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Thermoelastic Vibration Test Techniques

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ABSTRACT

The structural integrity of proposed high-speed aircraft can be seriously affected by the extremely high surface temperatures and large temperature gradients throughout the vehicle's structure. Variations in the structure's elastic characteristics as a result of thermal effects can be observed by changes in vibration frequency, damping, and mode shape. Analysis codes that predict these changes must be correlated and verified with experimental data. This paper presents the experimental modal test techniques and procedures used to conduct uniform, nonuniform, and transient thermoelastic vibration tests. Experimental setup and elevated temperature instrumentation considerations are also discussed. Modal data for a 12- by 50-in. aluminum plate heated to a temperature of 475°F are presented. These data show the effect of heat on the plate's modal characteristics. The results indicated that frequency decreased, damping increased, and mode shape remained unchanged as the temperature of the plate was increased.

INTRODUCTION

The structures of hypersonic flight vehicles will be subjected to extremely high surface temperatures and large temperature gradients. These conditions can seriously affect the structural integrity and the aeroelastic and aeroservoelastic stability of the vehicle. If analytical procedures are relied on to predict these changes in stability, then accurate determination of the modal characteristics of these structures at elevated temperatures is vital.

Prior research in the area of thermoelastic vibration testing was conducted for hypersonic vehicle programs of the 1960s. This research documented the effects of nonuniform heating on the fundamental vibration modes of simple panels(1) and on a prototype wing for the X-15 vehicle.(2) Results from this past research indicated that thermal stresses could have significant effects on structural stiffness.

There is a renewed interest in thermoelastic vibration testing with the advent of the National Aero-Space Plane (NASP) program.(3) Design and flight test considerations dictate that analysis methods be accurate enough to predict the structural stability of the vehicle when it is subjected to extremely high temperatures. High confidence in analytical results can only come through correlation and verification with experimental data.

A series of thermoelastic vibration tests are being conducted at the NASA Ames Research Center's Dryden Flight Research Facility. These test results will form a foundation of experimental data, which will permit correlation with computations and verification of analytical procedures. This paper presents the experimental equipment, instrumentation, and test procedures used to conduct uniform, nonuniform, and transient thermoelastic vibration testing. Measured modal data for an aluminum plate heated to a temperature of 475°F are also presented to show the effect of elevated temperature on the frequency, damping, and mode shape of the fundamental plate modes.

NOMENCLATURE

AC	alternating current
FRF	frequency response function
g	acceleration due to gravity
g	structural damping coefficient
lbf	pound-force
NASP	national aero-space plane
MAC	modal assurance criterion
MW	megawatt

mW	milliwatt
VAC	volts alternating current

TEST ARTICLE SETUP

The test article was a uniform flat 7075-T6 aluminum plate 50 in. long, 12 in. wide, and 0.190 in. thick. The plate weighed 12.2 lb without the accelerometers attached. The length of the plate was divided into three zones for instrumentation and heating purposes.

Instrumentation

The plate was instrumented with 18 accelerometers and 30 thermocouples. The maximum operating temperatures of the thermocouples and accelerometers were 2100°F and 550°F, respectively. Each accelerometer weighed 1 oz. Each plate zone contained six accelerometers and nine thermocouples on the front side of the plate. The rear side of the plate had one thermocouple positioned in the center of each zone to measure the temperature gradient across the thickness of the plate. A sketch of the instrumented plate and its suspension is shown in figure 1.

Plate Support Fixture

The plate was supported by a combination of 0.25-in.-diameter bungee cord and steel cables to provide a free-free boundary condition. The overall support fixture is shown in figure 2. The portion of the suspension cables that were inside of the oven were made of steel to withstand the heat. This length was kept as short as possible to avoid affecting the plate's modal characteristics. The steel cables, which were 15 in. long, were attached to the bungee cord with a clevis. The bungee cord was attached to L-shaped brackets at the top of the fixture.

It was important to protect the bungee cord from the heat. The connection of the bungee cord to the steel cable outside of the oven was wrapped with insulating tape. The tape protected the bungee cord from the heat escaping through the small openings for the steel cables located in the top of the oven. These connections were also instrumented with thermocouples to monitor the temperature of the bungee cord at the clevis.

EXPERIMENTAL EQUIPMENT

Overall Setup

A schematic of the heater control, thermocouple data acquisition equipment, and the accelerometer data acquisition equipment is shown in figure 3. The remote satellite computer provided closed-loop control of the plate's temperature. In addition, this system acquired the thermocouple data for display and storage.[4] The modal analysis computer system acquired the accelerometer data for display, analysis, and storage. A detailed description of each component follows.

Oven Description

The oven was composed of an aluminum box containing quartz lamps to heat the front of the test plate only. The oven (fig. 4) was constructed of an aluminum shell with a 1.125-in. layer of ceramic insulation on all of the inside surfaces. The interior of the oven was 74 in. long, 10.5 in. wide, and 34 in. high. The top of the oven was removable to aid in mounting and removing the test article. The bottom of the oven had a 1- by 50-in. opening to allow for routing of the instrumentation wires. A schematic of the oven's interior is shown in figure 5.

The oven was divided into three heating zones that corresponded to the dimensions of the three zones specified on the plate (fig. 1). Each oven zone was separated by fences to prevent radiation heat from the lamps of one zone from heating another zone. The fences extended from the lamps to within 1 in. of the test article surface and were made of ceramic material.

Infrared quartz lamps 0.5 in. in diameter, 42.625 in. long, and spaced 1 in. on center were installed in the oven to heat the front of the test article. The distance from the lamps to the plate was 4.5 in. The test plate was centered in the oven to ensure uniform heating. Centering the plate also allowed the lamps to extend well beyond the plate to avoid the nonuniform heating associated with the lamp ends. This arrangement of lamps provided the capability to heat the plate to a maximum temperature of approximately 1500°F at a maximum rate of 7°F/sec.

Remote Satellite Computer

The remote satellite computer served as a data acquisition and temperature control system. This system was physically connected to the main computer located in the control room. The heating tests were normally controlled and monitored from the control room but could be controlled at the test site from the satellite computer.

Thermal control of each of the plate's heating zones was accomplished with a digital, adaptive, closed-loop system. The temperature of each zone was forced to follow a specified, predefined profile. Control thermocouples located in the center of each zone on the plate provided feedback temperature information for the control system. Adaptive computer algorithms were used to determine the power output levels for the rectifier power controllers that provided the energy to illuminate the quartz lamps. For static temperature control, the oven temperatures were controlled to within ± 5°F of the specified value. For dynamic temperature control, the oven temperature was within ± 10°F of the specified value for a temperature change rate of 7°F/sec.

The thermocouple data were acquired at 12 samples/sec. A calibration was performed on all input channels to give data with engineering unit values.

Modal Analysis Computer

The accelerometer responses were acquired by the modal analysis computer, which was a separate system from the remote satellite computer. This modal analysis computer acquired the 18 accelerometer data channels at a sample rate of 12.8 kHz and then digitally filtered the data to a frequency bandwidth of 100 Hz. Frequency response functions were calculated for each data channel, displayed, and then stored on the system disk. These frequency response functions were used for modal analysis to determine frequency, damping, and mode shape. Hard copies of the frequency response functions and mode shapes were available from a laser printer.

Laser Vibrometer

A dedicated test was conducted with a laser vibrometer to evaluate the device's suitability for measuring vibration in a hostile environment. Lasers may be used in the future to measure vibrations in environments with extremely high temperatures. The laser vibrometer used had a single-point staring laser with a power rating of 1 mW. Reflective tape was attached to the rear side of the plate at the same location as the accelerometers. The tape was used to ensure sufficient back-scattered intensity at the photodetector of the laser unit.

TEST TECHNIQUE

Boundary Condition

A free-free boundary condition was selected to minimize the complexity of the test setup. This type of boundary condition alleviated the uncertainties associated with the interface between the plate and the mounting fixture. Uncertainties associated with the effects of heat conduction and thermally induced stresses at the mounting fixture interface are therefore removed. Correlation of experimental data with analytical predictions is more accurately accomplished with these effects removed.

Excitation

Single-input broadband random and impact excitation were used to excite the plate. Each type of excitation was applied to the plate by a rod which was attached to the plate and protruded through a hole in the oven. The location of the rod attachment point was selected to provide an adequate amount of excitation for the first four structural modes. The attachment point is shown in figure 1. The plate and rod were threaded, which provided a way of connecting them. A nut was placed on the threaded portion of the rod that extended through the plate to reduce the rod's freeplay.

Initially, single-input broadband random excitation was used. The forcing function was generated by a closed-loop system with the plate in the loop (fig. 6). This technique prevented reductions in force at the plate resonant frequencies that can occur when the mass of the test structure is small compared to the shaker armature mass.[5]

Approximately 5 min of random response data were acquired to ensure a statistically good sample. This length of time at elevated temperatures allowed the bungee cord temperature to rise high enough to cause concern about the cord burning through. As a result, impact excitation was seen as an alternative approach.

Impact excitation was provided to the plate by striking the rod, which was attached to the plate, with a calibrated hammer. Five averages of impact data were acquired in approximately 1 min. The shortened acquisition time significantly reduced the bungee cord temperature and provided satisfactory modal data. Impact excitation provided a way to excite the plate in the shortest amount of time, which was essential during transient heating of the plate. Therefore, impact excitation was selected to conduct the tests on the plate.

Uniform Plate Heating

Uniform heating of the plate was done by heating each zone of the plate to the same temperature. The thermocouple readings were monitored to ensure that there was no temperature gradient across the plate's thickness and that the plate was uniformly heated. Once these conditions were met, the plate was excited by impact excitation. The accelerometer response data were acquired by the modal analysis computer. A hard copy of the plate temperature distribution was obtained from the thermal data acquisition host computer. After accelerometer data acquisition, the frequency response functions were displayed on the modal analysis computer to verify the quality of the data. The data quality was determined by examining coherence and frequency response functions. If the data quality was satisfactory, the frequency response functions were stored on the system disk for later analysis. The temperature of the oven was then increased to the next higher temperature and the process was repeated.

The absense of plate warpage was determined by comparing measurements of the first four fundamental plate frequencies before and after each uniform heating test. These measurements were made at room temperature using impact excitation. Differences in these frequencies was an indication that the plate had permanently deformed because of the heating test.

Nonuniform Plate Heating

Nonuniform heating of the plate consisted of heating the plate's three zones to a different temperature. The plate was uniformly heated until the lowest target temperature of a particular zone was reached. At this point, the oven tried to maintain the temperature of that zone while heating the two remaining zones to the next highest target temperature. Once reached, the oven heated the remaining zone, while attempting to maintain the temperatures of the two other zones.

The temperature distribution of each zone was monitored closely, particularly for the zones of the plate that were heated to lower temperatures. The plate was excited by impact excitation and accelerometer responses were acquired when the highest target temperature of the plate had been reached. If the temperature of any zone varied by more than 15°F from the initial target temperatures, testing was terminated. This often resulted in less than five averages of plate impact response data, particularly at temperatures above 400°F.

After data acquisition, the frequency response functions were displayed to verify the quality of the data. If the data quality was satisfactory, the frequency response functions were stored on the system disk for later analysis. The plate was then allowed to cool to room temperature before the next test was conducted.

Plate warpage from testing was monitored, as described earlier.

Transient, Nonuniform Plate Heating

Transient, nonuniform plate heating was conducted by heating an end zone of the plate. The zone was heated at different rates up to a maximum temperature of 475°F. The three different heating rates used were 3, 5, and 7°F/sec. The plate was continually excited while it was heated and each plate time history response was stored directly to the system disk.

Data were also acquired while the plate cooled down. In addition, the time for each impact was noted for correlation with the temperature distributions stored on the thermal control system disk. The plate was allowed to cool to room temperature before another test was attempted. The plate time history responses were recalled after each test, and frequency response functions and the modal parameters for the plate were then calculated.

Plate warpage from testing was monitored, as described earlier.

DATA ANALYSIS METHODS

Once data acquisition was completed for a given heating profile, frequency and damping for the first four plate modes were estimated. The technique used operated on a single frequency response function. The frequency response function at the plate corner was selected because it contained the response of the first four modes. The modal parameter estimates were made by fitting a second-order polynomial to each frequency peak in the function. Values of frequency, damping, phase, and amplitude were generated for each peak.

Mode shapes were generated using a single-degree-of-freedom technique. This technique extracted amplitude and phase information from each plate frequency response function at the specified modal frequency. The information was then used for viewing animated mode shapes and static deformation plots.

RESULTS AND DISCUSSION

Instrumentation Noise

The electromagnetic field and heat radiation of the quartz lamps as they fired to heat the plate added noise to the accelerometer signals. This noise is seen in a comparison of frequency response functions (FRF) obtained at 75 and 400°F (fig. 7).

Excitation

The plate was initially excited with broadband random excitation. The noise on the frequency response functions at elevated temperatures was virtually eliminated, with 50 averages of response data using this type of excitation. A comparison of frequency response functions obtained at 400°F with random and impact excitation is shown in figure 8. One advantage of random excitation is the reduction of signal noise through the averaging process. However, random excitation required longer data acquisition times, which was acceptable for uniform heating but not for nonuniform or transient heating.

The random excitation frequency response function data also indicated that the plate resonant frequencies were lower in value when compared to the impact excitation frequency response data. This effect was caused by the electrodynamic shaker armature mass. The one mode not affected by this additional mass was the second plate bending mode at 38 Hz. This resonant frequency remained unchanged because the shaker was attached close to a node line on the plate.(6)

Although noise was present on the frequency response functions obtained from impact excitation, accurate estimates of the modal parameters were still possible. Commercially available modal analysis software packages offer several techniques that can accurately estimate frequency, damping, and mode shape from data noisier than that obtained from the plate.

Accelerometer and Laser Vibrometer Modal Data Response

A comparison of the modal parameters estimated from accelerometer and laser vibrometer responses at 400°F is shown in table 1. Note that the frequency and damping values for both sets of data are nearly identical. These data indicate that a laser vibrometer can replace an accelerometer in a hostile environment. Typical lightweight accelerometers are currently rated to a maximum operating temperature of only 550°F.

Bungee Cord Thermal Considerations

The tests conducted with the laser vibrometer required the oven to heat the plate for long periods of time because the laser had to be physically moved to each plate response measurement location. The long heating times caused the bungee cord to overheat, resulting in burn through and loss of resiliency.

One test required heating the plate to 400°F for 45 min to acquire the necessary data. During this test the rubber of one bungee cord had burnt through and only the outer cloth shield remained intact. The thermocouple reading for this bungee cord was as high as 350°F for 25 min.

There are several possible solutions to the overheating of the bungee cord. These include conducting tests of shorter duration, installing water jackets, and using multiple laser vibrometers. However, none of these were tried.

Plate Temperature Distribution

Typical plate temperature distributions for uniform, nonuniform, and transient heating are shown in figure 9. The temperature distributions were extrapolated from temperature measurements of the 27 thermocouples placed on the front of the plate. The temperature distribution plot for uniform heating showed that the top of the plate was approximately 20°F higher than the bottom. This effect was a result of the heat rising within the oven and being trapped at the top. The temperature at the center of the plate was maintained at 475°F because the controller thermocouples were placed in the center. The temperature difference between the plate's top and bottom was particularly noticeable above 400°F.

The nonuniform and transient temperature distributions showed the effectiveness of the oven fences in confining the lamp heat to the zone being heated. This was particularly evident for the transient heating in which one zone at the end on the plate was rapidly heated to 475°F.

The 27 thermocouples that measured the plate temperatures on the front side of the plate were adequate to define the temperature distribution. However, the rear of the plate was only instrumented with three thermocouples. These were adequate for uniform and nonuniform heating because there was no temperature gradient across the thickness of the plate. For transient heating, there was a significant temperature gradient across the plate's thickness. This gradient increased simultaneously with the heating rate. The temperature gradient was measured at the center of the heated plate zone and is shown in figure 10 as a function of control temperature. The data indicate a maximum temperature gradient of 80°F when the plate was at 475°F. This gradient was measured at a heating rate of 7°F/sec. To accurately measure the temperature distribution on the rear side of the plate, 27 thermocouples would be needed.

Modal Data

The plate modal frequency as a function of temperature for uniform heating is shown in figure 11. The data indicate that the frequency decreased as the temperature increased. The smallest change in frequency was for the plate first bending mode and the largest change was for the plate second torsion mode. The percent change in frequency from room temperature to 475°F was 7.8 percent for first plate bending, 5.6 percent for first plate torsion, 7.1 percent for second plate bending, and 7.0 percent for second plate torsion. Also, the damping increased and the magnitude of the frequency response function decreased as the temperature increased. These data are presented in table 2.

The decrease in plate frequency was a result of the decrease in the modulus of elasticity as temperature was increased. The decreased modulus of elasticity represented a decrease in plate stiffness as the temperature was increased. Also, as the plate was heated it became more viscous, thus allowing the plate to dissipate more energy than in its cold state. The result was a reduction of the frequency response function magnitude and an increase in modal damping as the plate temperature increased.

The modal assurance criterion (MAC),[7] which can be used as an approximation of an orthogonality check, was used to compare the plate's mode shapes at each temperature. Values above 0.90 indicate reasonably close agreement between mode shapes. The MAC values for the first four elastic modes are shown in table 3. None of the values shown in the table are below 0.98, which indicates insignificant change in the mode shapes.

CONCLUDING REMARKS

Analysis codes that predict the aeroelastic and aeroservoelastic stability of proposed hypersonic vehicles at high temperatures must be correlated and validated with experimental data. Experimental modal test techniques and procedures for thermoelastic vibration testing for uniform, nonuniform, and transient heating were used on an aluminum plate heated to 475°F.

An enclosed oven was used to heat the test specimen. The oven incorporated a programmable, closed-loop thermal control system to precisely control the temperature and heating rate.

The electromagnetic field and heat radiation of the quartz heater lamps used to heat the oven were sensed by the accelerometers mounted on the plate. These effects resulted in the addition of noise to the accelerometer signals. However, the amount of noise present on these signals did not prevent accurate estimates of the modal parameters from the data.

It was also found that a laser vibrometer can measure plate vibrations in an elevated temperature environment. The modal data acquired with the laser vibrometer correlated well with data acquired with accelerometers.

Broadband random excitation provided a means for averaging out the noise in the accelerometer signals. However, the data acquisition time associated with this type of excitation was not acceptable for nonuniform or transient-type heating when data acquisition must be accomplished quickly. Impact excitation not only provided high-quality data, but it also provided short data acquisition times.

For transient heating, a thin plate must be extensively instrumented on both sides with thermocouples. This instrumentation is necessary to accurately map the temperature distributions because of large temperature gradients. For steady-state uniform and nonuniform heating, only one side must be extensively instrumented as there was virtually no temperature gradient across the thickness of the plate.

The measured modal data of a uniformly heated aluminum plate indicated that frequency decreased and damping increased as the plate temperature increased. The mode shapes for the first four elastic modes remained unchanged as a function of temperature.

Dryden Flight Research Facility
National Aeronautics and Space Administration
Edwards, California, August 22, 1990.

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Table 1. Accelerometer and laser vibrometer modal parameter comparison for an aluminum plate heated to 400°F.

Mode	Accelerometer		Laser vibrometer	
	Frequency, Hz	Damping, g	Frequency, Hz	Damping, g
1	13.563	0.023	13.563	0.026
2	34.313	0.024	34.563	0.023
3	39.313	0.014	39.250	0.013
4	69.875	0.022	69.625	0.025

Table 2. Plate modal data for uniform heating.

Description	Frequency, Hz	Damping, g	FRF magnitude, g/lbf
Mode 1, first plate bending, °F			
75	14.375	0.009	14.4
202	14.063	0.009	10.2
306	13.875	0.014	7.3
339	13.750	0.018	5.4
400	13.563	0.023	4.5
474	13.250	0.033	3.0
Mode 2, first plate torsion, °F			
75	36.000	0.010	12.3
202	35.125	0.016	10.0
306	34.875	0.014	10.1
339	34.688	0.023	7.3
400	34.313	0.024	6.3
474	34.000	0.022	5.0
Mode 3, second plate bending, °F			
75	41.438	0.006	6.9
202	40.625	0.009	8.7
306	40.063	0.008	9.3
339	39.875	0.011	7.1
400	39.313	0.014	5.3
474	38.500	0.021	3.5
Mode 4, second plate torsion, °F			
75	73.813	0.007	13.2
202	71.875	0.021	10.4
306	71.188	0.011	14.0
339	70.875	0.017	10.7
400	69.875	0.022	8.3
474	68.625	0.021	7.4

Table 3. Modal assurance criterion for plate uniform heating.

Description	Mode 1, first plate bending, 75°F	Mode 2, first plate torsion, 75°F	Mode 3, second plate bending, 75°F	Mode 4, second plate torsion, 75°F
Mode 1, °F				
75	1.000	0.000	0.000	0.000
202	0.998	0.000	0.000	0.000
306	0.997	0.000	0.000	0.000
339	0.997	0.000	0.000	0.000
400	0.996	0.000	0.000	0.000
474	0.985	0.003	0.000	0.000
Mode 2, °F				
75	0.000	1.000	0.000	0.001
202	0.000	1.000	0.000	0.002
306	0.000	1.000	0.000	0.002
339	0.000	1.000	0.000	0.002
400	0.000	1.000	0.000	0.002
474	0.001	0.999	0.000	0.001
Mode 3, °F				
75	0.000	0.000	1.000	0.000
202	0.000	0.000	1.000	0.000
306	0.000	0.000	1.000	0.000
339	0.000	0.000	1.000	0.000
400	0.000	0.000	1.000	0.000
474	0.000	0.000	0.999	0.001
Mode 4, °F				
75	0.000	0.001	0.000	1.000
202	0.000	0.002	0.000	1.000
306	0.000	0.002	0.000	1.000
339	0.000	0.002	0.000	1.000
400	0.000	0.002	0.001	1.000
474	0.000	0.001	0.001	1.000

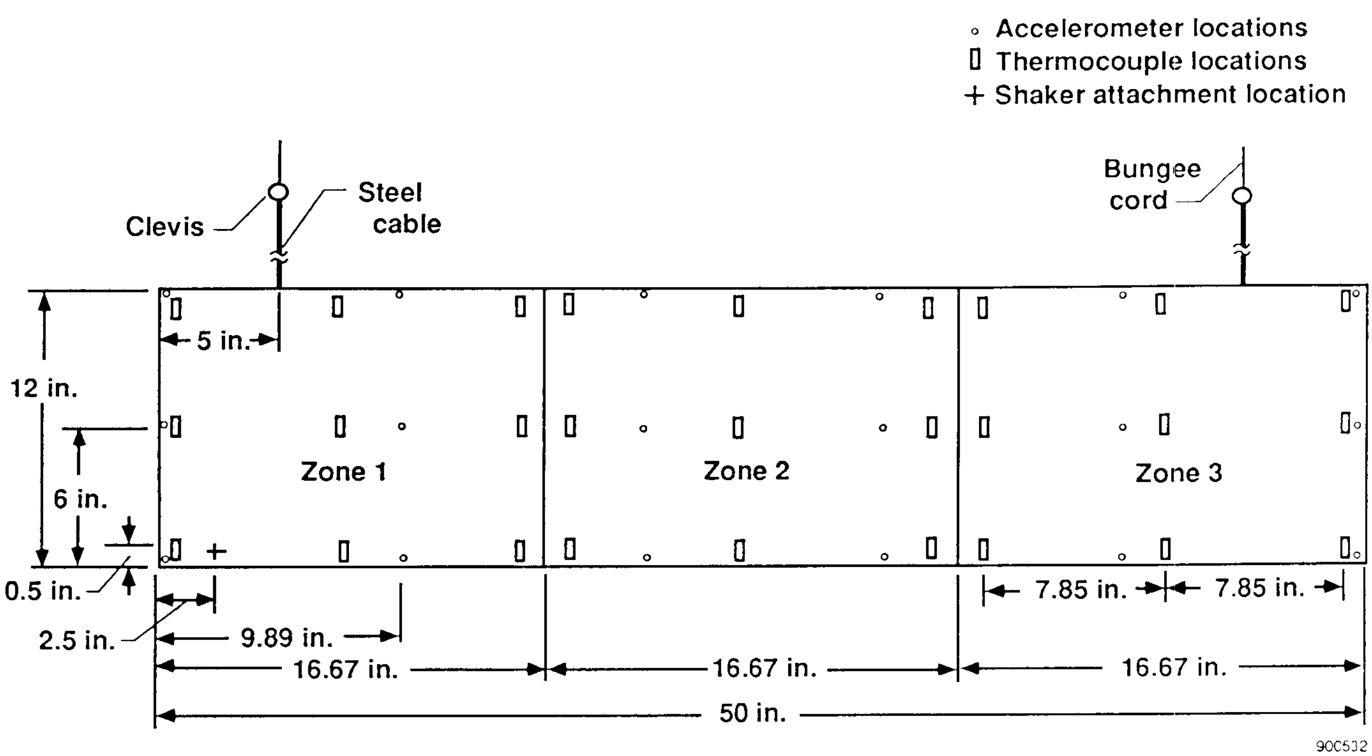

Figure 1. Heating zones and instrumentation locations on the front of the test plate.

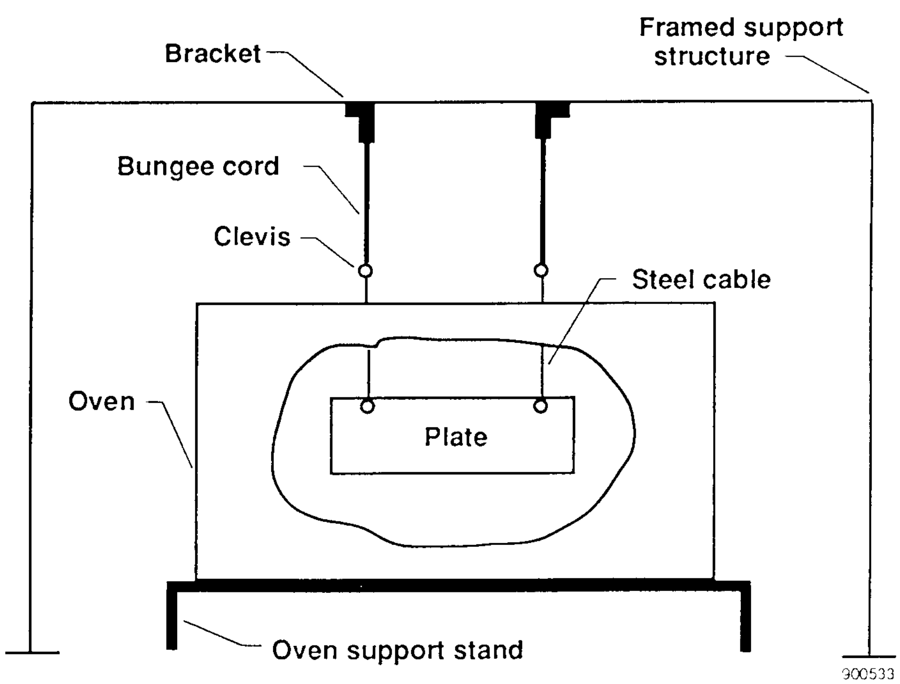

Figure 2. Plate support fixture.

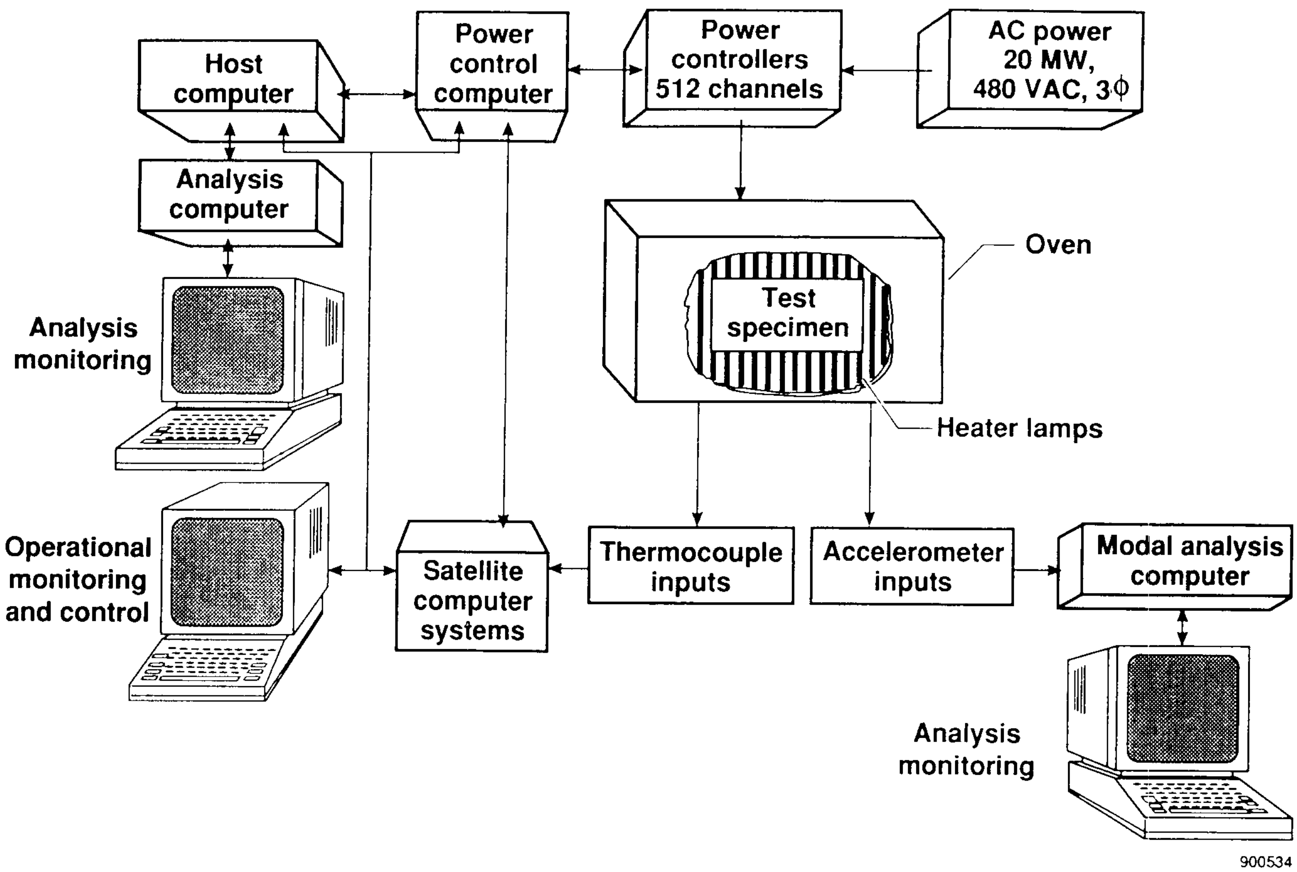

Figure 3. Oven control and data acquisition.

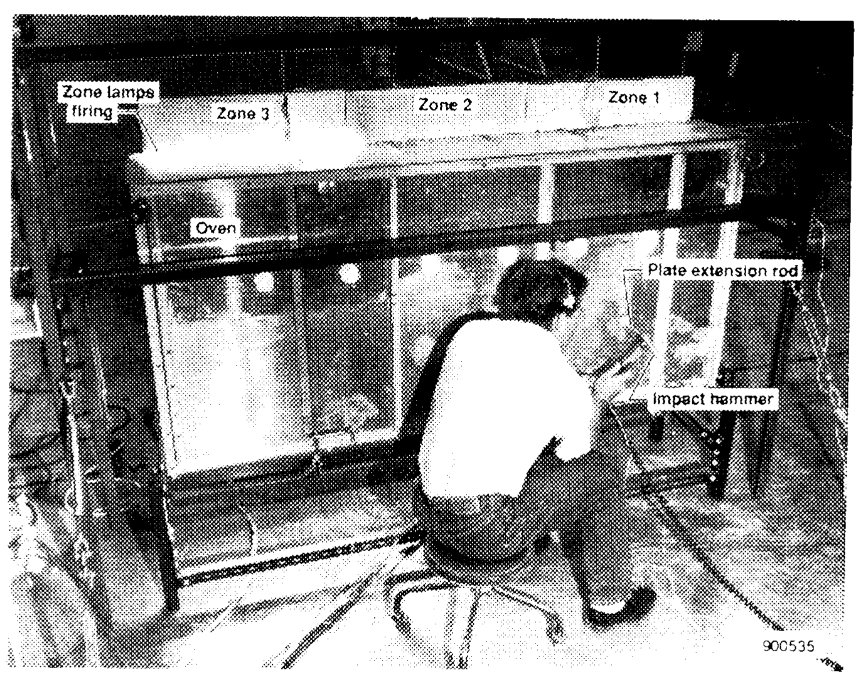

Figure 4. Enclosed oven heating an aluminum plate.

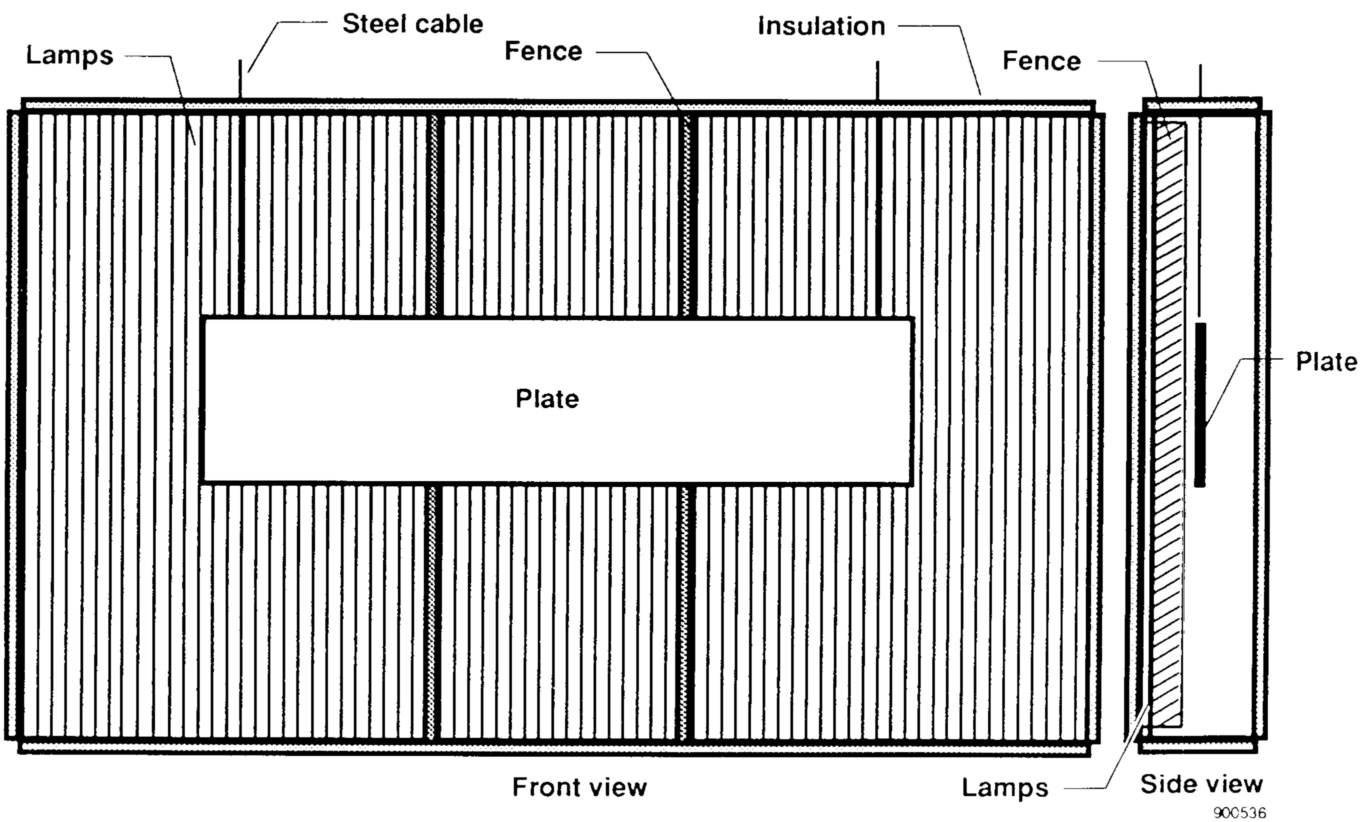

Figure 5. Schematic of the oven interior.

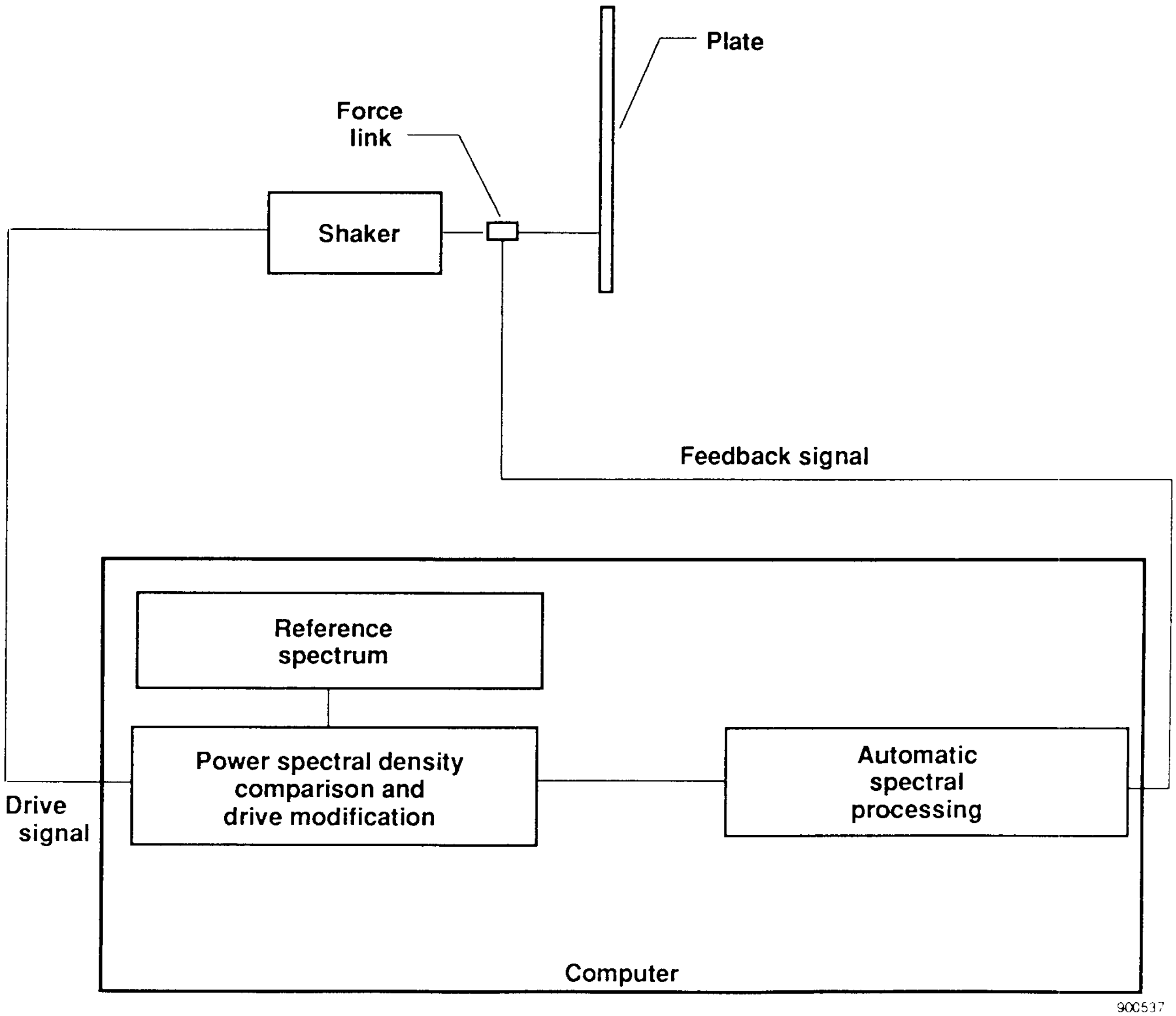

Figure 6. Random vibration control system.

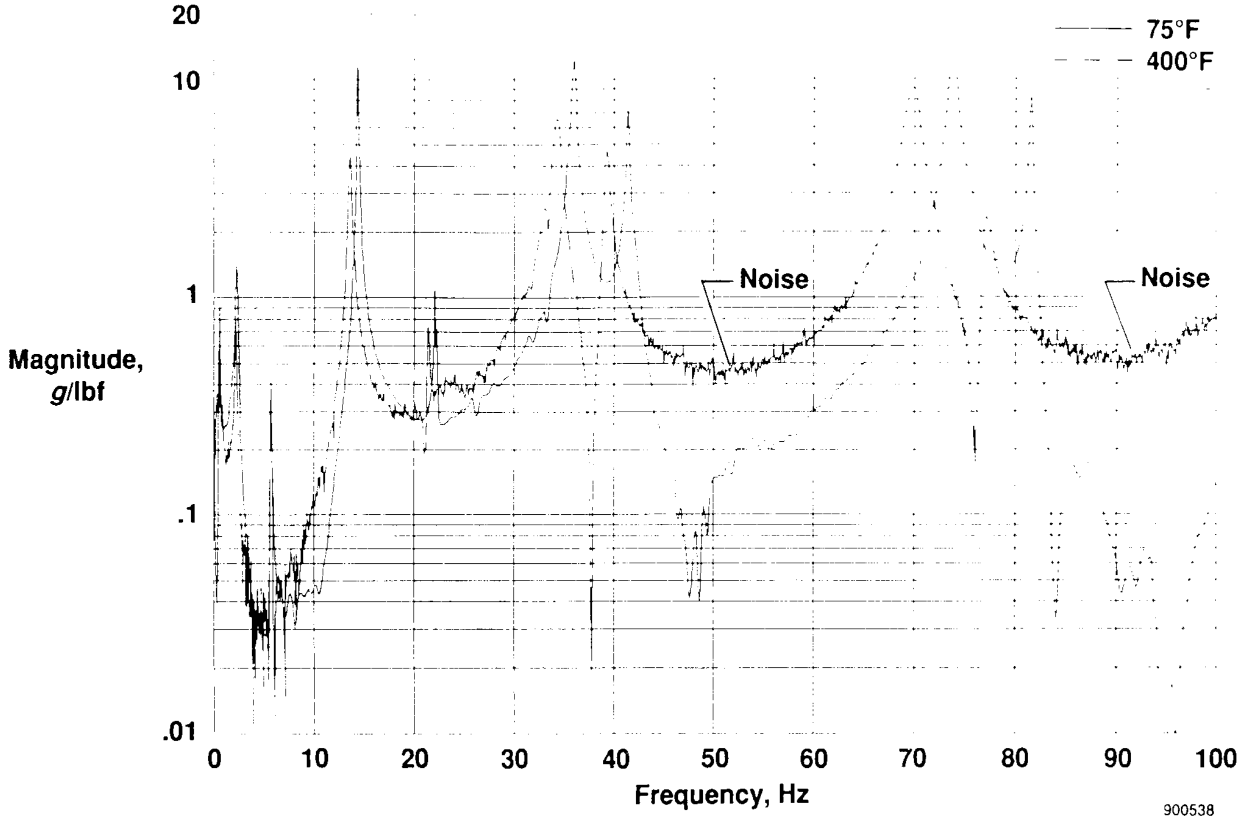

Figure 7. Comparison of frequency response plots obtained at room and elevated temperature with impact excitation.

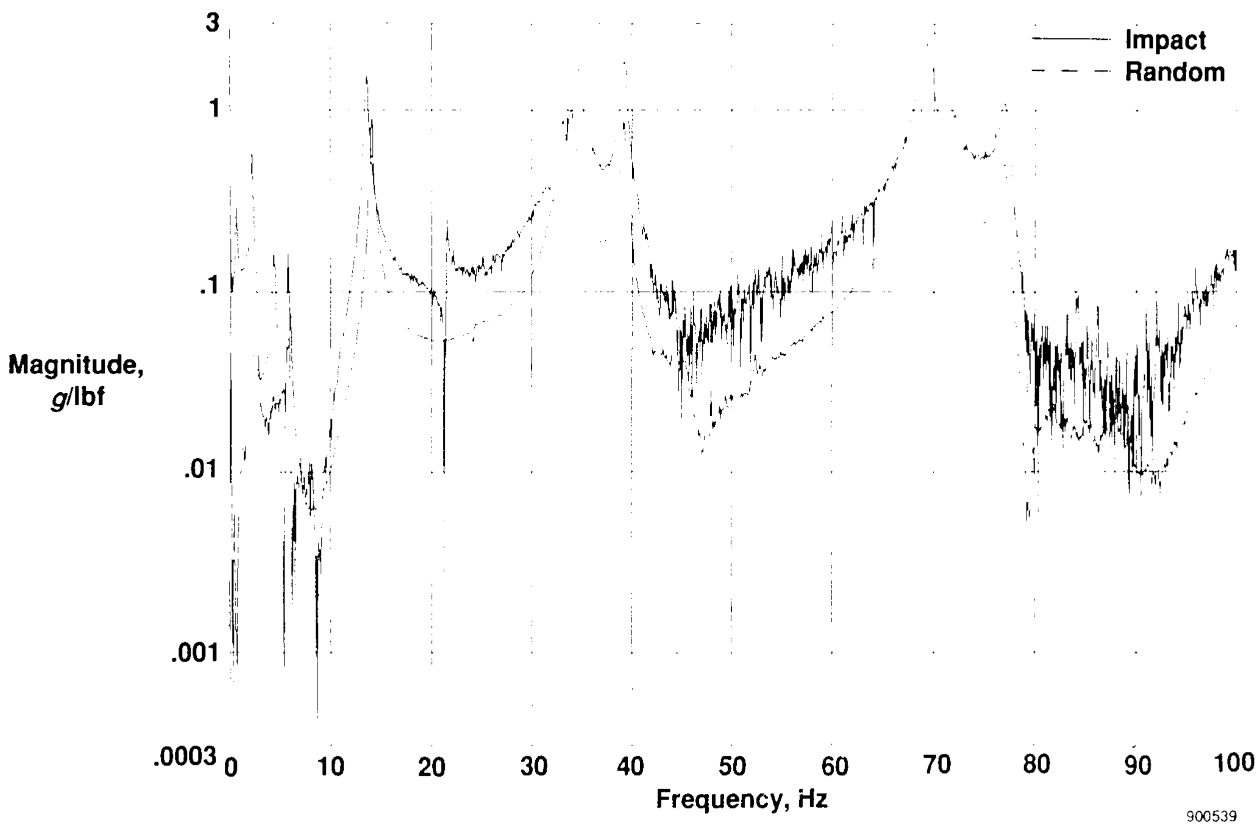

Figure 8. Comparison of frequency response plots for impact and random excitation at 400 °F.

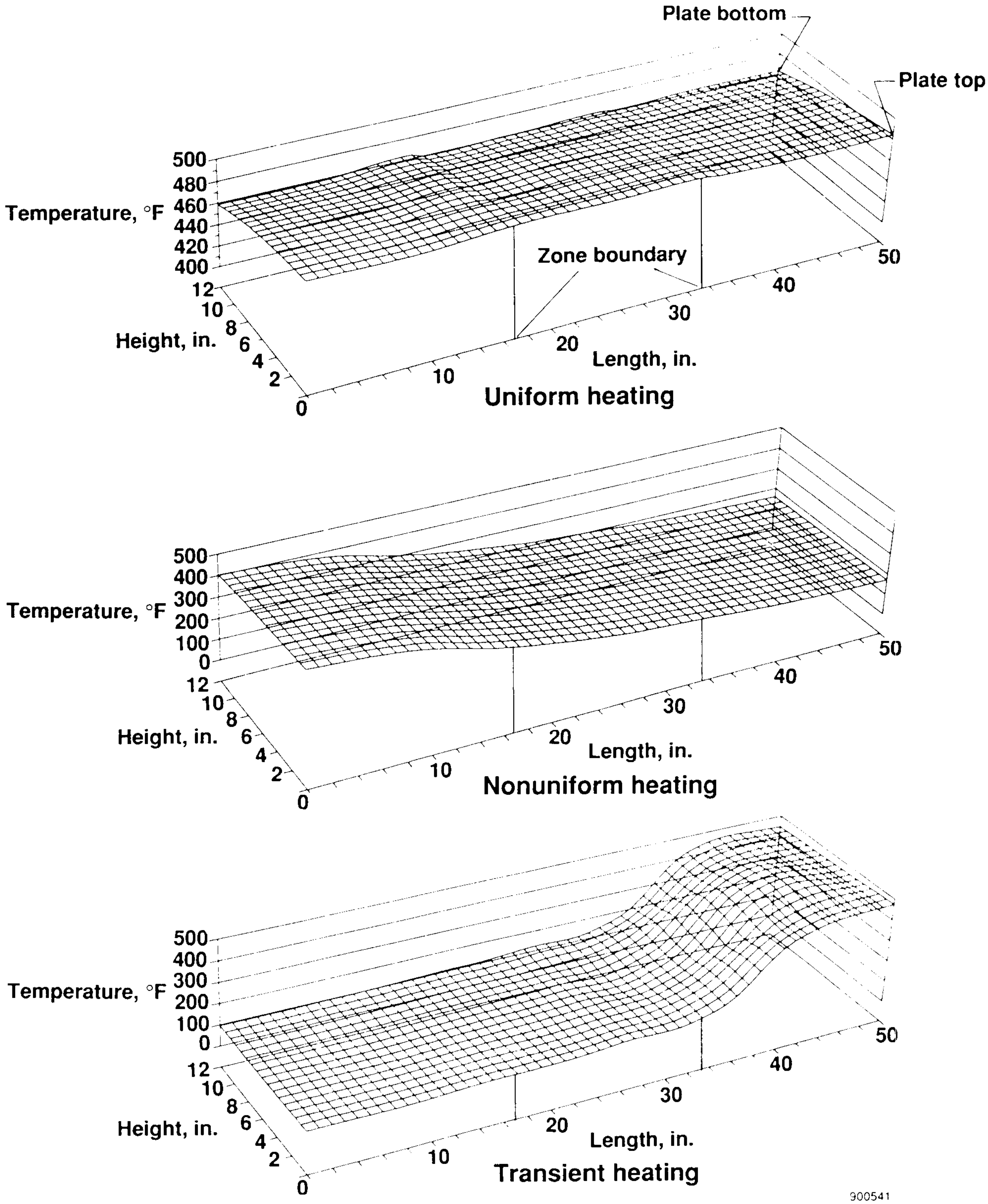

Figure 9. Comparison of plate temperature distribution plots.

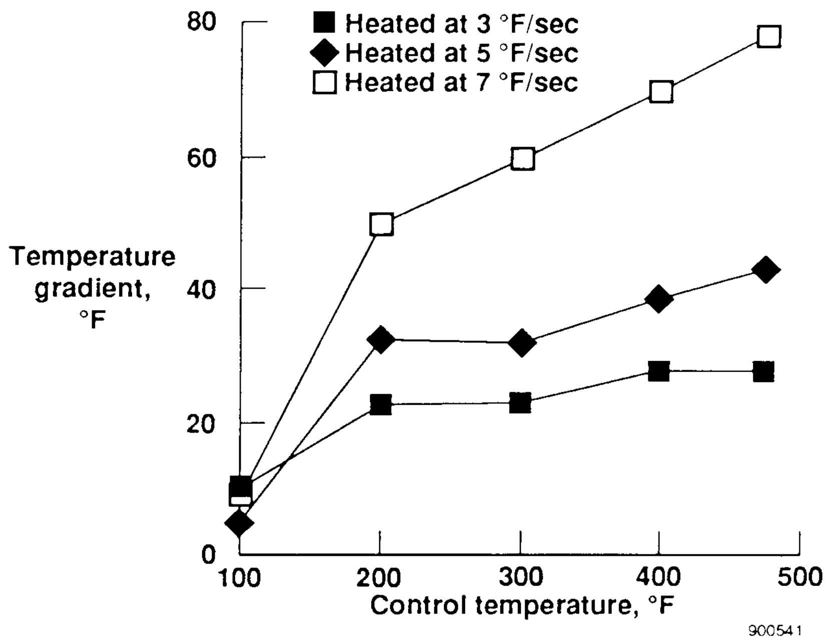

Figure 10. Plate thickness temperature gradient during transient heating of zone 3.

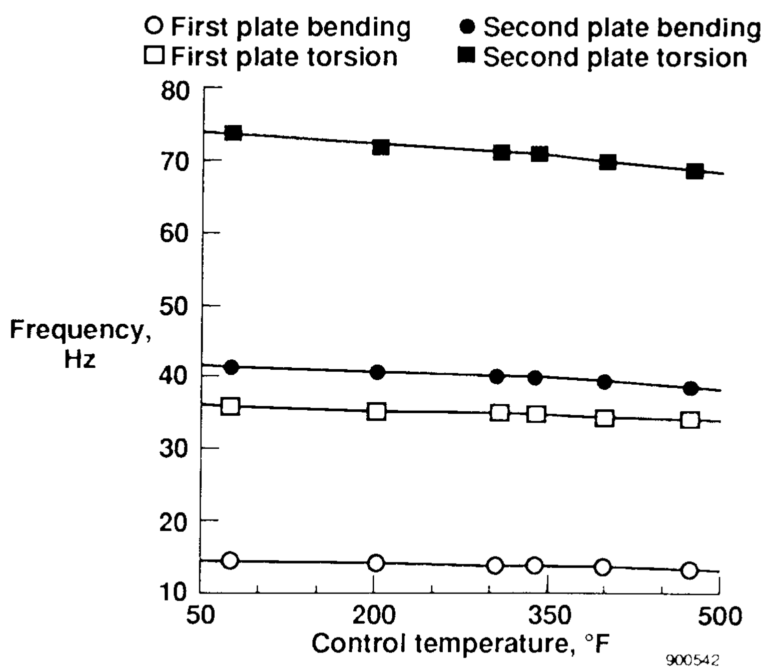

Figure 11. Frequency as a function of temperature for a uniformly heated aluminum plate.

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15. Supplementary Notes

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16. Abstract

The structural integrity of proposed high-speed aircraft can be seriously affected by the extremely high surface temperatures and large temperature gradients throughout the vehicle's structure. Variations in the structure's elastic characteristics as a result of thermal effects can be observed by changes in vibration frequency, damping, and mode shape. Analysis codes that predict these changes must be correlated and verified with experimental data. This paper presents the experimental modal test techniques and procedures used to conduct uniform, nonuniform, and transient thermoelastic vibration tests. Experimental setup and elevated temperature instrumentation considerations are also discussed. Modal data for a 12- by 50-in. aluminum plate heated to a temperature of 475°F are presented. These data show the effect of heat on the plate's modal characteristics. The results indicated that frequency decreased, damping increased, and mode shape remained unchanged as the temperature of the plate was increased.

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