
11	475.3		Plate twist
12	668.6	a	First forward and aft wing bending
13	677.1		End support bending
14	951.3		First plate bending mode
15	965.9	a	Second forward and aft wing bending
16	966.4	882.9	Third wing bending
17	1037.0	963.8	First wing torsion
18	1196.0		Second plate bending mode
19	1198.0	1133.1	Plate bending
20	1326.0		Second plate torsion
21	1586.0	1422.7	Plate bending mode
22	1705.0	1524.4	Fourth wing bending
23	1935.0	1803.2	Second plate torsion
24	2126.0	a	Third forward and aft wing bending

[a]Not measured

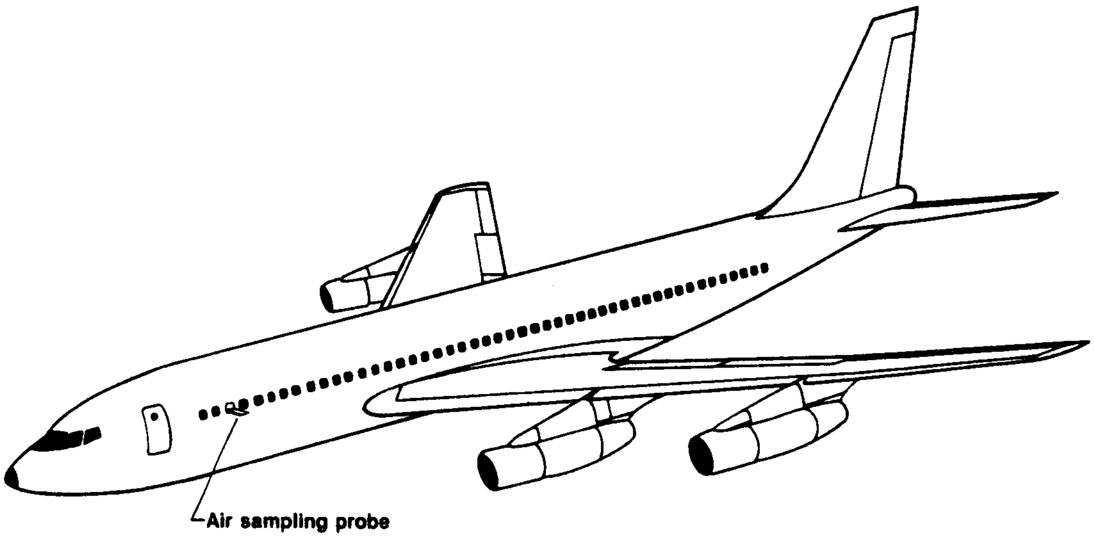


Figure 1. Air sampling probe installed on Convair 990 aircraft.

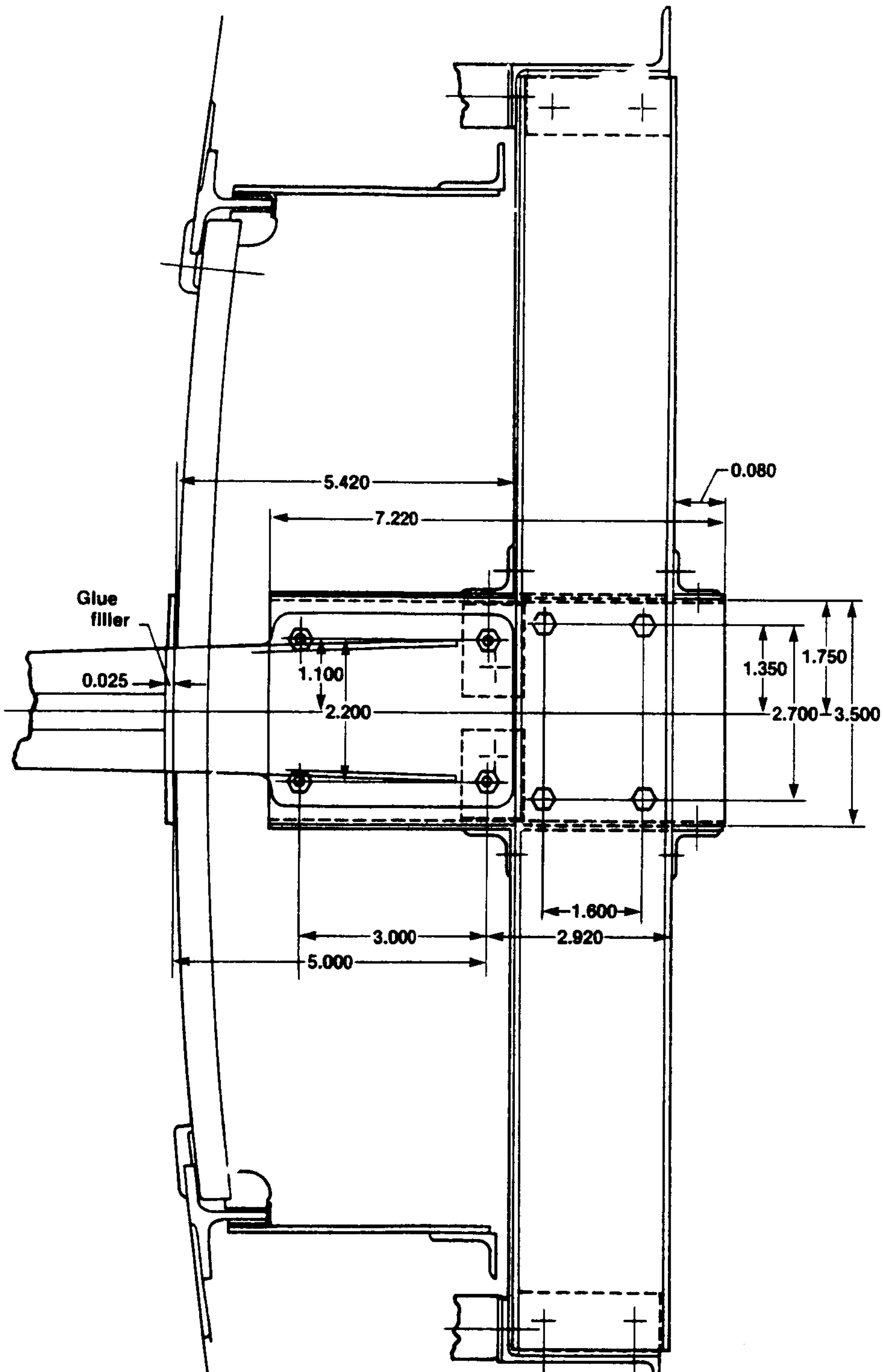


Figure 2. Structural assembly of air sampling probe mounted on support structure, view looking forward. (All dimensions are in inches.)

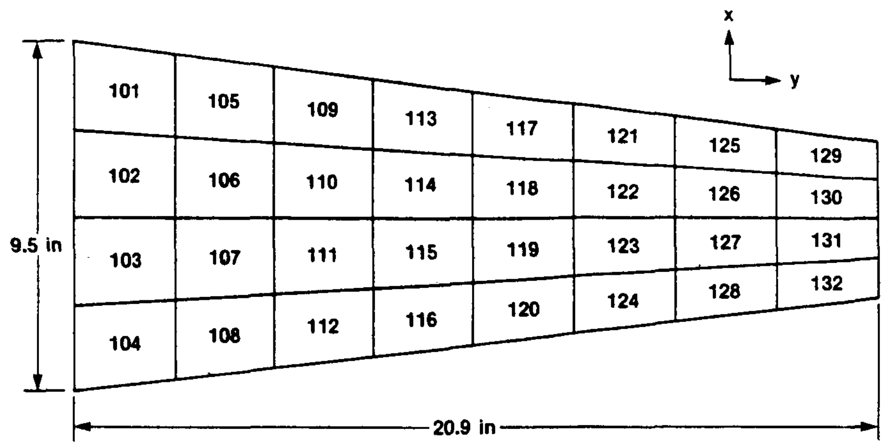
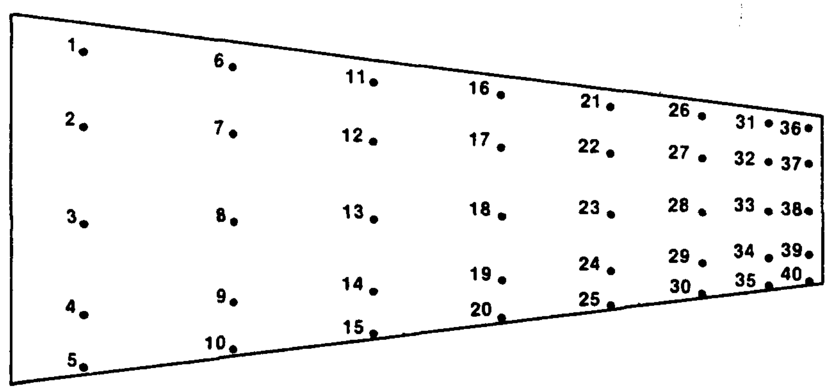


Figure 3. NASTRAN aerodynamic model. (Numbers indicate doublet-lattice panel.)



Collocation point	Percent semichord[a]	Percent span	Collocation point	Percent semichord[a]	Percent span
1	−0.7904	0.0923	21	−0.4957	0.7390
2	−0.3903	0.0923	22	−0.2448	0.7390
3	0.1337	0.0923	23	0.0839	0.7390
4	0.6152	0.0923	24	0.3859	0.7390
5	0.9014	0.0923	25	0.5654	0.7390
6	−0.7077	0.2737	26	−0.4450	0.8502
7	−0.3495	0.2737	27	−0.2198	0.8502
8	0.1197	0.2737	28	0.0753	0.8502
9	0.5509	0.2737	29	0.3464	0.8502
10	0.8072	0.2737	30	0.5076	0.8502
11	−0.6293	0.4457	31	−0.4075	0.9325
12	−0.3108	0.4457	32	−0.2012	0.9325
13	0.1065	0.4457	33	0.0689	0.9325
14	0.4899	0.4457	34	0.3172	0.9325
15	0.7178	0.4457	35	0.4648	0.9325
16	−0.5573	0.6026	36	−0.3845	0.9830
17	−0.2755	0.6026	37	−0.1899	0.9830
18	0.0944	0.6026	38	0.0651	0.9830
19	0.4342	0.6026	39	0.2993	0.9830
20	0.6362.	0.6026	40	0.4386	0.9830

[a]Based on reference semichord

Figure 4. Collocation points used in FAST analysis.

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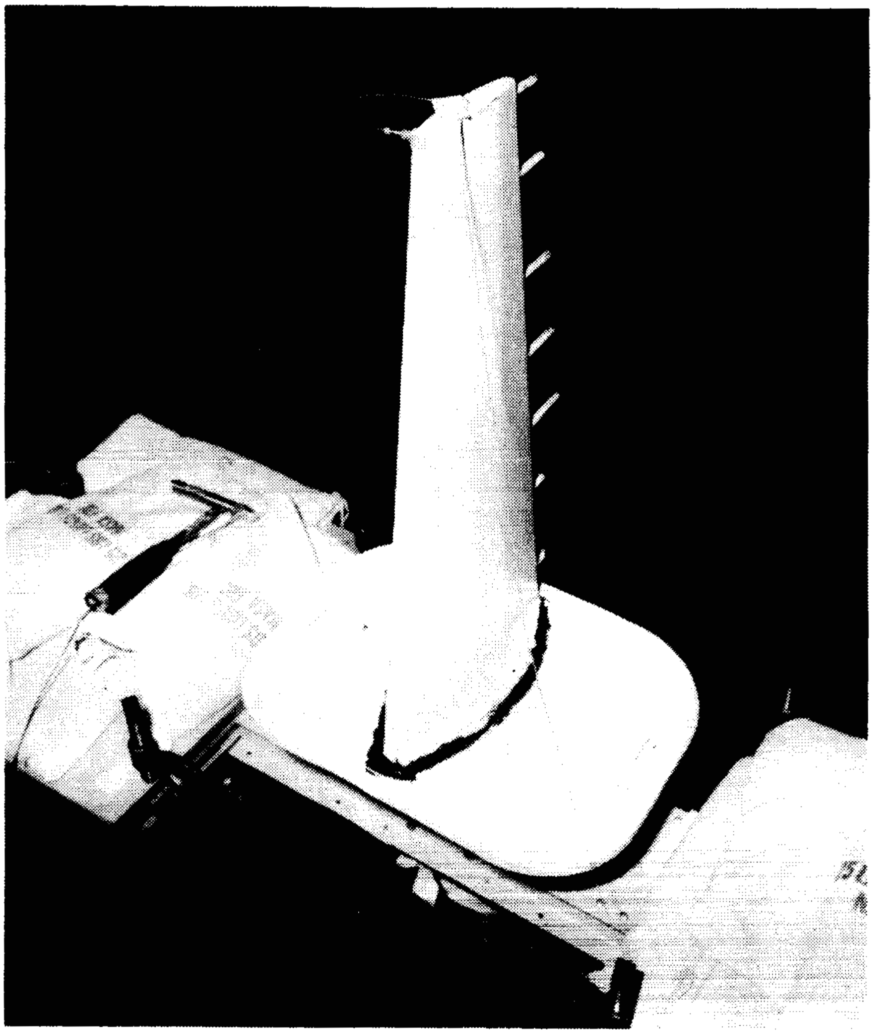

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Figure 5. Ground vibration test setup.

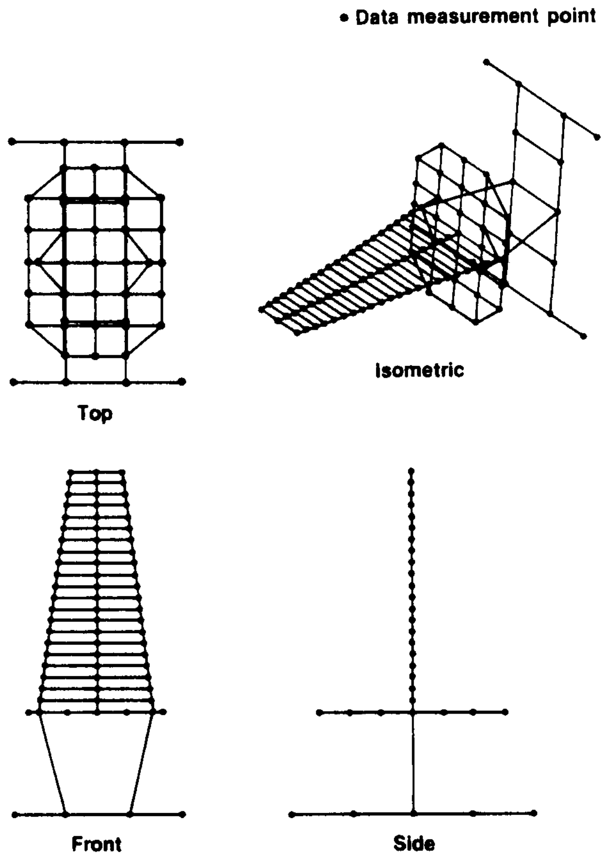


Figure 6. Ground vibration test data measurement points.

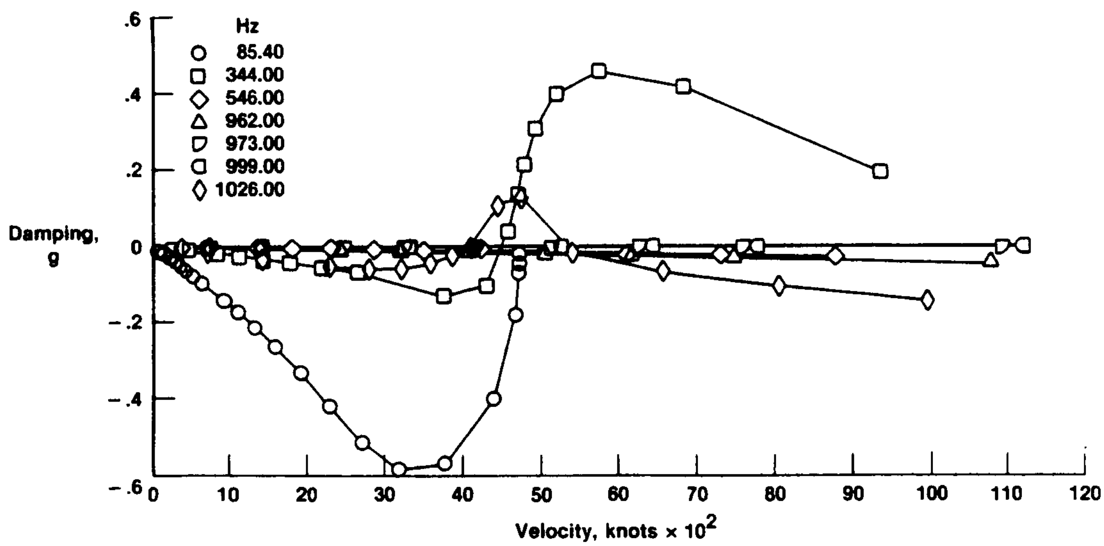


Figure 7. NASTRAN flutter analysis results showing damping as a function of velocity at Mach 0.40 and 21,000-ft altitude.

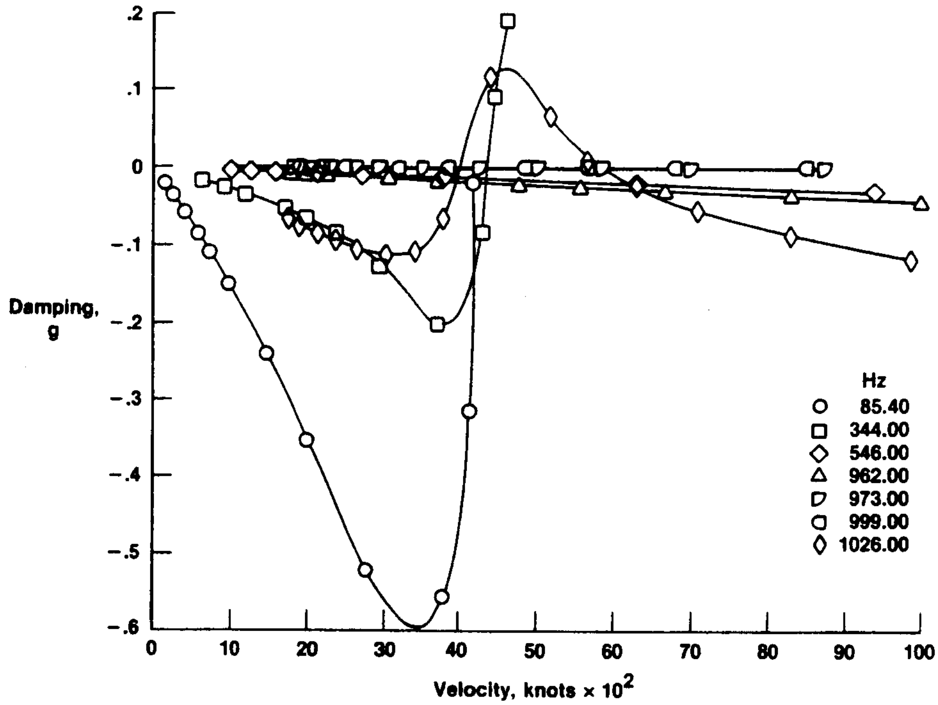


Figure 8. FAST flutter analysis results showing damping as a function of velocity at Mach 0.40 and 21,000-ft altitude.

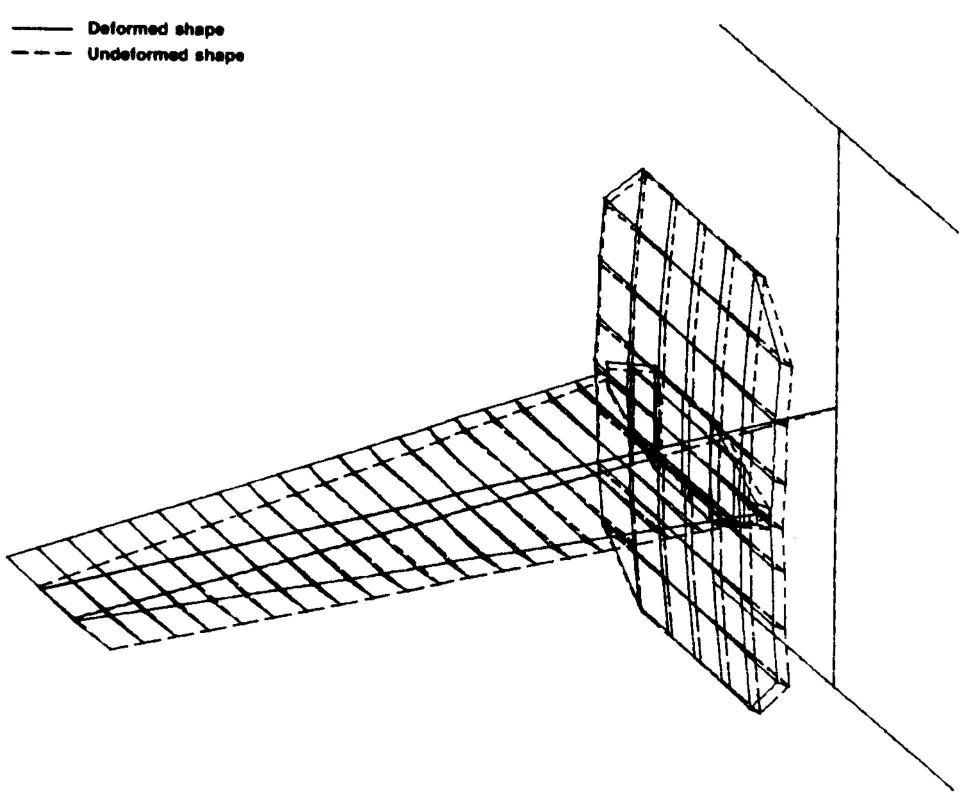
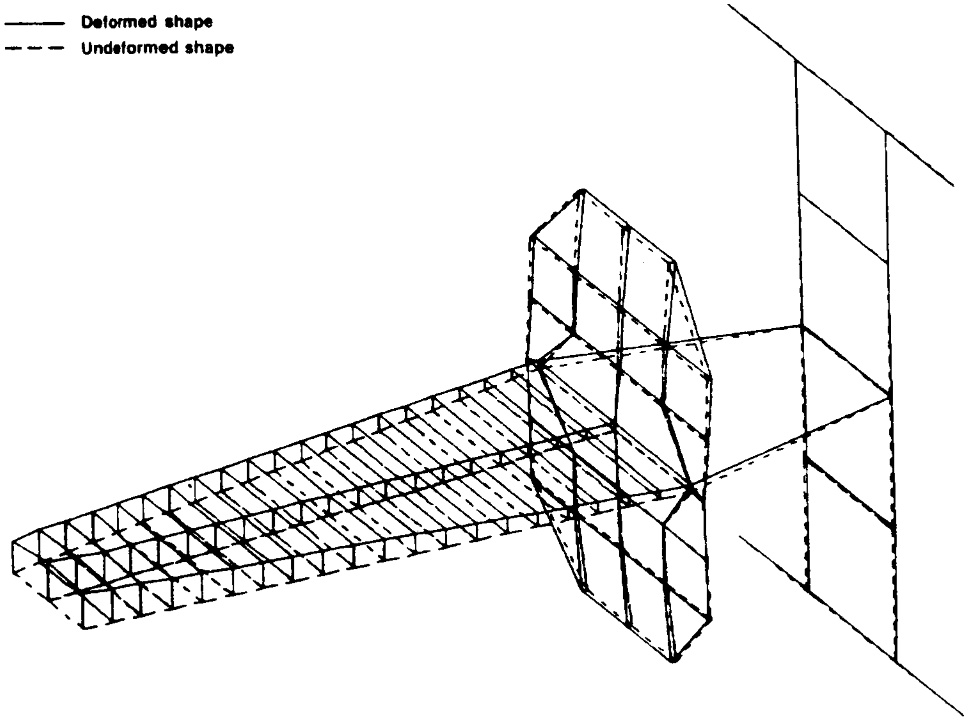
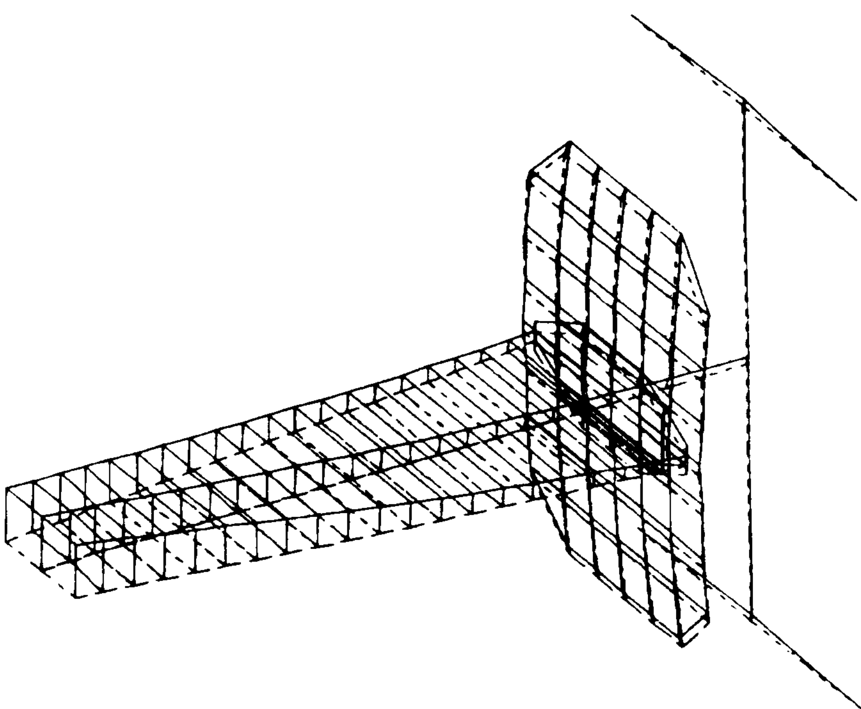


Figure 9. Mode shape of NASTRAN analysis at 40.0 Hz.



Ground vibration test



NASTRAN analysis

Figure 10. Mode shape comparison of ground vibration test at 64.0 Hz and NASTRAN analysis at 67.6 Hz.

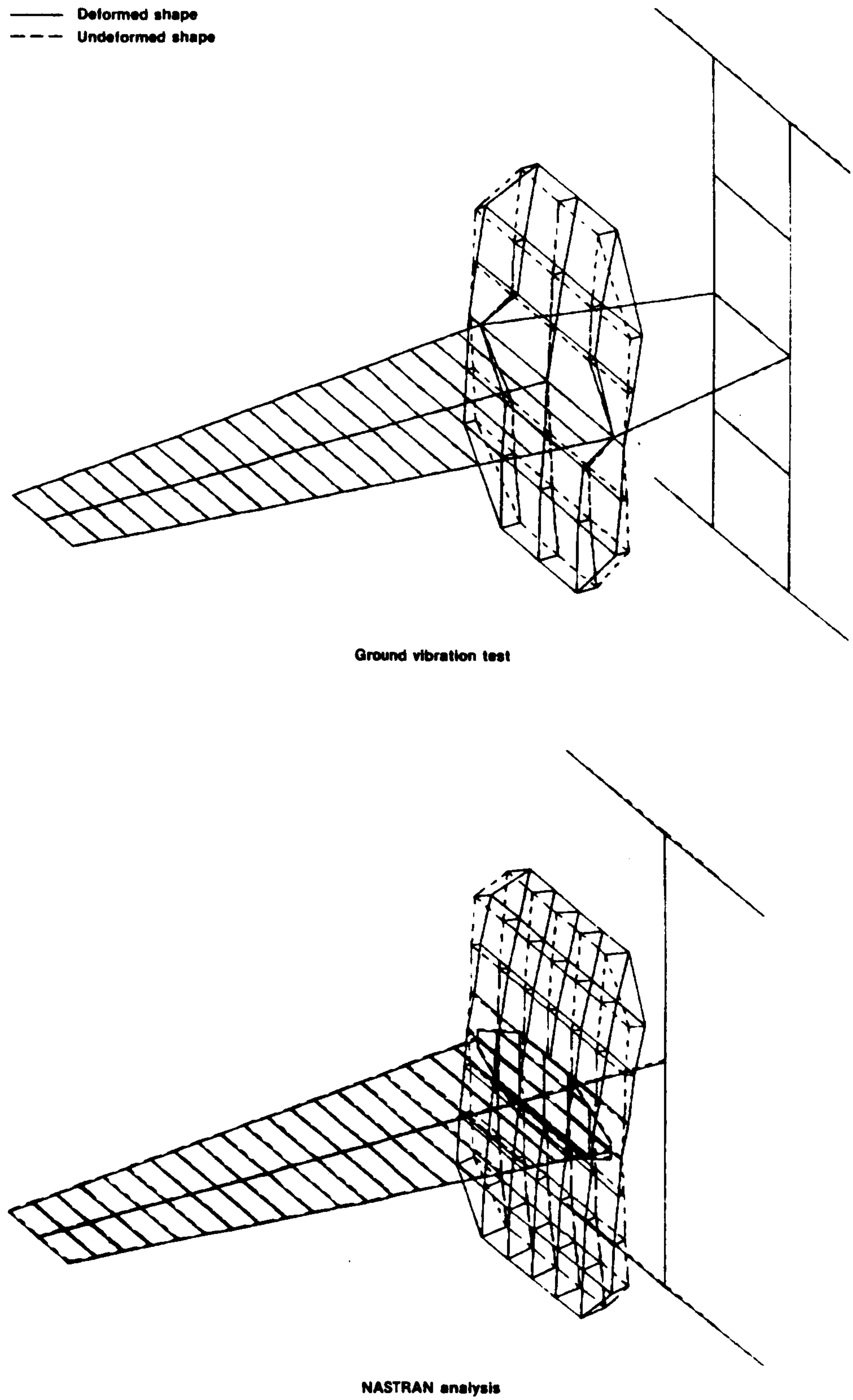


Figure 11. Mode shape comparison of ground vibration test at 136.4 Hz and NASTRAN analysis at 118.7 Hz.

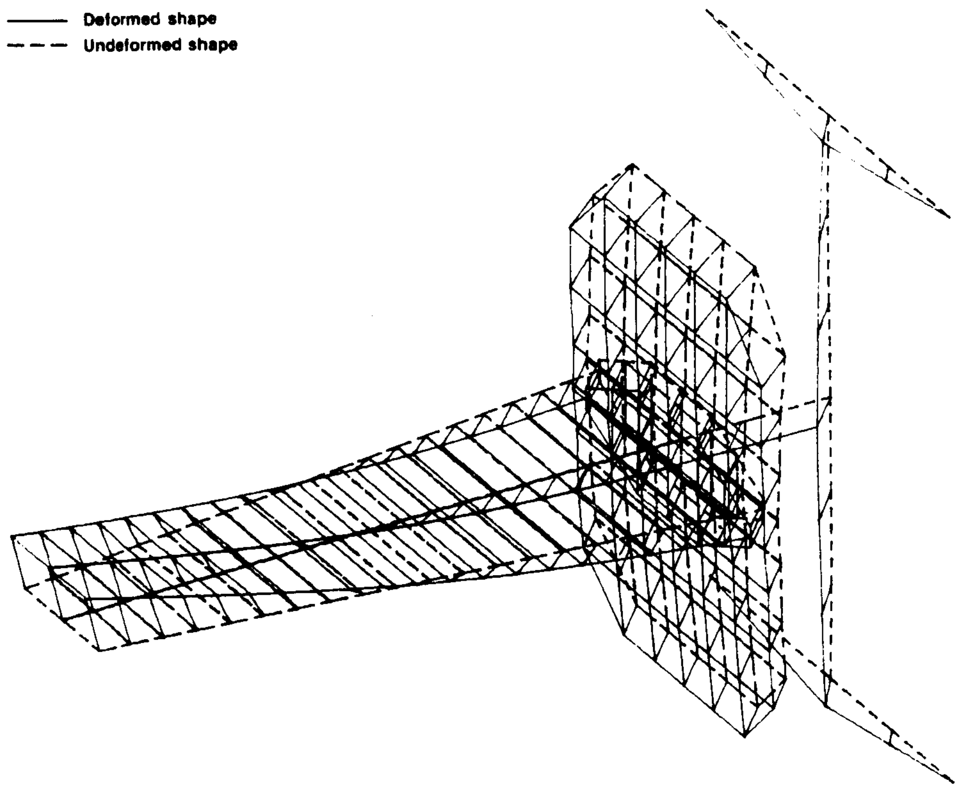


Figure 12. Mode shape of NASTRAN analysis at 140.7 Hz.

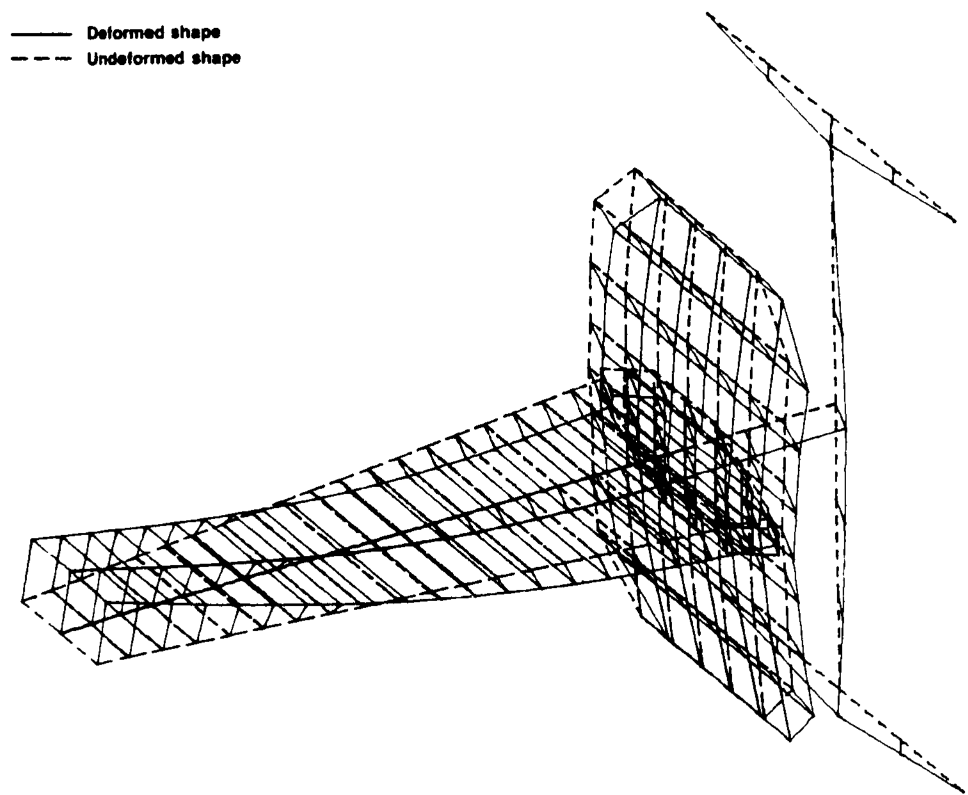


Figure 13. Mode shape of NASTRAN analysis at 184.0 Hz.

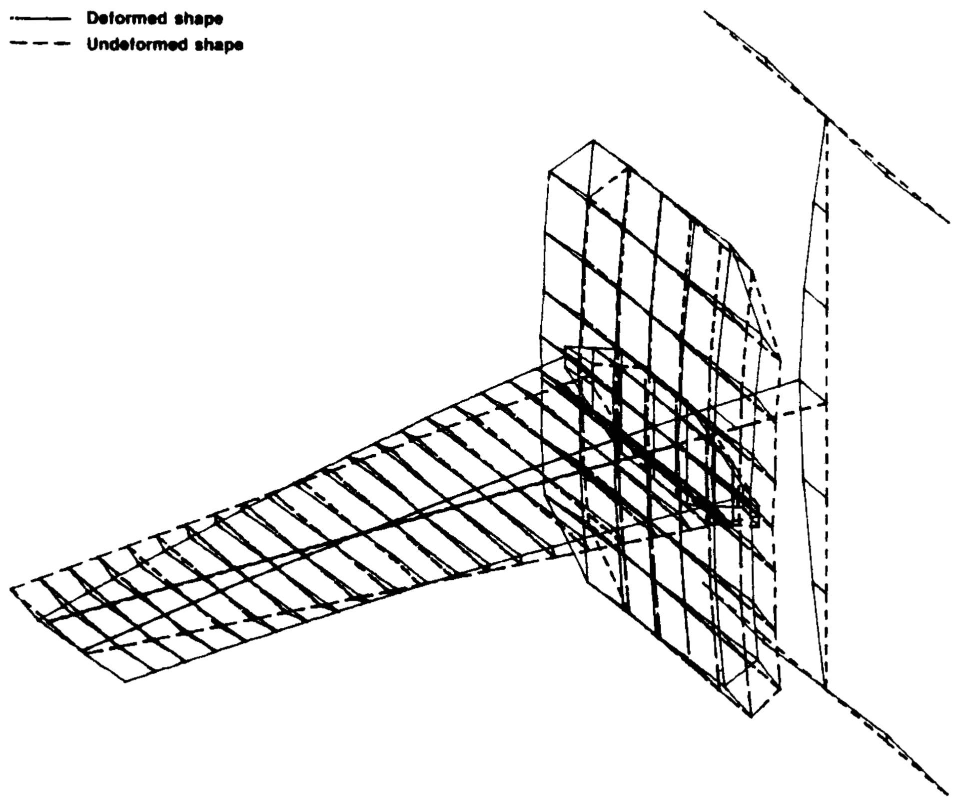
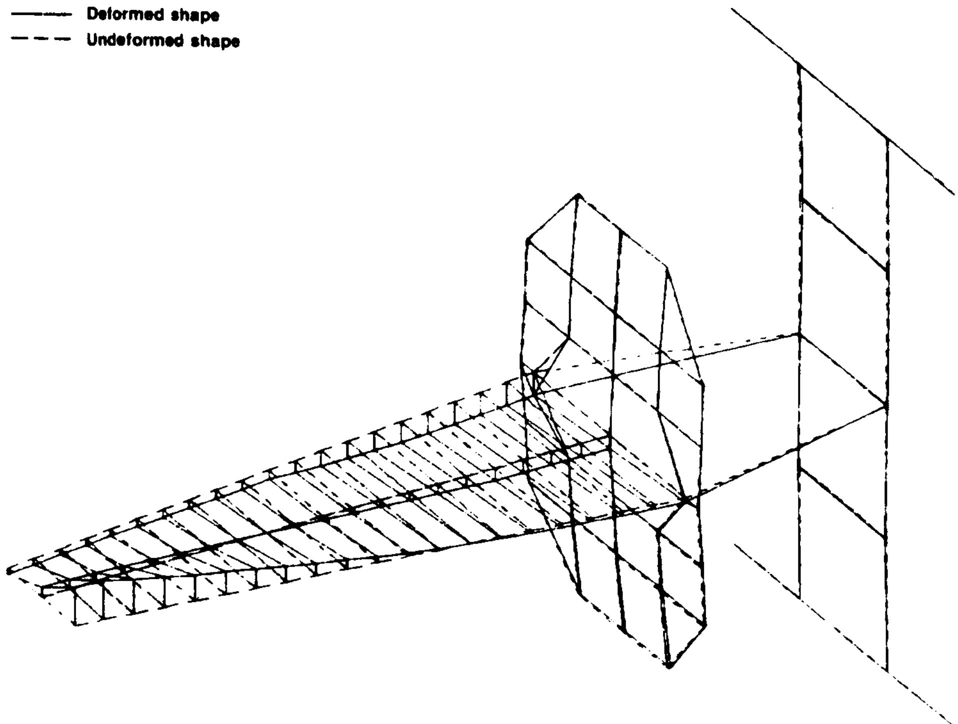
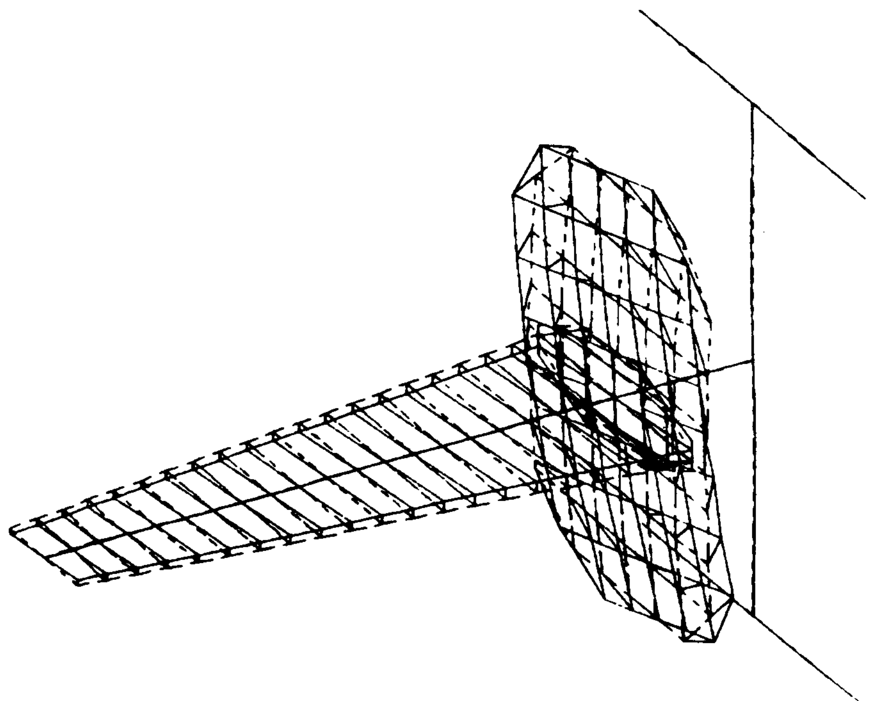


Figure 14. Mode shape of NASTRAN analysis at 284.8 Hz.



Ground vibration test



NASTRAN analysis

Figure 15. Mode shape comparison of ground vibration test at 267.5 Hz and NASTRAN analysis at 288.8 Hz.

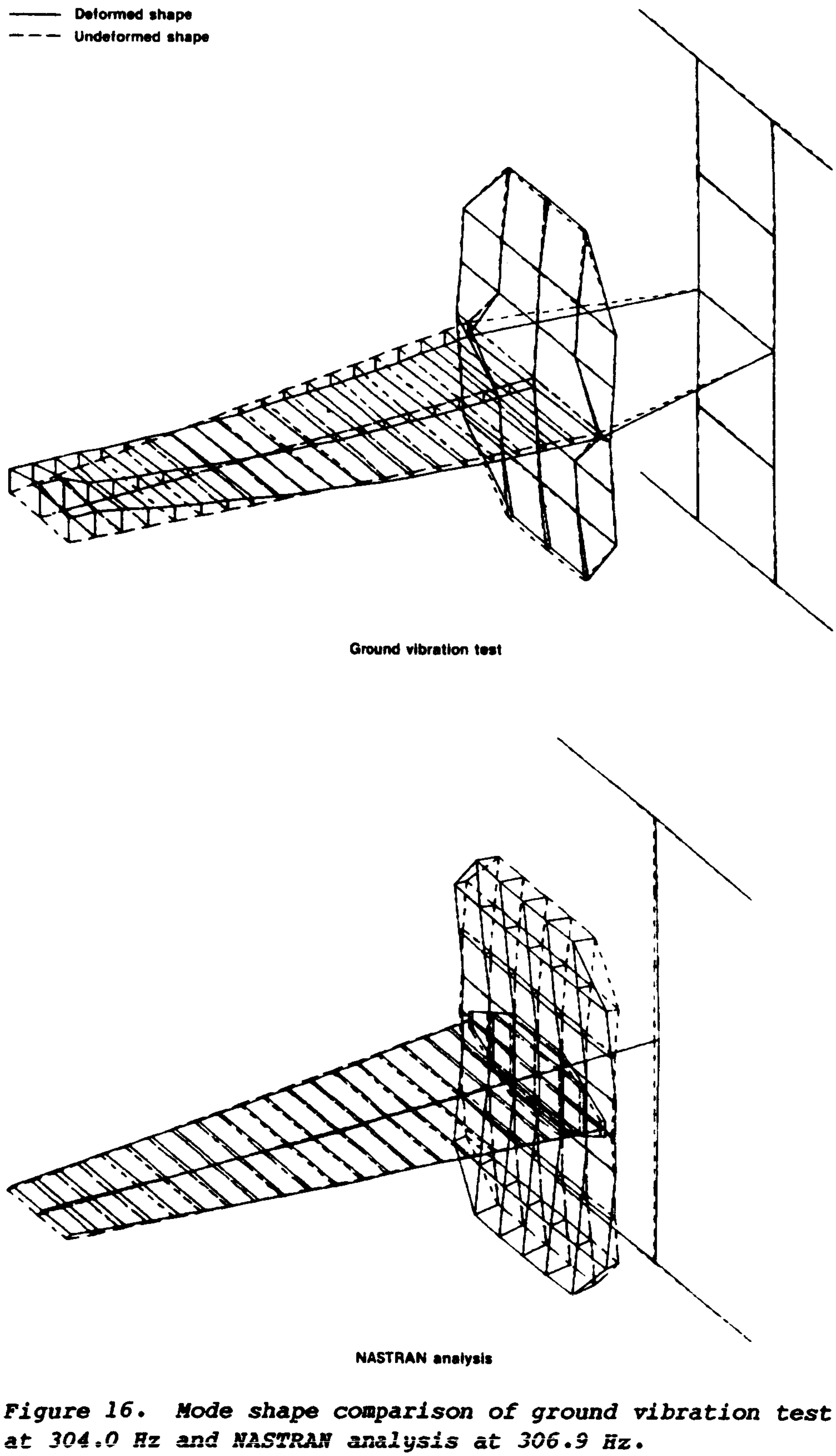


Figure 16. Mode shape comparison of ground vibration test at 304.0 Hz and NASTRAN analysis at 306.9 Hz.

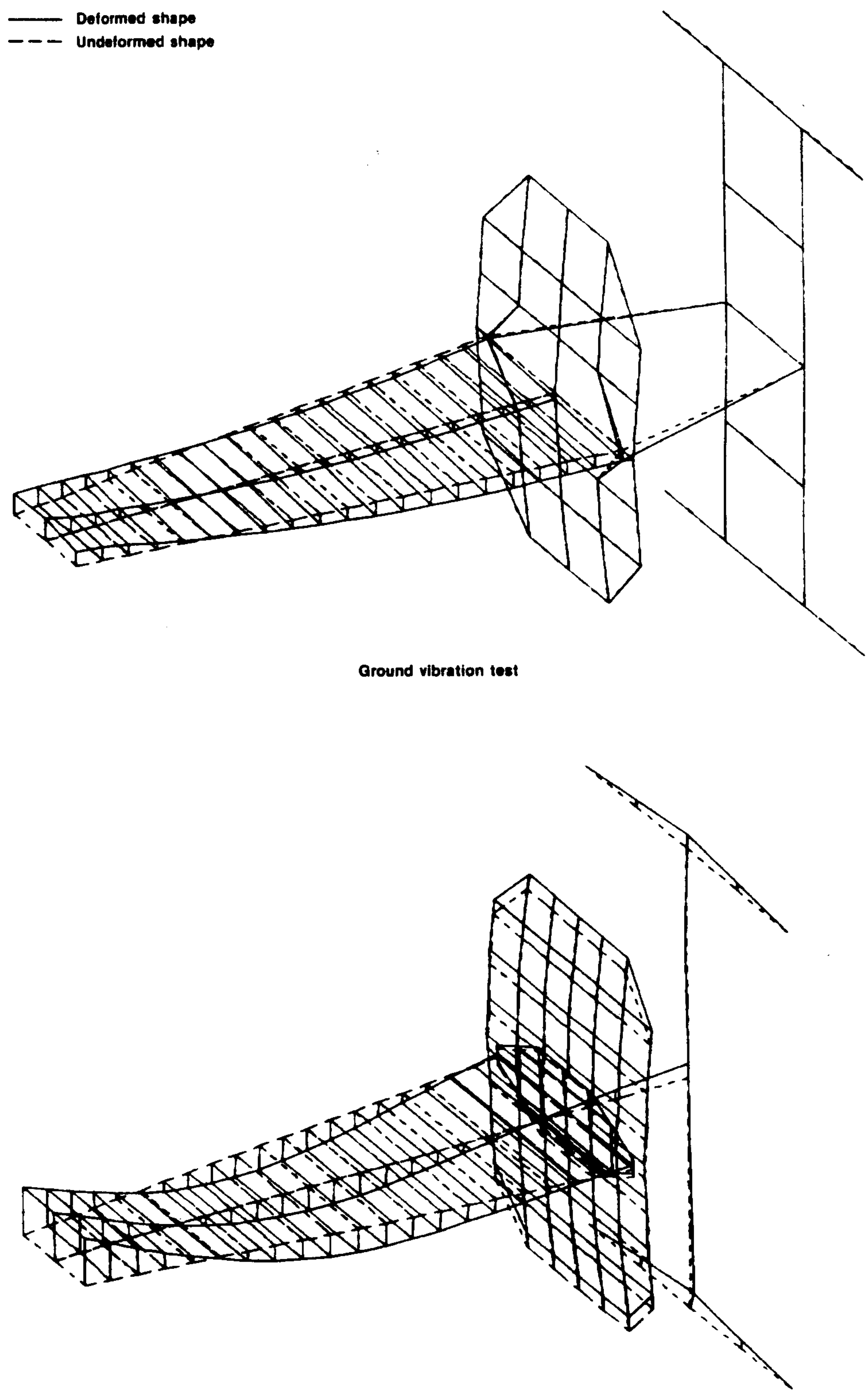
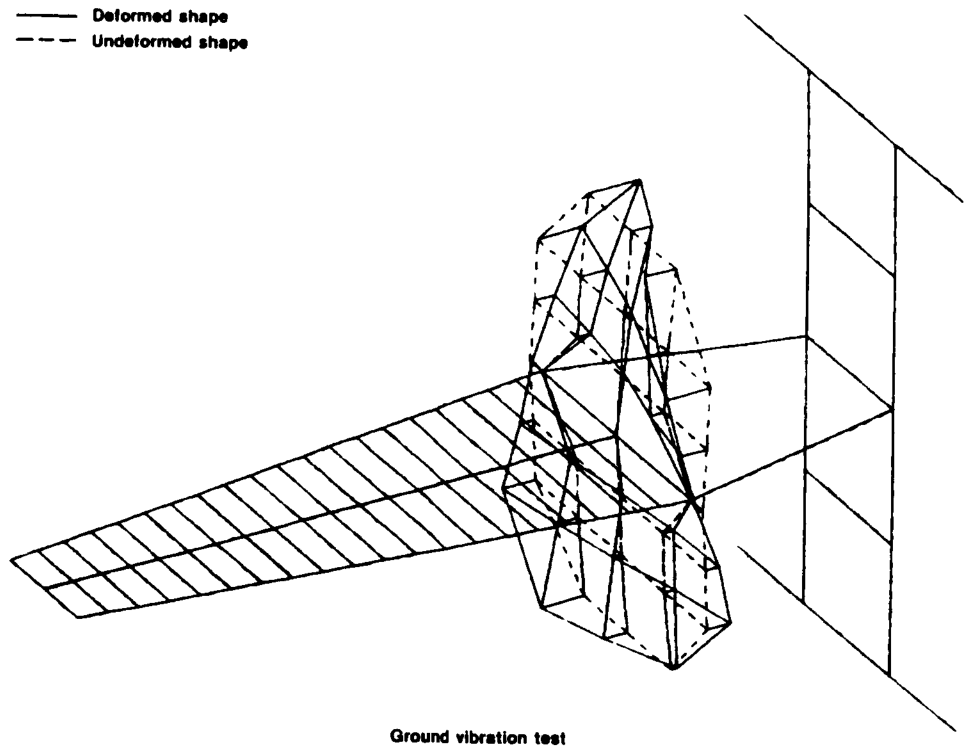
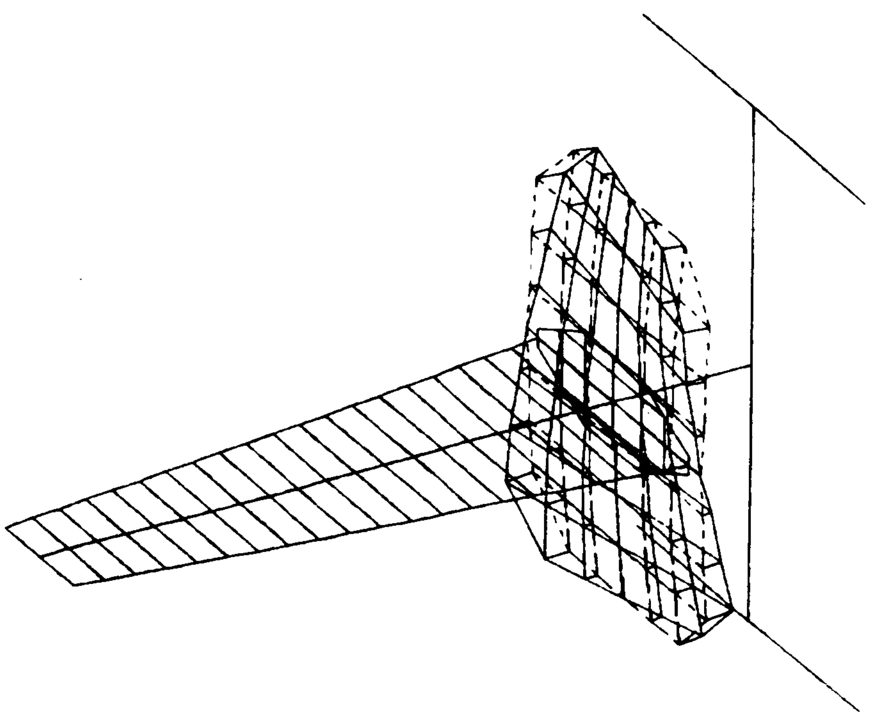


Figure 17. Mode shape comparison of ground vibration test at 425.0 Hz and NASTRAN analysis at 434.7 Hz.



Ground vibration test



NASTRAN analysis

Figure 18. Mode shape comparison of ground vibration test at 507.4 Hz and NASTRAN analysis at 445.3 Hz.

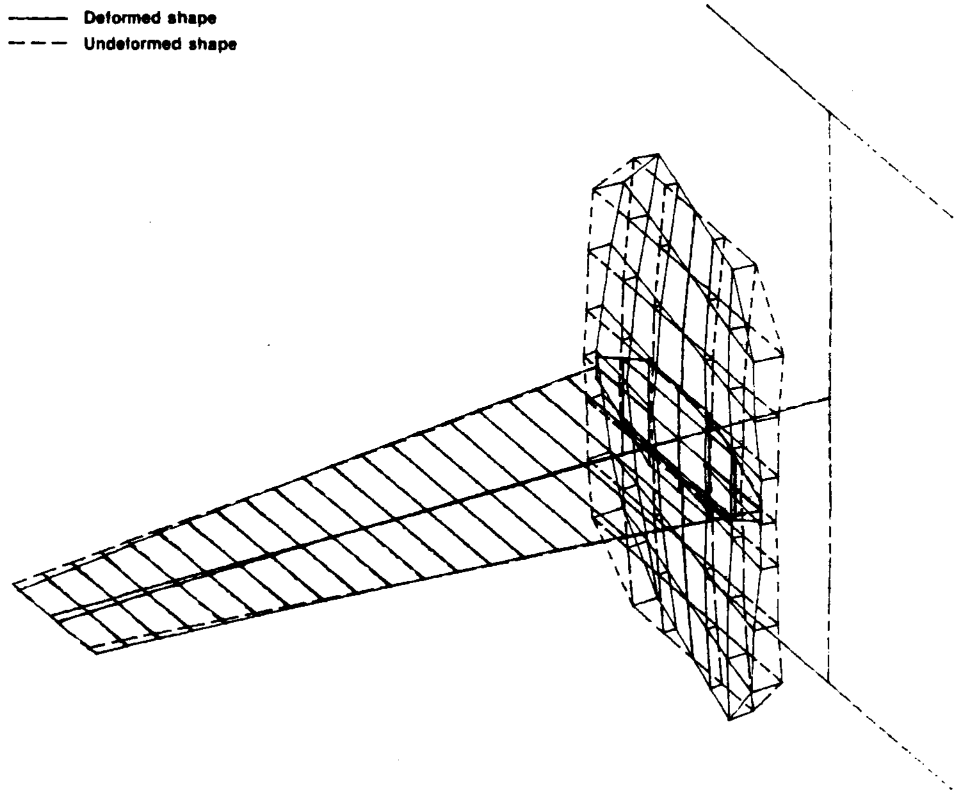


Figure 19. Mode shape of NASTRAN analysis at 475.3 Hz.

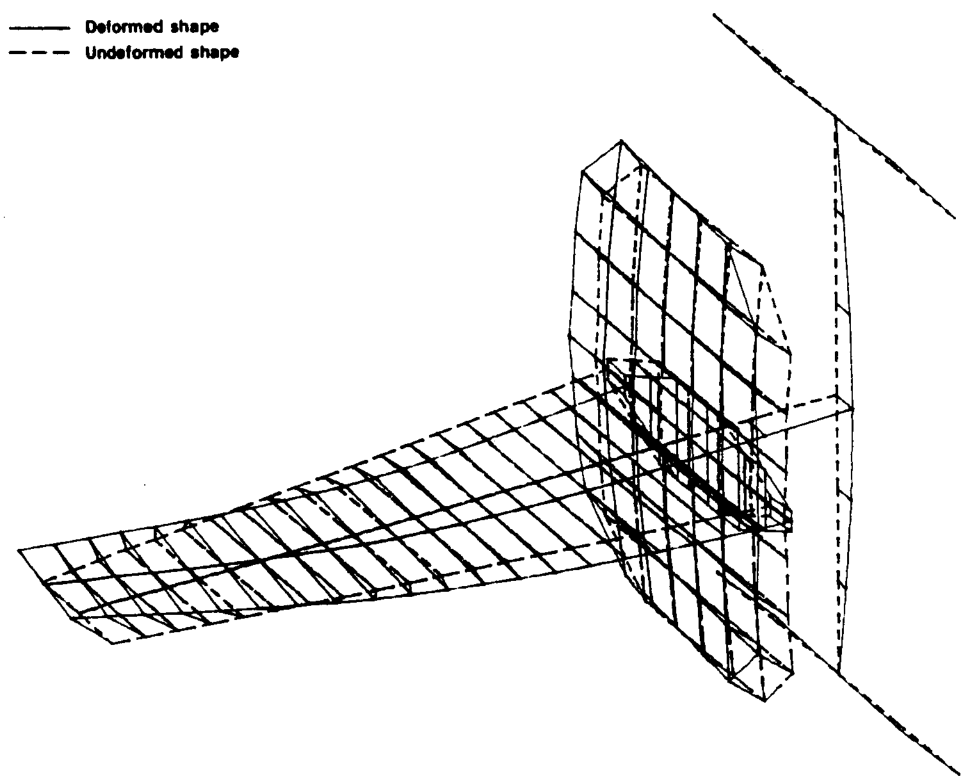


Figure 20. Mode shape of NASTRAN analysis at 668.6 Hz.

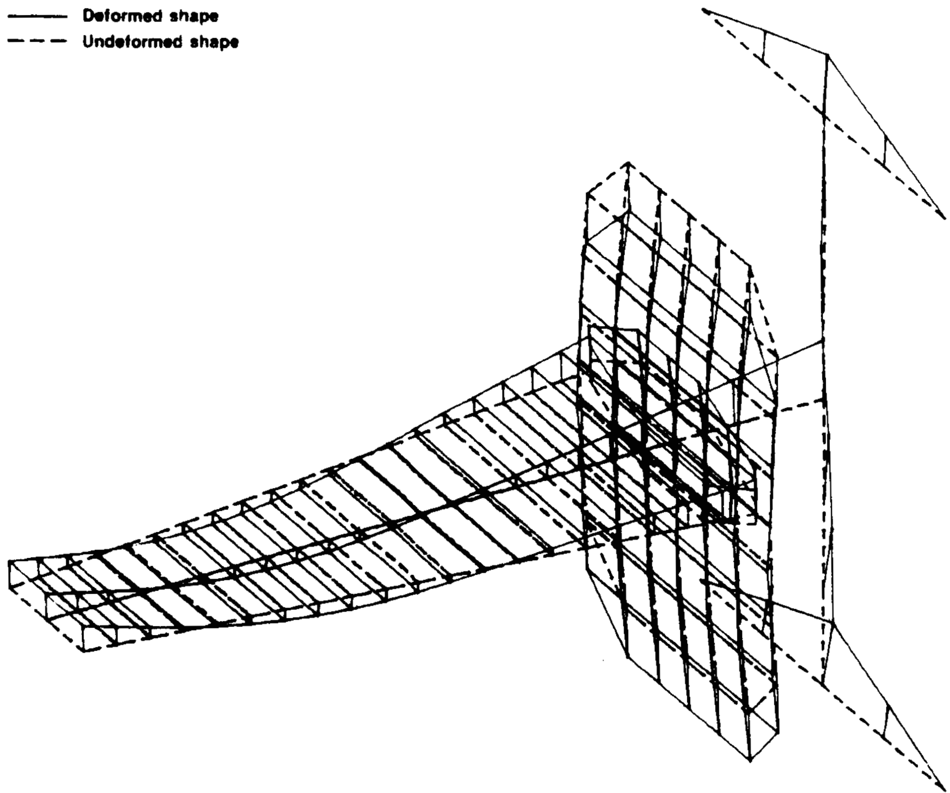


Figure 21. Mode shape of NASTRAN analysis at 677.1 Hz.

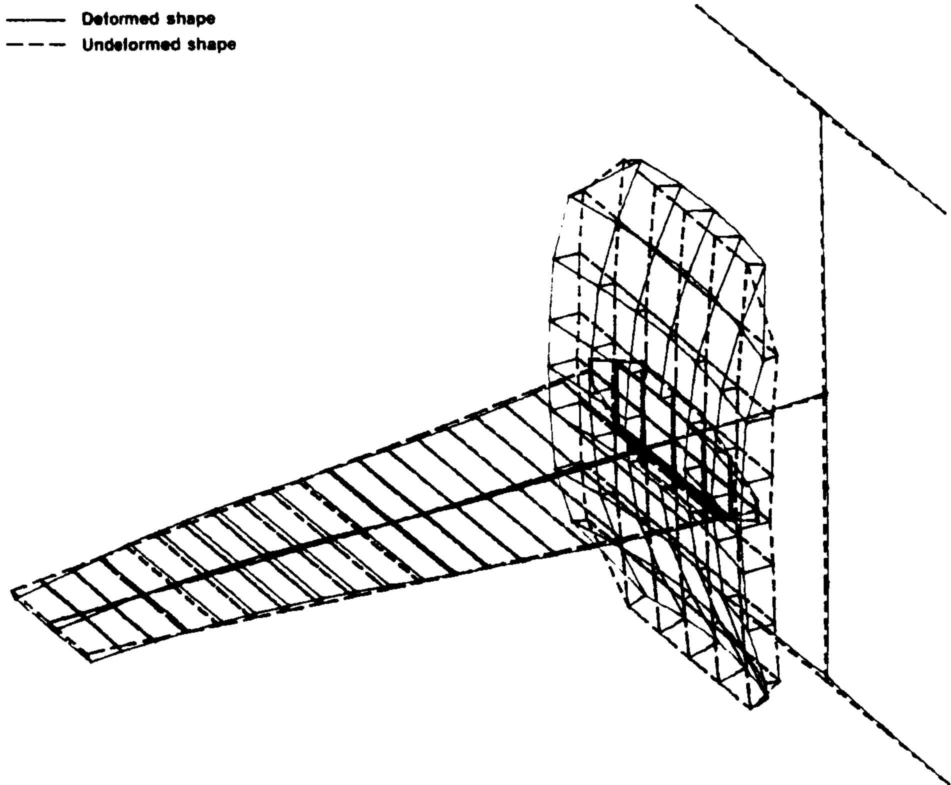


Figure 22. Mode shape of NASTRAN analysis at 951.3 Hz.

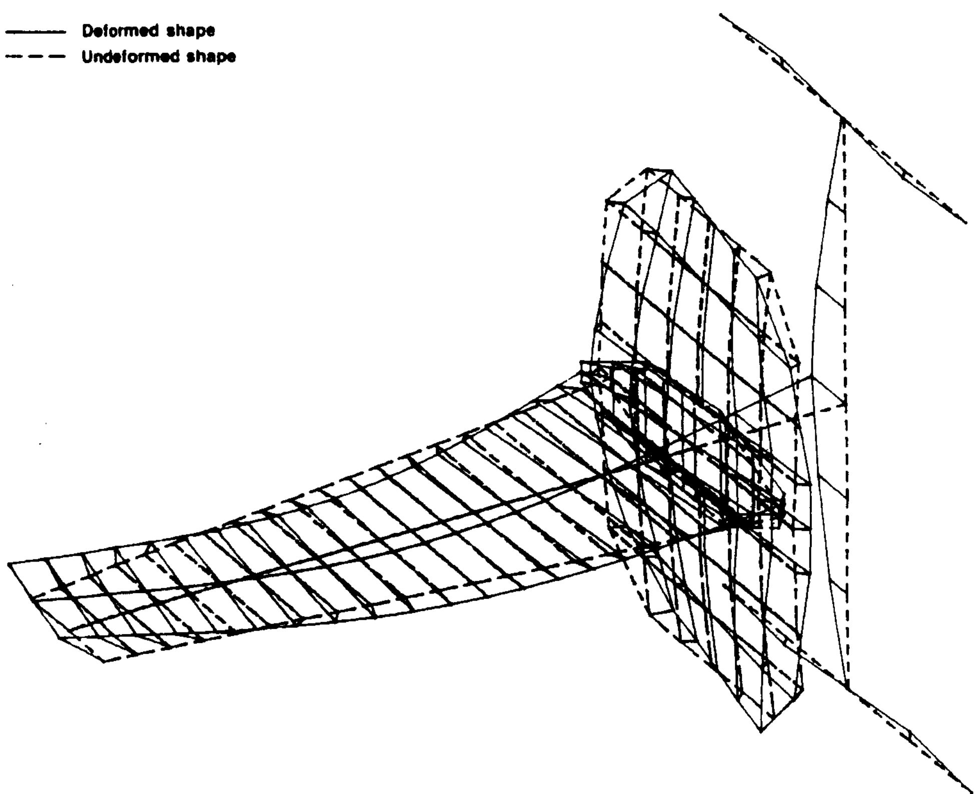


Figure 23. Mode shape of NASTRAN analysis at 965.9 Hz.

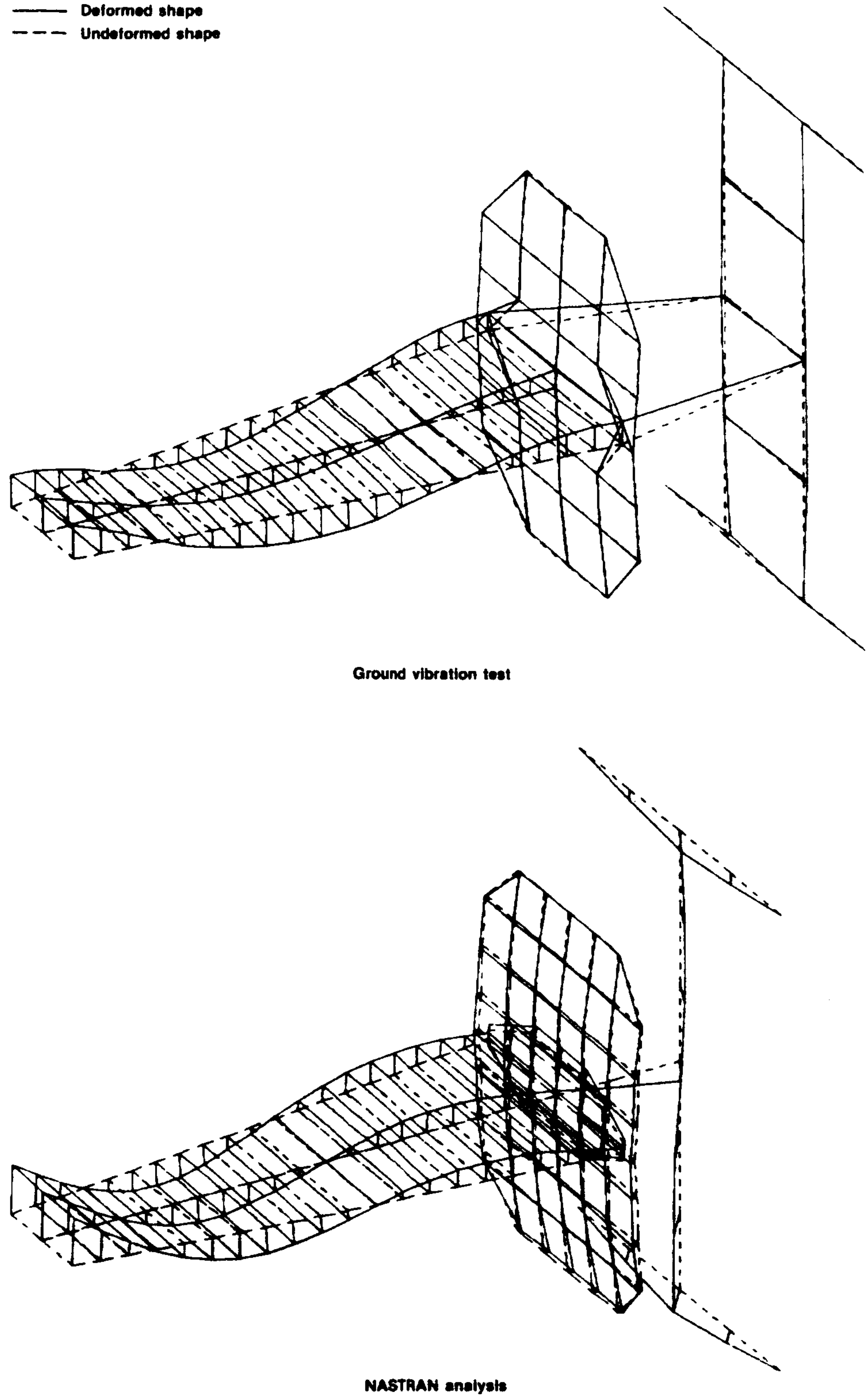
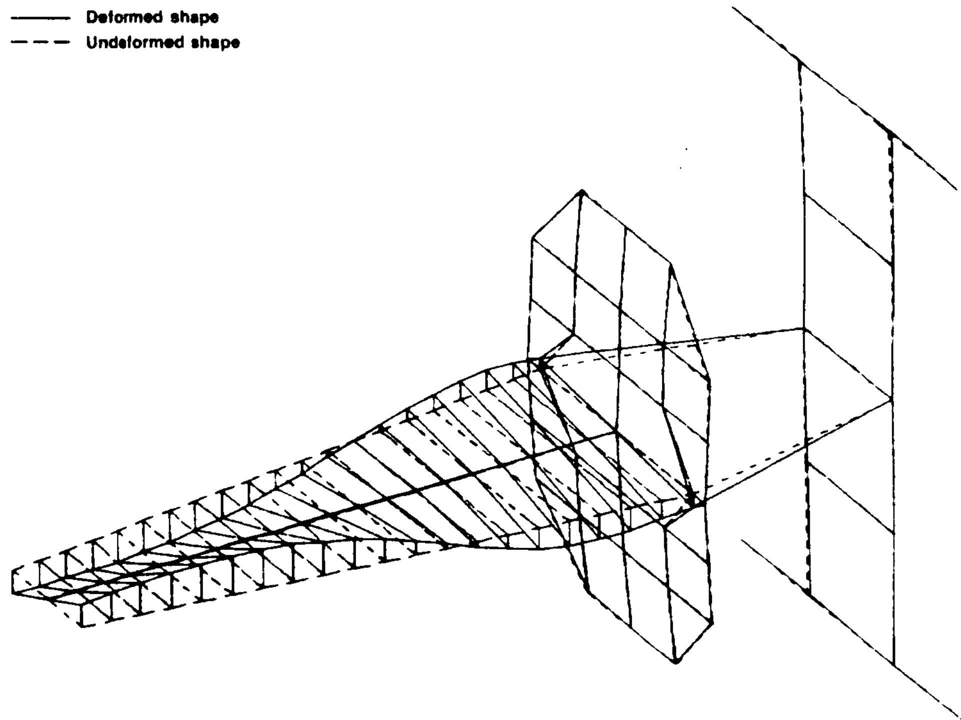
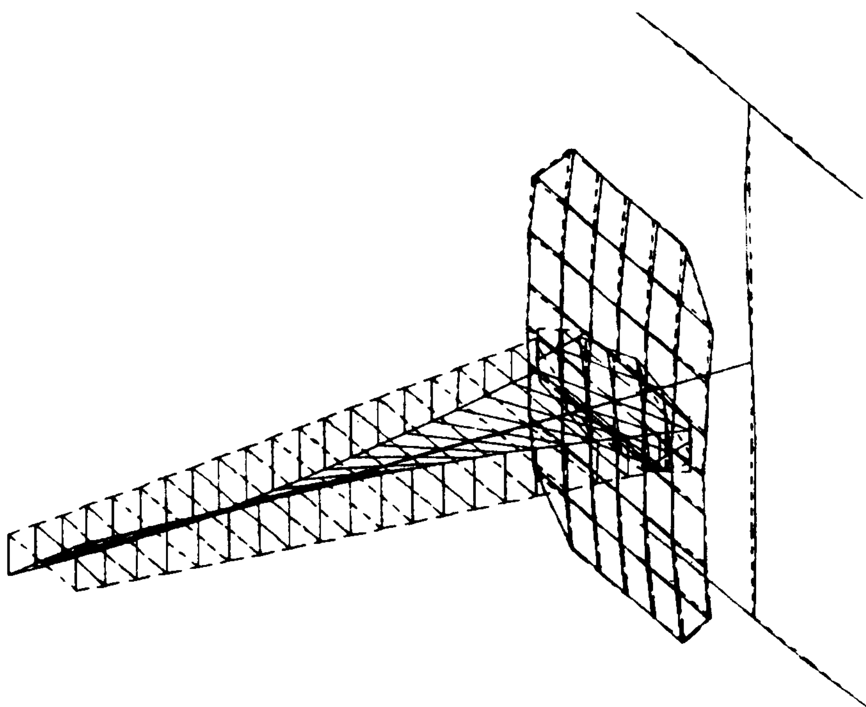


Figure 24. Mode shape comparison of ground vibration test at 882.9 Hz and NASTRAN analysis at 966.4 Hz.



Ground vibration test



NASTRAN analysis

Figure 25. Mode shape comparison of ground vibration test at 963.8 Hz and NASTRAN analysis at 1037.0 Hz.

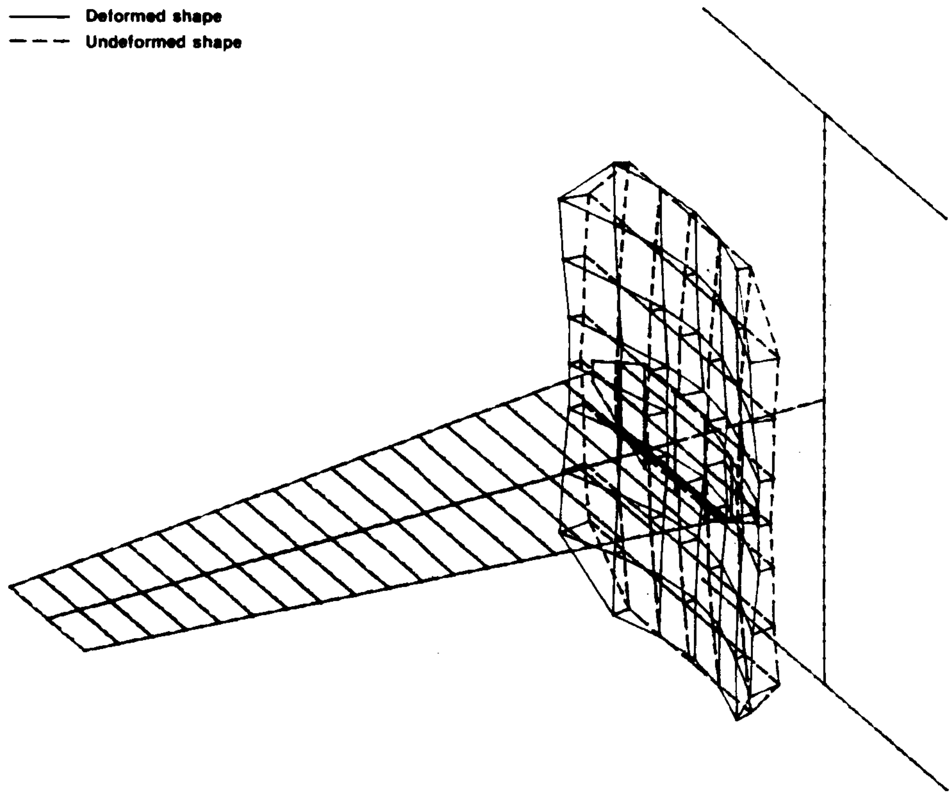
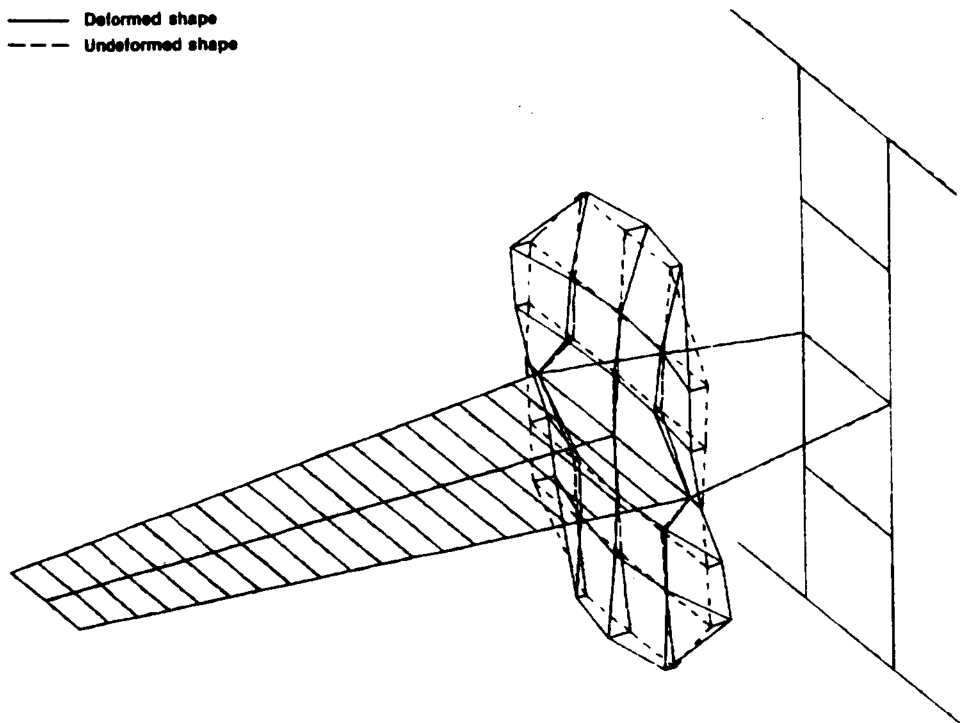
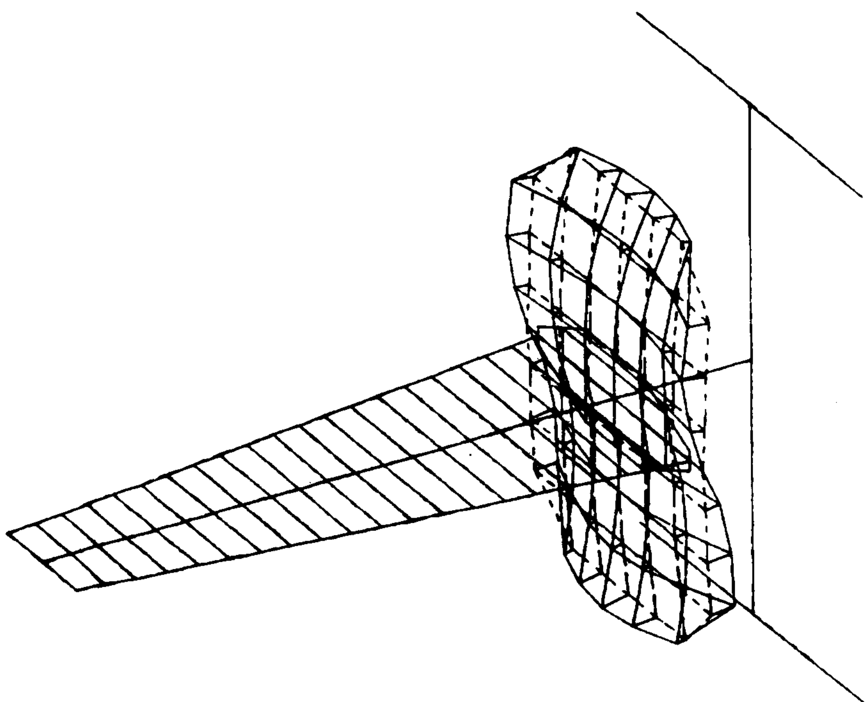


Figure 26. Mode shape of NASTRAN analysis at 1196.0 Hz.



Ground vibration test



NASTRAN analysis

Figure 27. Mode shape comparison of ground vibration test at 1133.1 Hz and NASTRAN analysis at 1198.0 Hz.

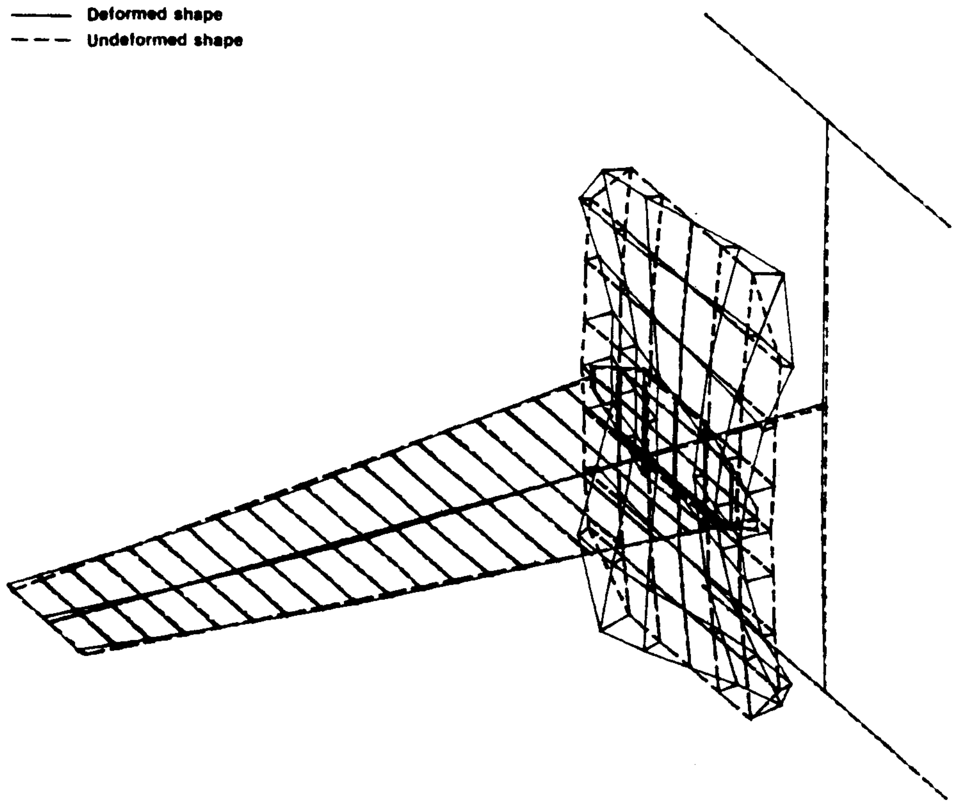


Figure 28. Mode shape of NASTRAN analysis at 1326.0 Hz.

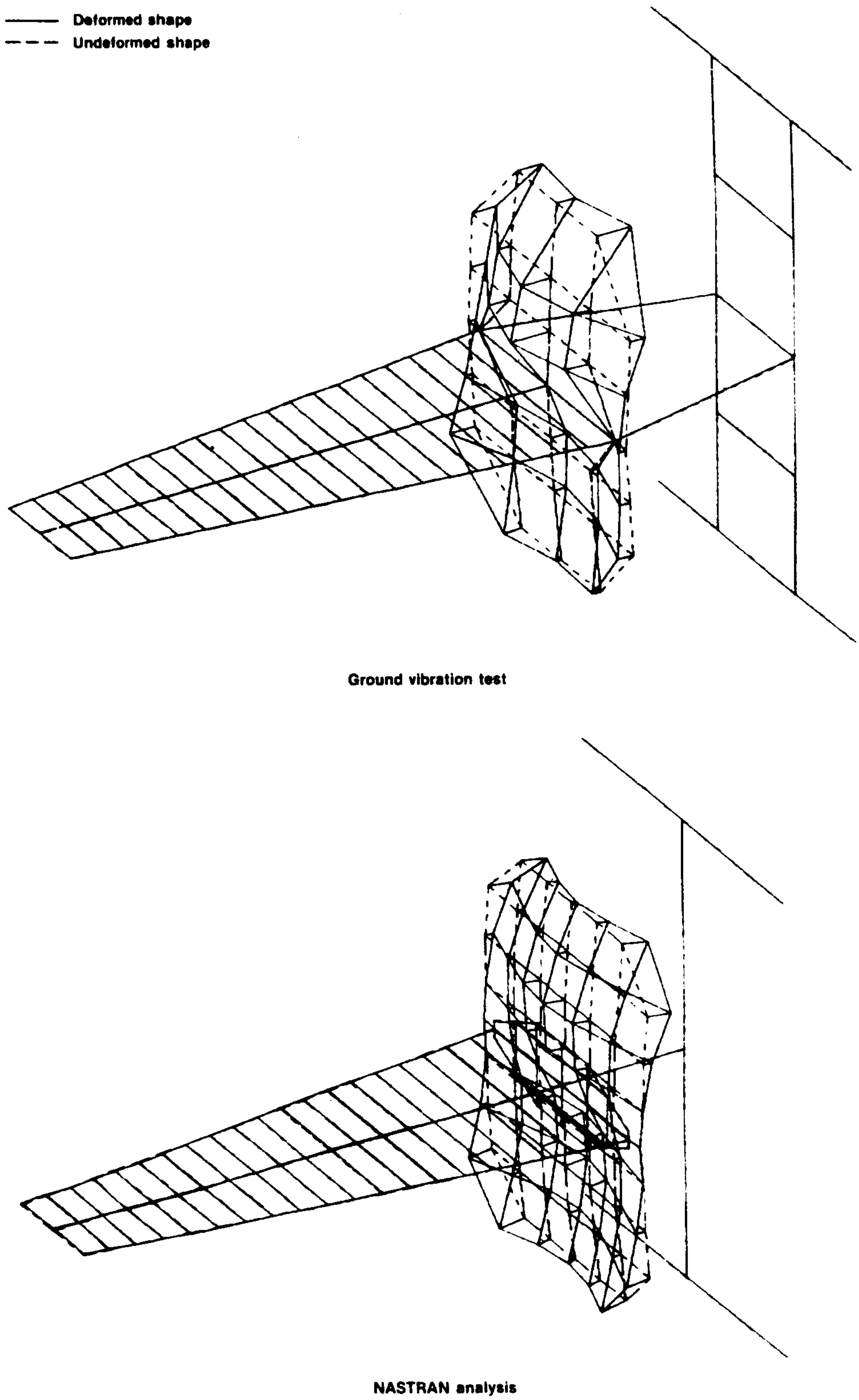
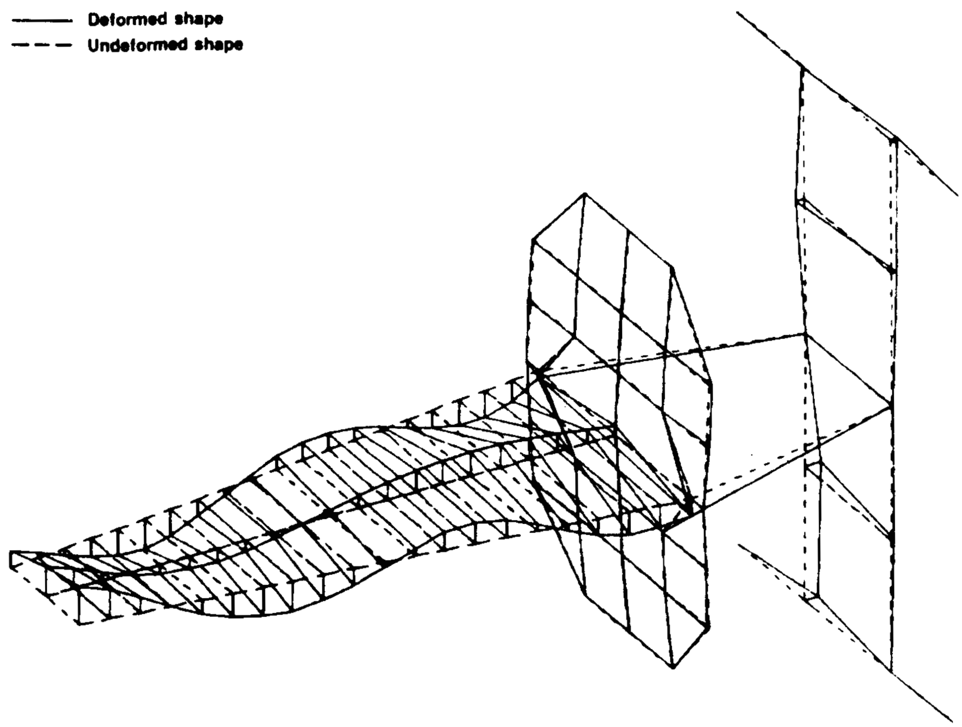
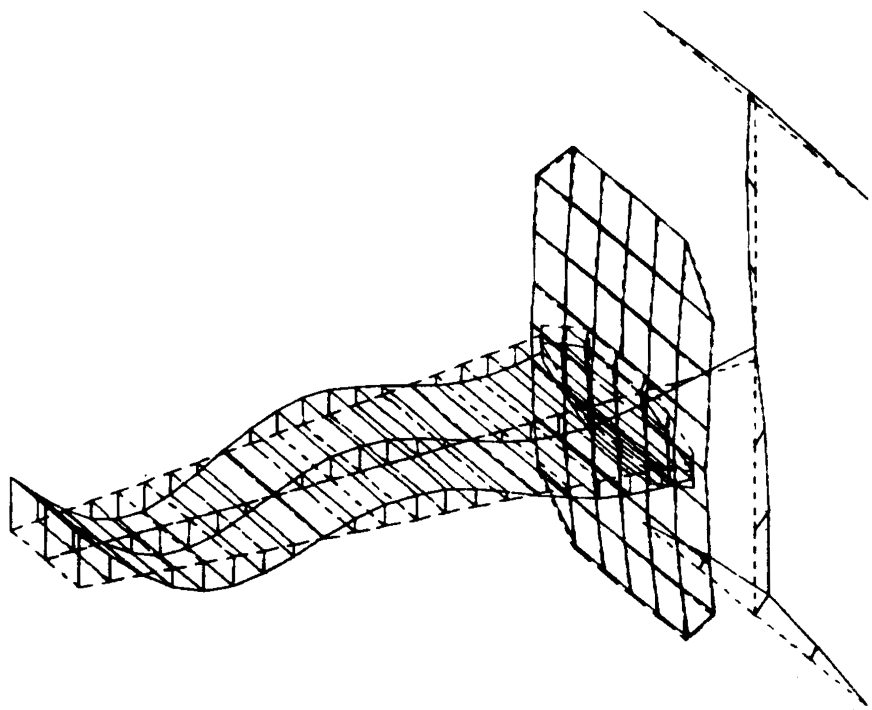


Figure 29. Mode shape comparison of ground vibration test at 1422.7 Hz and NASTRAN analysis at 1586.0 Hz.



Ground vibration test



NASTRAN analysis

Figure 30. Mode shape comparison of ground vibration test at 1524.4 Hz and NASTRAN analysis at 1705.0 Hz.

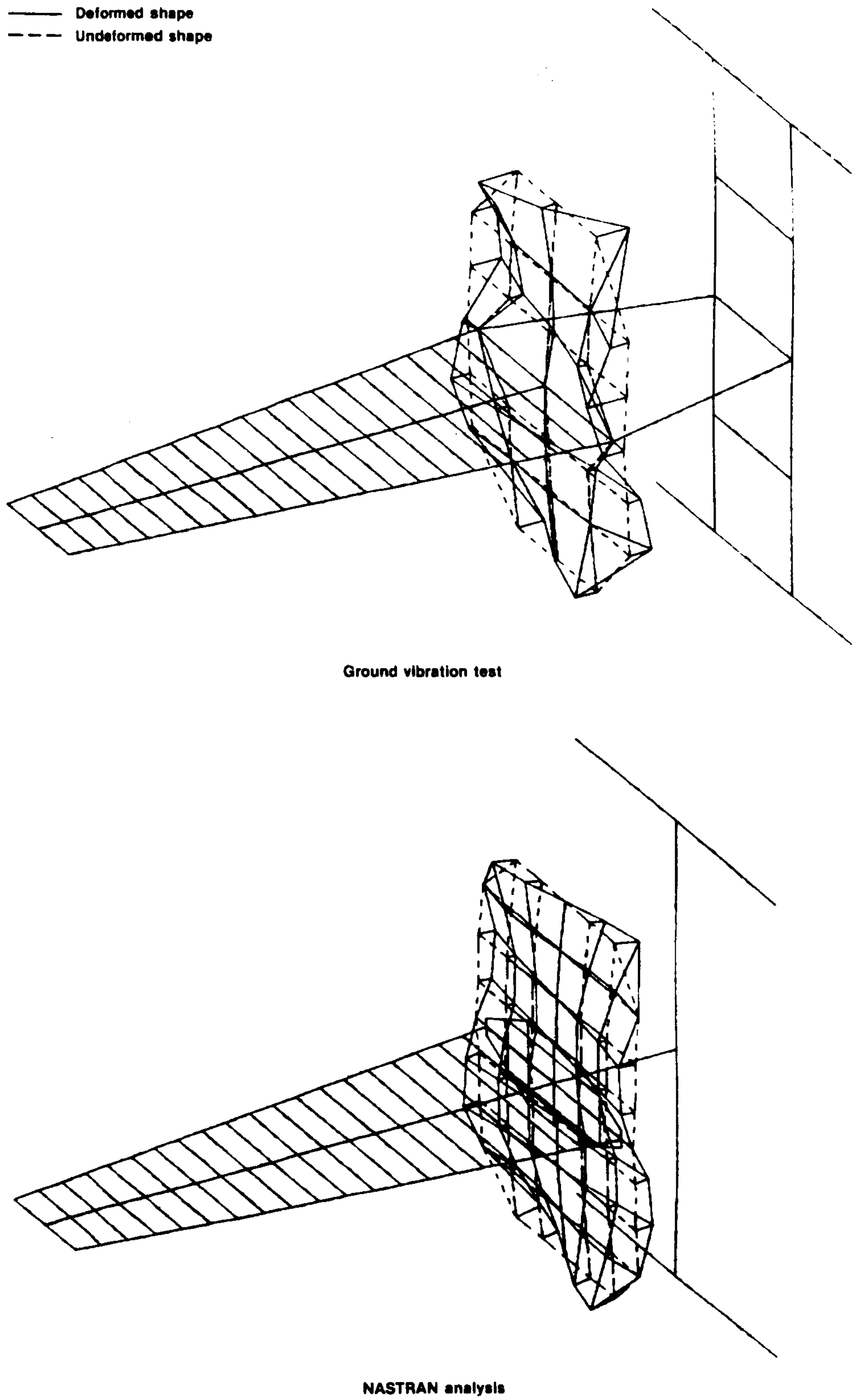


Figure 31. Mode shape comparison of ground vibration test at 1803.2 Hz and NASTRAN analysis at 1935.0 Hz.

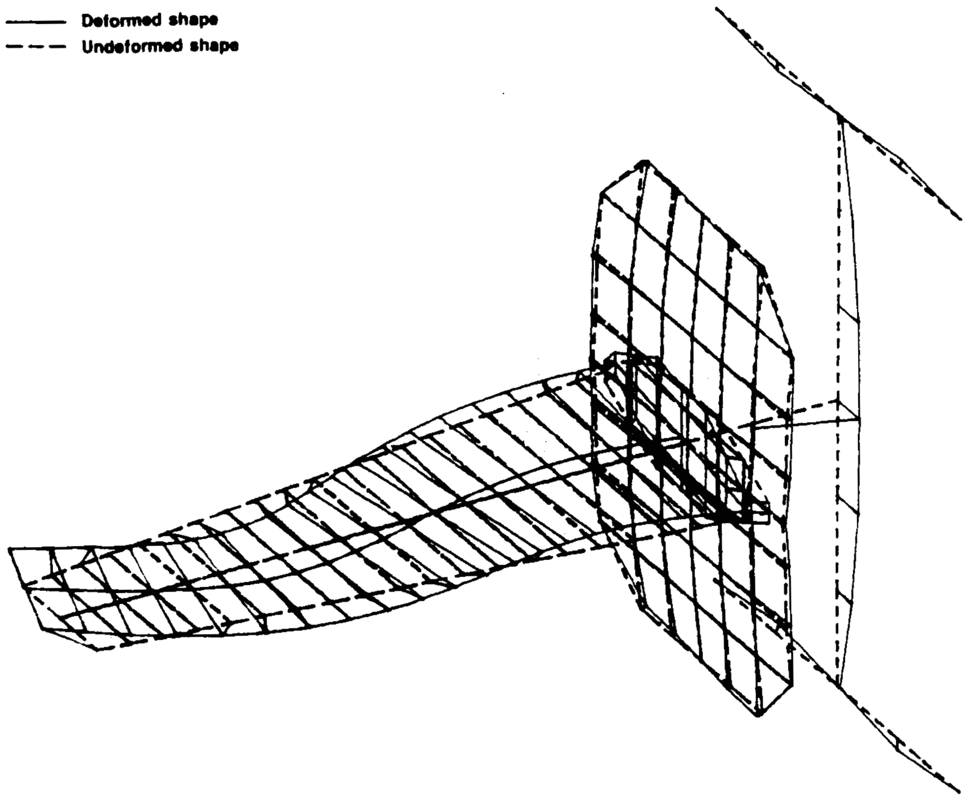


Figure 32. Mode shape of NASTRAN analysis at 2126.0 Hz.

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16. Abstract

The Dryden Flight Research Facility of NASA Ames Research Center conducted a ground vibration test and a flutter analysis of an air sampling probe that was to be mounted on a Convair 990 airplane. The probe was a steel, wing-shaped structure used to gather atmospheric data. The ground vibration test was conducted to update the finite-element model used in the flutter analysis. The analysis predicted flutter speeds well outside the operating flight envelope of the Convair 990 airplane.

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