High-Intensity Acoustic Tests of a Thermally Stressed Plate

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An investigation was conducted in the Thermal Acoustic Fatigue Apparatus to study the random motion of a buckled aluminum plate exposed to heat and intense acoustic loads. Plate buckling was due to thermal stress. The plate was exposed to noise levels up to 160 dB and temperatures to 250°F. Two different thermal boundary conditions of the plate were studied; one condition with the plate clamped in a steel frame and the other with the plate insulated from the steel frame. For the second condition, the temperature distribution and buckling deflection were considerably different from the first condition. The acoustic response was also significantly different for the two boundary conditions. The general trends of the changes in resonant frequencies and random response of the plate agree with previous theoretical prediction and experimental results.

Introduction

ONE of the problems to be encountered by future hypersonic aircraft such as the National Aerospace Plane (NASP) will be the high thermal and acoustic environments to which the aircraft will be subjected during a significant portion of the flight envelope. The heating will cause internal stress within the structure and possibly buckling of external plates. Acoustic fatigue of plates at elevated temperatures were investigated on metallic structures by Schneider[1] and on composite structures by Jacobson,[2] but the nonlinear characteristics of acoustic response associated with a buckled state were not studied. High-intensity acoustic loads can cause snap-through (oil canning) of buckled plates.[3] Some research on acoustic response has been conducted on snap-through of aluminum plates by uniaxial compression (mechanical)[4,5] with no research on heating effects. The Thermal Acoustic Fatigue Apparatus (TAFA) at Langley Research Center has a limited capability to study this problem of combined heating and acoustic loads.

This paper will present the results of an investigation using a thermally stressed aluminum plate. For one boundary condition, the plate was restrained on all four edges with steel mounting brackets. For the second condition, the plate was insulated from the steel brackets. Results include buckling due to thermal loads, responses due to acoustic and thermal loads, and snap-through. A comparison of the results with theory is made. In addition, a description of TAFA is given.

Experimental Method

Thermal Acoustic Fatigue Apparatus

The TAFA is a grazing incidence, high-intensity noise facility with the capability for sound pressure levels from 120 to 160 dB, both sinusoidal and random in the frequency range of 40 to 500 Hz (see Fig. 1). The noise source is two 30,000-W acoustic modulators using filtered pressurized air. The sound is coupled to the test section by an exponential horn with a 27-Hz low frequency cutoff. Test panels or plates with maximum dimensions of 12 in. × 15 in. can be mounted in one wall of the test section. Heat is provided by 12 2500-W quartz lamps (see Fig. 2) located in the opposite wall, 12 in. from the test specimen. Heat is controlled to either a percentage of the heat output available or a fixed temperature at some point on the test specimen.

The thermal capability of the facility was determined with a 12 in. × 15 in. × 0.030 in. steel plate instrumented with high temperature thermocouples with stainless steel coverings over the lead-in wires (see Fig. 3). The photograph shows the plate after it had been subjected to the maximum temperatures. The darkened area surrounding the plate is the slightly charred insulation protecting the wall around the test specimen. From Fig. 4, for 0 psig, (no airflow), slightly over 1050°F was obtained at maximum power (30 kW). At normal operating pressure (30 psig) and nearly maximum acoustic level (160 dB), 780°F was obtained. Note that the temperature decreased as the noise level increased, especially at the higher noise levels. This decrease is due partly to the increased airflow and partly to increased convection resulting from high acoustic particle velocity. A temperature survey over the upper half of a steel plate is shown in Fig. 5. Note that the highest temperatures were along the horizontal centerline (6 in. down from the

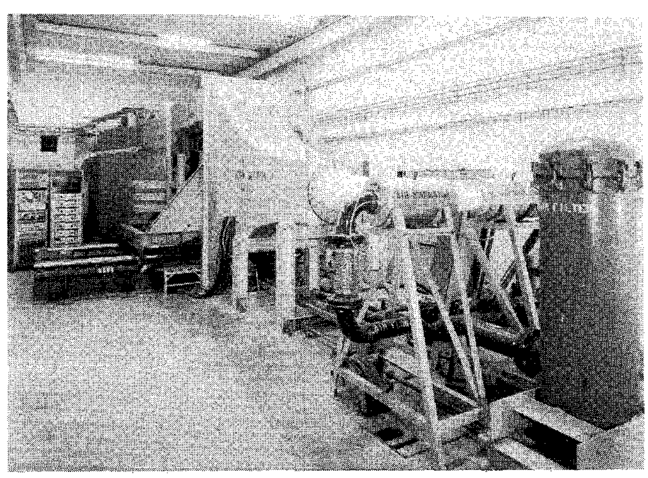

Fig. 1 Photograph of the TAFA apparatus.

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Fig. 2 Photograph of 12 quartz lamps in the TAFA wall.

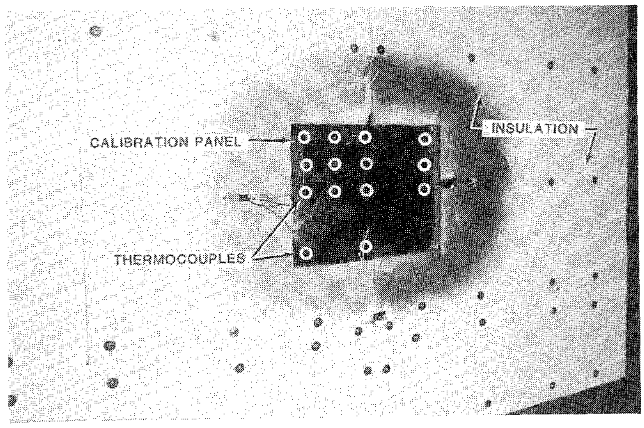

Fig. 3 Photograph of the steel calibration panel after measurements.

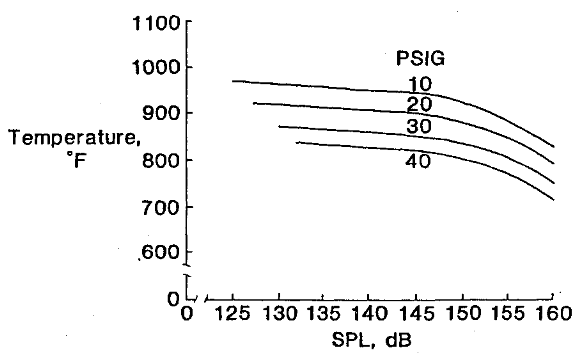

Fig. 4 Effects of airflow, sound pressure level temperature of calibration panel.

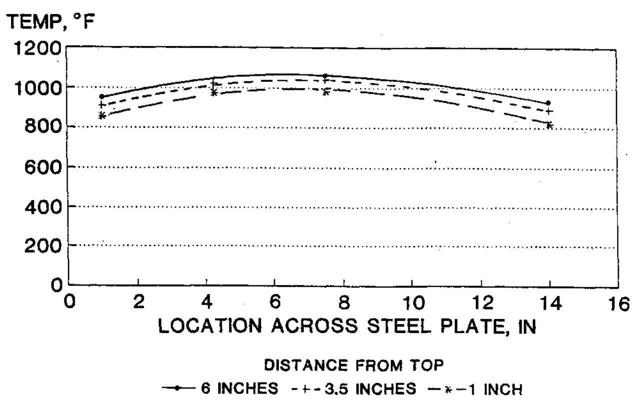

Fig. 5 Temperature distribution of the top half of the steel plate; no airflow.

top of the plate). There is some temperature drop as the top of the plate is approached and a greater drop as the leading or trailing edge of the plate is approached.

Experimental Setup

One aluminum plate with two mounting conditions (boundary conditions) was used in this investigation. Its planform was 12 in. × 15 in. and was 0.063 in. thick (see Fig. 6). For one boundary condition, the plate was mounted in steel brackets clamping the plate on all four edges. Great care was required in tightening the brackets to assure that no buckling (or biaxial stress) occurred. For the second boundary condition, the same plate was mounted with 10 layers of 0.006-in. fiberglass tape around each mounting surface and then held in the steel brackets. However, in-plane slippage is found in both boundary conditions.

Instrumentation

The instrumentation on the aluminum plate consisted of both strain gauges and thermocouples as shown in the photograph in Fig. 6, which displays the front or sound incident side. Eight thermocouples were mounted on the front of the plate, and three sets of strain gauges were located on the front and back of the plate as shown in Fig. 7. The outputs of the thermocouples were recorded on a multichannel data-logging system. The strain gauges were on each side of the plate to form one-half of a bridge completion unit. The gauges in the center and one set of gauges near the edge of the plate were wired to read bending, and the other set of gauges near the edge of the plate was wired to read tension. The outputs of the

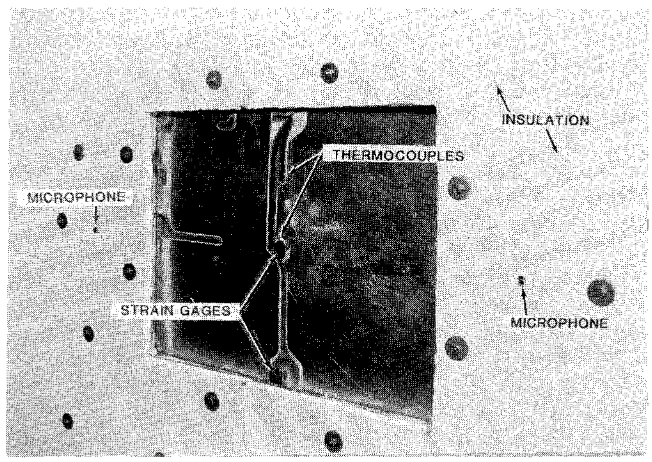

Fig. 6 Photograph of the aluminum test plate.

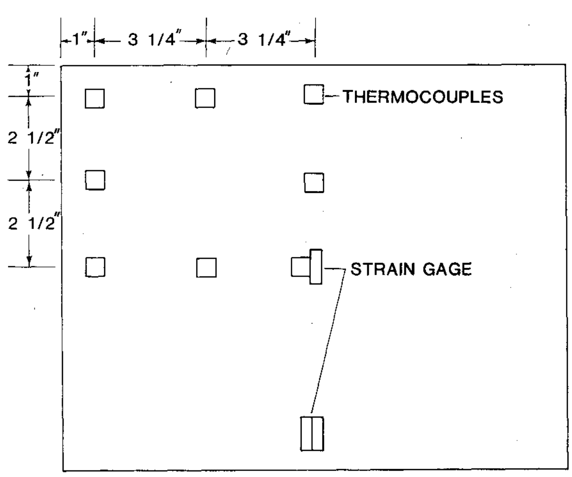

Fig. 7 Location of strain gauges and thermocouples on the aluminum plate.

bridge completion units were both recorded on a multichannel analog data recorder and were also directed to oscilloscopes and to a real-time data analyzer.

Microphones were used for determining noise level and spectra over the plate (see Fig. 6). These microphones were flush mounted in tubes (i.d. = 0.201 in.) about 17 in. outside the wall of TAFA to move them away from the heat. Attached to the tubes, just beyond the microphone locations, were 50-ft coils of ¼-in. copper tubing as shown in Fig. 8. (The photograph shows the locations for the tubes and microphones for a 12-in. × 12-in. test plate.) These coils were not plugged and reduced back reflections of noise from reaching the microphones.

Measurements and Analyses

Measurements were made of noise level, temperature, static deflection, and strain. The noise levels were determined as the arithmetic average between the two microphones. These indicated sound pressure levels (SPL) from each microphone were within 1 dB of each other and had very similar spectra. The spectra over a 500-Hz bandwidth obtained for the various noise levels are shown in Fig. 9. Note that the spectra indicate lower levels between 200 and 250 Hz, although the electrical input to the modulators is white noise in the range of 20–500 Hz.

Sound pressure levels are measured with a third calibrated microphone in TAFA for the random noise that would be used in this investigation. Results of noise measurements of the tube microphones and the standard microphones showed excellent agreement. In addition, the tube microphones were installed and calibrated one at a time in a 1-in. pipe opposite a calibrated microphone. At one end of the pipe was an acoustic driver and the other end was open.

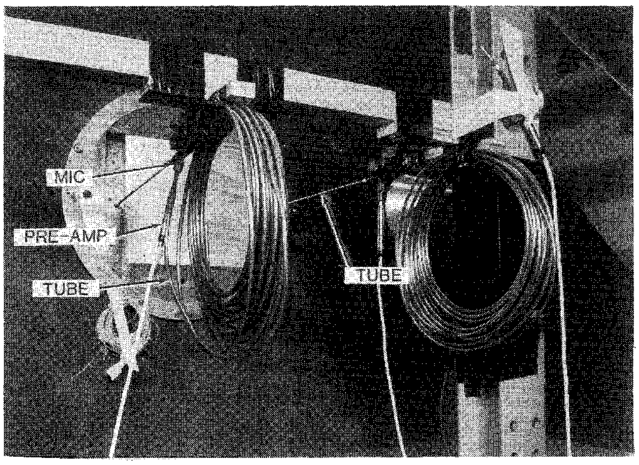

Fig. 8 Photograph of the coils behind the "tube" microphones.

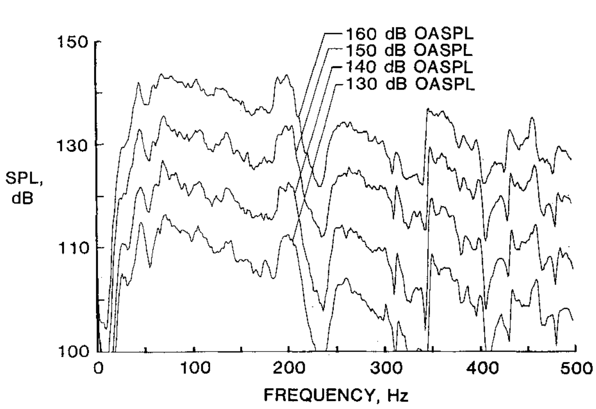

Fig. 9 Acoustic spectra to which the aluminum plates were subjected.

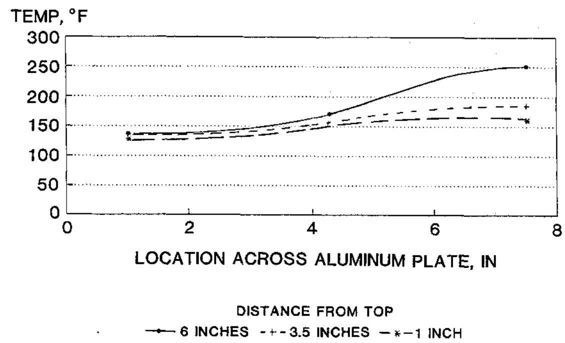

Fig. 10 Temperature distribution over one quadrant of the aluminum plate with no insulation.

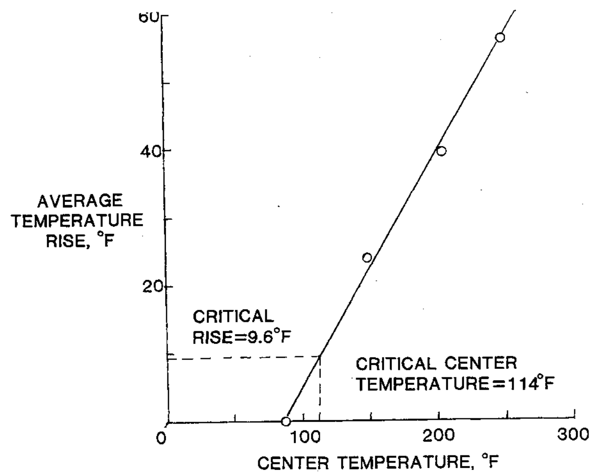

Fig. 11 Average temperature rise above the edge temperature as a function of plate center temperature for the uninsulated plate.

Since the output voltage from the strain gauge was a function of both temperature and buckling magnitude, the static buckling strain is derived from the static deflection measured at the center. The amplification factor and balancing point of the bridge completion units were adjusted so that the outputs were less than 1 V. In an analysis, the dc components of the strain were used because there was significant change of mean values of the response because of snap-through motion. Snap-through motion is sudden movement from one static position into another. When the snap-through motion is intermittent (i.e., there is oscillation around each of the two static positions), the mean value is unsteady. When the snap-through is persistent (i.e., very little oscillation around static positions), the mean value is approximately zero.

Results

Uninsulated Plate

Thermal Effects

From the temperature distribution at center temperature of 250°F (see Fig. 10), the average temperature rise (denoted by ΔT) above the edge temperature (110°F) is 56°F. The steel clamping frame should expand less than the edge of the aluminum specimen, but the edges can be assumed to expand freely because of in-plane slippage. Thus the resulting overall thermal stresses depend on the difference between the temperature in the central region and that at the edge, i.e., ΔT. The variation of ΔT with central temperature is plotted in Fig. 11, and this is used to predict postbuckling responses.

Thermal Buckling Displacement

From a finite element analysis[7] and Von Karman's nonlinear equation,[8] the buckling at $\Delta T = 9.6$°F with 1,1 mode. The theoretical results[8] of postbuckling deflection vs

ΔT agree very well with experimental results (see Fig. 12) except for those results near the buckling point because of the effects of imperfection. The corresponding approximate bending strains at the midpoint of the longer edge (see Fig. 7) were calculated from the measured deflection assuming a clamped beam displacement pattern and are shown on the right axis of Fig. 12.

Dynamic Bending Strain

Figure 13 shows the variation with temperature of rms dynamic bending strain resulting from broadband acoustic excitation. At 160 dB SPL, the maximum response of 571 microstrain is obtained at 120°F. This trend of variation of rms strain agrees with previous theoretical and experimental results.[4,5] Inspection of the time history of the response at 120°F (see Fig. 13, insert A) shows that at 160 dB SPL there is persistent snap-through motion. Only intermittent snap-through motion is found at 150°F (see Fig. 13, insert B), and no snap-through motion is found at 200° and 250°F (see Fig. 13, insert C). The buckling displacement of 150°F (see Fig. 12) is about twice the thickness of the plate. For higher buckling deflection at 200°F and higher, the overall rms strain responses decrease considerably because of the stiffening effect of the curvature.

Bending Strain Spectral Response—Ambient, 87°F

The fundamental plate frequency at 130 dB SPL was found to be 103 Hz (see Fig. 14), which is lower than the theoretically predicted value of 120 Hz. This may be because of the nonideal clamping condition. The strain levels for the second and third modal resonances, at 190 and 302 Hz respectively, are several orders of magnitude lower than the fundamental resonance. At 140 dB SPL, the resonant frequency decreases slightly, and there is a significant peak at 1 Hz compared to the fundamental resonant peak response. This may be because of the curvature effects of the considerable amount of imperfection in the plate. At 160 dB SPL, the resonant frequency peak broadens with the center of the peak response at 120 Hz.

Bending Strain Spectral Response—120°F

At this higher temperature, the peak response for 140 dB SPL was at 200 Hz (see Fig. 15). The resonant frequency decreased to 170 Hz as SPL increased to 150 dB SPL. At 152 dB SPL, the peak in the modal response at 150 Hz is less than the peak at 150 dB SPL (170 Hz). In addition, there is a dominant peak in response at 1 Hz, which is due to the intermittent snap-through. This intermittent motion results in low frequency and large amplitude vibration. The peak at 105 Hz dominates the response at 160 dB SPL, and the response at 1 Hz decreases from that observed at 152 dB SPL because the snap-through motion is nearly continuous. For persistent snap-through motion, the rms bending strain response was only 20% higher than that of the flat plate. This small increase resulted because the 160 dB SPL can only excite persistent snap-through motion of the thermally buckled plate at 120°F, for which the center deflection is only 62% of the thickness.

Bending Strain Spectral Response—150°F

Modal peak responses are found at 140 Hz for 135 dB and 200 Hz for 145 dB (see Fig. 16). There is a very dominant peak at 2 Hz for 160 dB SPL. The response is greater than that found at 1 Hz at 120F for 162 dB because of the larger snap-through motion.

Tensile Strain Spectral Density

The tensile strain spectrum is compared with the bending strain spectrum in Fig. 17 at 120°F and 160 dB SPL. The peak response of tensile strain was at 210 Hz, twice that of bending strain at 105 Hz, and was also much more broadened. In addition, there is a peak tensile strain at 5 Hz. These two peaks occur because the tensile strain is proportional to the square of

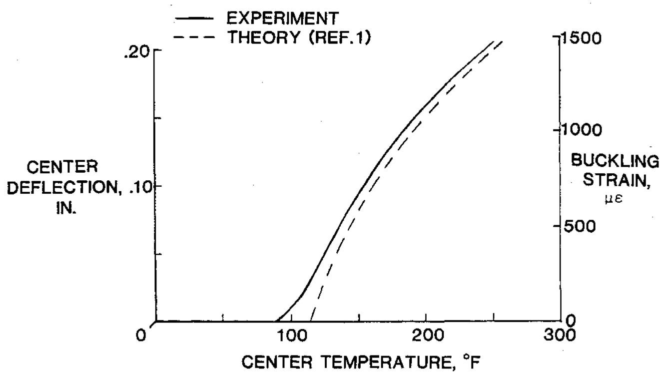

Fig. 12 Center deflection due to buckling as a function of plate center temperature.

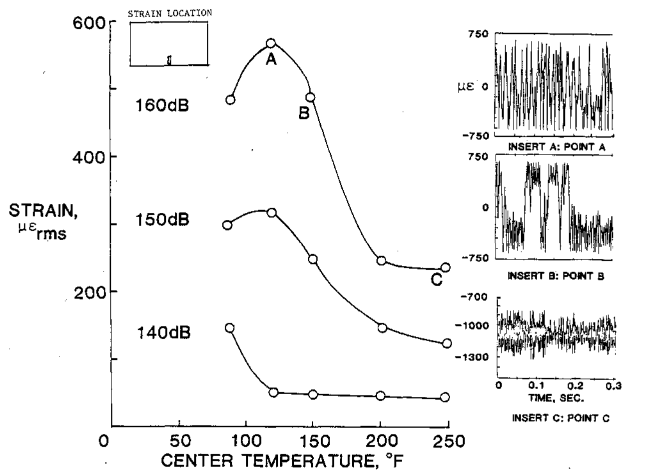

Fig. 13 Acoustic response at various SPL as a function of plate center temperature with inserts of various motions.

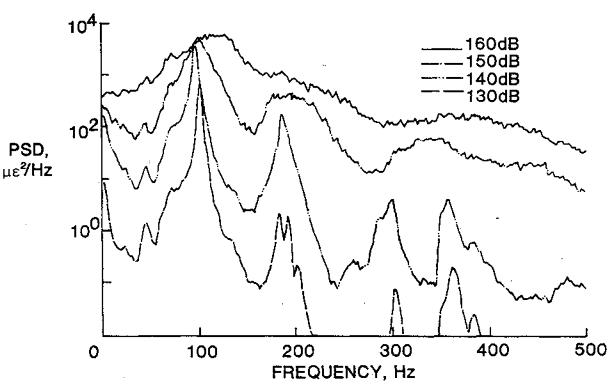

Fig. 14 Power spectral density (PSD) of the bending strain at various SPL at ambient temperature (87°F).

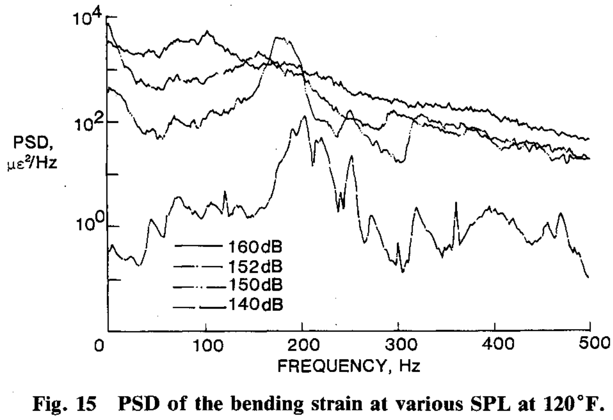

Fig. 15 PSD of the bending strain at various SPL at 120°F.

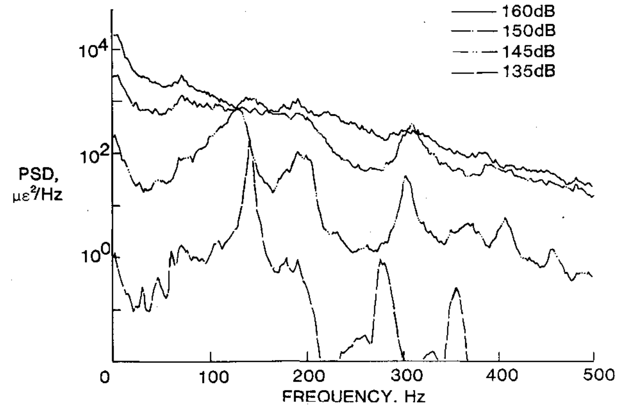

Fig. 16 PSD of the bending strain at various SPL at 150°F.

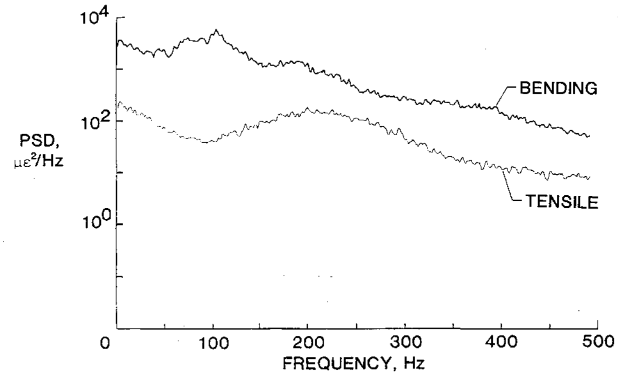

Fig. 17 Comparison of bending and tensile PSD at 120°F for 160 dB SPL.

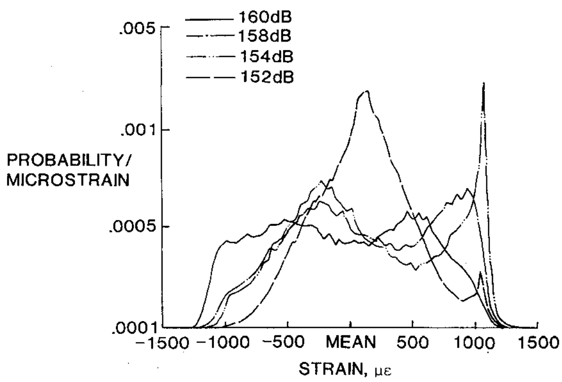

Fig. 18 Probability density distribution of bending strain responses at 120°F for various SPL.

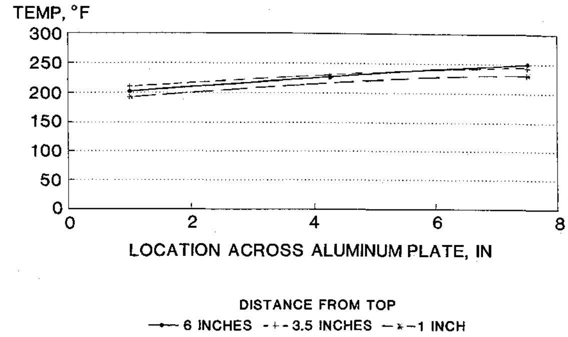

Fig. 19 Temperature distribution over one quadrant of the aluminum plate with fiberblass insulation.

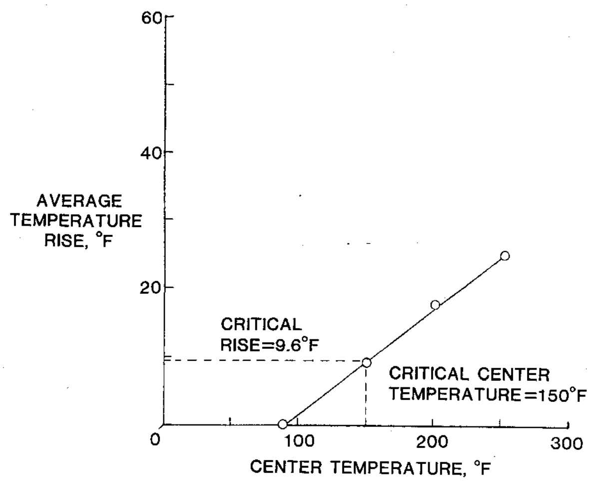

Fig. 20 Average temperature rise above the edge temperature as a function of plate center temperature for the insulated plate.

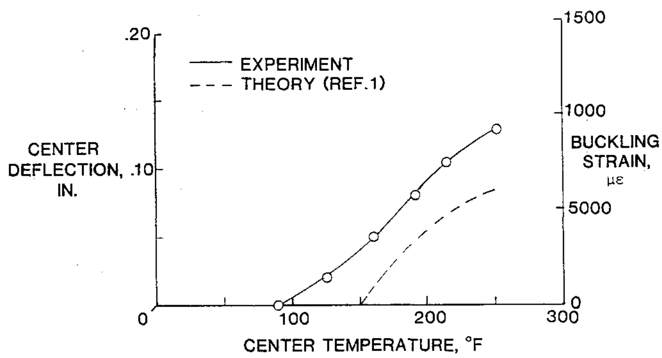

Fig. 21 Center deflection due to buckling as a function of plate center temperature.

the dynamic displacement. The overall rms tensile strain is about one-eighth of that of the bending strain.

Probability Density

Figure 18 shows the probability density distribution of the bending strain response at 120°F. At 152 dB SPL, there is one dominant peak, but at 154 dB SPL, as snap-through motion starts, there is also a second peak to the right of the first peak at higher magnitude. The two peaks correspond to the two static positions around which the oscillations are centered. The peaks are not symmetric because the vibration motions are nonlinear. The probability density between the peaks increases as the snap-through motion between the two static positions becomes more frequent (158 dB) and the probability density plot looks like a broad plateau at 160 dB. The above results of double peaks and plateau in the probability density of random response are new characteristics of nonlinear behavior that have not been reported before in experimental work but were described in a theoretical study.[10]

Insulated Plate

Thermal Effects

The temperatures at the edge of the insulated plate are closer to the temperature at the center of the plate (see Fig. 19) than for the plate with the uninsulated edges. The average rise in temperature above the surrounding edges is thus lower and is plotted against center temperature in Fig. 20. The center temperature for buckling is 150°F.

Thermal Buckling Displacement

The experimental results for the deflections are much higher than the theoretical results based on a 100% clamped plate (see Fig. 21). This discrepancy may be because of the nonideal

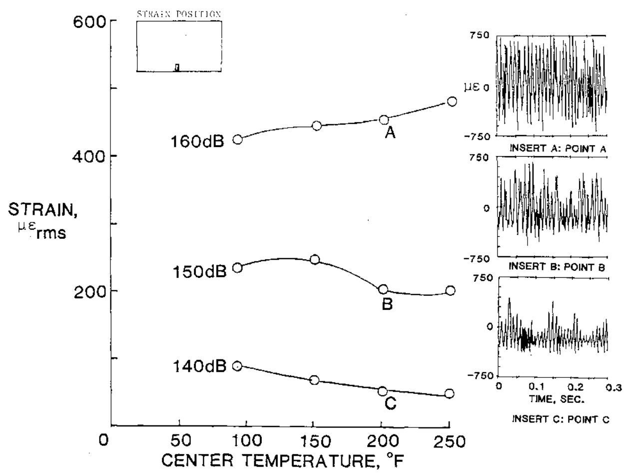

Fig. 22 Acoustic response at various SPL as a function of plate center temperature with inserts of various motions.

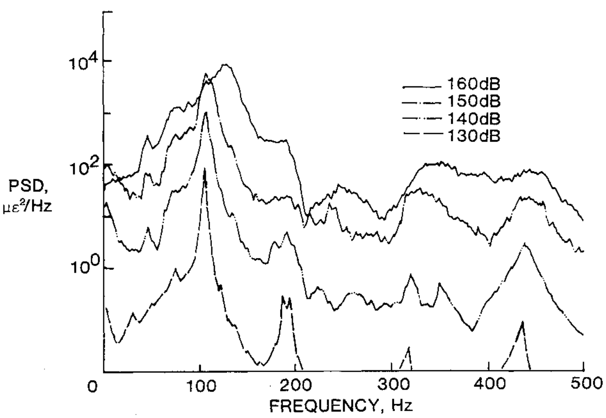

Fig. 23 PSD of the bending strains for various SPL at ambient temperature (89°F).

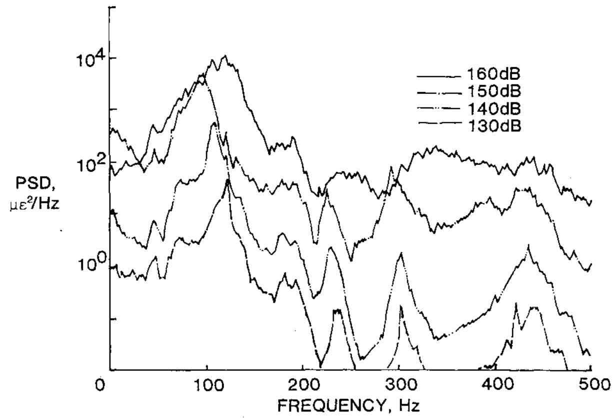

Fig. 24 PSD of the bending strains for various SPL at 150°F.

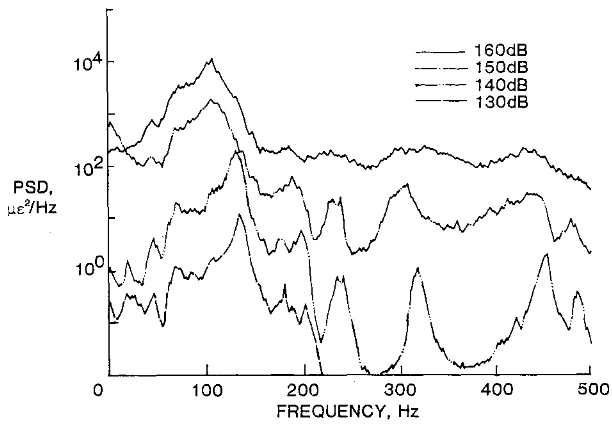

Fig. 25 PSD of the bending strains for various SPL at 200°F.

clamping of the edges containing the flexible insulating material.

Dynamic Bending Response

For 160 dB SPL, the response increases with temperature (see Fig. 22) because persistent snap-through motion can be excited (see Fig. 22, insert A). The maximum response may be found at a temperature higher than 250°F. For 150 dB SPL, the maximum response is found at 150°F and the response decreases at 200°F because only intermittent snap-through motion can be excited at 200°F (see Fig. 22, insert B). For 200°F and 140 dB SPL, the oscillation is nonsymmetric (see Fig. 22, insert C) with only occasional snap-through.

Bending Strain Spectral Density—Ambient, 89°F

The initial fundamental frequency at 130 dB SPL is 107 Hz (see Fig. 23). There is an increase in resonant frequency and a broadening of the peak frequency at 160 dB SPL.

Bending Strain Spectral Density—150°F

The fundamental frequency is initially 121 Hz at 130 dB SPL (see Fig. 24) and decreases to 98 Hz at 150 dB SPL for which intermittent snap-through is found. The low frequency peak at 1 Hz is not very high compared with the peak at 98 Hz, showing that the magnitude of the snap-through is small. At 160 dB SPL, the peak response is found at 120 Hz again and the response peak at 1 Hz has disappeared.

Bending Strain Spectral Density—200°F

The fundamental frequency is initially 132 Hz (see Fig. 25) and decreases to 105 Hz at 150 dB SPL, for which intermittent snap-through is indicated by the peak response at 2 Hz. This low frequency peak response disappears at 160 dB SPL.

Concluding Remarks

An acoustic level of 160 dB can excite intermittent snap-through motion of thermally buckled plates with center deflection twice that of the plate thickness. The snap-through motion had significant effects on the resonant frequencies of the random response summarized as follows.

1) The resonant frequencies decrease with an increase of SPL and also increase with the initiation of snap-through.

2) The response peak broadens when persistent snap-through motions are present, and the degree of broadening depends on the magnitude of the thermal buckling displacement.

3) The peak responses at low frequencies (1-5 Hz) appear as intermittent snap-through motion starts. The low frequency peaks decrease as persistent snap-through is achieved. The magnitude of the peak response depends on the magnitude of the thermal buckling displacement.

For persistent snap-through motion of the uninsulated plate at 120°F and 160 dB SPL, the rms strain response was only 20% higher than that of the flat plate. This small increase resulted because the 160 dB SPL can only excite persistent snap-through motion of the thermally buckled plate at 120°F, for which the center deflection is only 62% of the thickness. For higher buckling deflection of the plate at higher temperatures, the stiffening effect of the curvature becomes more important, and the overall acoustic response decreases considerably.

From the above results, it can be concluded that the amount of increase or decrease of acoustic response of a heated plate compared to that of a plate at ambient temperature depends on the magnitude of thermal buckling and the ability of the acoustic loads to excite snap-through motion.

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