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TECHNICAL NOTE 4054

EFFECT OF TRANSIENT HEATING ON VIBRATION FREQUENCIES
OF SOME SIMPLE WING STRUCTURES

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and Robert G. Thomson

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SUMMARY

Thermal stresses caused by nonuniform temperature distributions associated with transient heating can cause changes in the effective stiffness of wing structures. Some of the effects of this change in stiffness were investigated experimentally by testing three types of simple wing structures under various radiant-heating conditions. The structures tested were a uniform plate, a solid double-wedge section, and a circular-arc multiweb-wing section. Changes in stiffness were determined by measuring the changes in natural frequency of vibration during transient heating. In order to measure changes in frequency, a resonance-following system was developed which keeps the model vibrating at its natural frequency. Some of the data are compared with theoretical calculations and show that, at temperature differences near those required for thermal buckling, distortions have a marked effect on the frequency. The conclusion was made that, in order to predict the effects of aerodynamic heating on the stiffness of wing structures by means of laboratory radiant-heating tests, care must be taken to simulate closely the temperature distributions produced aerodynamically.

INTRODUCTION

One of the effects of the nonuniform temperature distributions produced by aerodynamic heating is a change in the effective structural stiffness caused by thermal stresses. Changes in stiffness have been observed in laboratory tests of several types of simple wing structures, and, in reference 1, thermal stresses were cited as the cause of failure of wing models subjected to aerodynamic heating. In order to obtain more information on this thermoelastic phenomenon, laboratory tests were conducted on several types of simplified wing structures for which changes in stiffness were measured during rapid heating. The results of these tests are presented and some comparisons with theoretical calculations are made.

The structures considered and the manner in which they were heated are shown in figure 1. The structures had a square plan form and were mounted as cantilevers. The first structure is a plate of uniform thickness which was heated radiantly along the longitudinal edges. The second is a solid double-wedge section which was subjected to a constant heat input over the top and bottom surfaces. The third is a symmetrical circular-arc multiweb airfoil. The heat input varied along the chord as indicated in the figure.

TEST PROCEDURE AND RESULTS

Resonance-Following System

Inasmuch as the natural frequency of vibration is a function of the model stiffness, changes in stiffness can be determined by measuring the changes in natural frequency during transient heating. The mechanism used to detect the changes in frequency is shown schematically in figure 2. The mechanism consists basically of a forcing system, the vibrating body, a vibration pickup, and the servo detecting system. The system is operated by setting the frequency of the signal generator so that the model is forced in one of its natural modes of vibration. The phase detector is then set to maintain the phase relation that exists between the applied force, as indicated by the signal generator, and the response of the model, as indicated by the vibration pickup. If the natural frequency of the model changes, the phase relation between the force and the response will change. The servo system detects this change, and, through a servomotor, mechanically drives the signal generator until the resonant phase relation is recovered. In this manner the model is continuously forced at its resonant frequency.

Uniform Plate

The plate tested was of aluminum alloy 20 inches square and 1/4 inch thick. As the plate was heated, the temperature at the edges rose rapidly, but the center section remained relatively cool. The thermal stresses which resulted caused a change in the natural frequencies of the plate. In reference 2 results were presented for changes in frequency of the first two modes. These tests were repeated by using the resonance-following system; in addition, the next three higher modes were investigated. The frequency histories which were obtained during transient heating are shown in figure 3.

The variation with time of the temperature difference ΔT , between the edge and the midchord in degrees Fahrenheit, is shown at the top of figure 3. Heat was applied to the plate for about 20 seconds at which

time the temperature difference between the edge and the midchord was about 190° F. In the lower portion of the figure the ratio of the frequency measured during heating f to that of the unheated plate f_0 is plotted as a function of time in seconds for the first five natural modes. The mode shape and corresponding initial frequency are shown for each curve. Of these five modes, the first torsion mode underwent the largest change in frequency, a reduction of about 35 percent. The first chordwise bending mode was least affected by this type of heating. Since the plate was not initially flat, the heating also caused the plate to deform. These deformations were primarily torsional and, therefore, an analysis that considered only torsional deflections was made for the effect of heating on the torsional mode of vibration and some results of this analysis are shown in figure 4.

In figure 4 the ratio of the frequency of a heated plate to that of a flat unheated plate is shown as a function of the ratio of the temperature difference between the edge and the midchord ΔT to the theoretical temperature difference required to produce thermal buckling of the flat plate ΔT_{cr} . Curves are shown for various values of initial distortion which have been expressed as a twist parameter θ_0 . For the perfect plate, $\theta_0 = 0$, the frequency ratio decreases until the buckling temperature of the plate is reached. At this time the plate buckles; and, since the stiffness of the buckled plate is greater than that of the flat plate, the torsional frequency begins to increase. For a plate which has an initial twist, the heating has two effects. The thermal stresses lower the frequency, but, since the plate is also deforming, its stiffness due to twist is increasing. The frequency therefore reaches a minimum below the buckling temperature and any further heating causes the frequency to increase. The plate tested had a value of θ_0 of 0.06 which corresponded to a tip twist of about one-third degree. As the frequency history indicates, the stiffness actually began to increase while heat was still being applied.

Figure 5 shows a comparison between measured and calculated frequency histories. The ratio of the frequency during heating to the frequency of the unheated plate is shown as a function of time in seconds. A small-deflection theory which neglects the effects of distortion on the stiffness overestimates the frequency change. When a large-deflection theory which includes the effects of distortion is used, the agreement is substantially improved.

Double-Wedge Section

The double-wedge section tested was made of stainless steel 1 inch thick and 20 inches square. Both the upper and lower surfaces were

subjected to a constant heat input by means of radiant heating. The temperature distribution in the chordwise direction is then primarily a function of the mass distribution. Again the changes in stiffness were measured by measuring the changes in natural frequency. Some of the test results are shown in figure 6.

The variation of temperature rise T with time for an edge, the surface at the midchord, and a point at the centroid of the section is shown at the top of figure 6. The changes in frequency ratio with time are shown for the first five modes in the lower part of the figure. The mode shapes and their corresponding starting frequencies are shown for each curve.

The reductions in frequency which occurred during heating are surprisingly small in comparison with the reductions calculated by Budiansky and Mayers (ref. 3) for the aerodynamic heating of similar wings instantaneously accelerated to moderately high Mach numbers. The discrepancies arise because of the marked difference between aerodynamic heating and this type of radiant heating. In aerodynamic heating, the temperature at the leading and trailing edges is limited by the boundary-layer temperature. In the radiant heating, the temperature right at the leading and trailing edges becomes prohibitively high before a temperature distribution is obtained which results in large stiffness changes. A theoretical calculation was made for the first torsion mode by using the same method as that used by Budiansky and Mayers but based on the experimental temperature distribution obtained from the radiant-heating test. These calculations gave a frequency reduction about the same as that obtained in the test. Therefore, larger reductions in frequency probably would have been obtained if the test could have been continued for a longer time or if the temperature distribution had more closely simulated that generated aerodynamically.

Multiweb-Wing Section

The third section tested was a 5-percent-thick multiweb-wing section of aluminum-alloy construction with a 20-inch chord and span. This specimen is the same as one which was tested in the preflight jet of the Langley Pilotless Aircraft Research Station at Wallops Island, Va., at a Mach number of 2. A description of the test of this model, designated MW-2, is given in reference 1. The radiant-heating test did not simulate the aerodynamic heating correctly although an effort was made to reproduce the average heat input. The test results are shown in figure 7.

The temperature in degrees Fahrenheit is plotted as a function of time in seconds for a point on the skin and at the center of a spar at the top of figure 7. The changes in the frequency ratio with time have been shown for five modes of vibration at the bottom of the figure. The

largest reduction in frequency, as shown by the lowest curve, occurred for a mode which involved chordwise bending. The smallest reduction in frequency occurred for the first torsion mode.

The radiant heating has not simulated the aerodynamic heating very well; therefore, these results cannot be applied directly to aerodynamic tests. However, the type of frequency reductions obtained here are significant. The similar model (described in ref. 1) tested at a Mach number of 2 fluttered in a mode which involved a large amount of chordwise bending as did the one which had the largest frequency reduction.

At the present time, no theoretical method is available for predicting the effects of transient heating on the frequencies of the more complicated types of modes which are the important ones for this structure.

CONCLUDING REMARKS

Three types of simple wing structures have been tested under various radiant-heating conditions and changes in stiffness as indicated by changes in natural frequency of vibration were measured. In order to measure the changes in frequency during transient heating, a resonance-following system was developed which keeps the specimen vibrating at its natural frequency.

For temperature differences near those required for thermal buckling, initial distortions have a marked effect on the frequency. Calculations which include the effects of these distortions are found to be in good agreement with the measured frequency.

The results obtained from these tests indicate that the magnitude of the effects of thermal stress depends strongly on the manner in which the structure is heated. Therefore, in order to determine the effects of aerodynamic heating on the stiffness of wing structures by means of laboratory radiant-heating tests, care must be taken to simulate closely the temperature distributions produced aerodynamically.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., March 6, 1957.

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1. Heldenfels, Richard R., and Rosecrans, Richard: Preliminary Results of Supersonic-Jet Tests of Simplified Wing Structures. NACA RM L53E26a, 1953.
2. Vosteen, Louis F., and Fuller, Kenneth E.: Behavior of a Cantilever Plate Under Rapid-Heating Conditions. NACA RM L55E20c, 1955.
3. Budiansky, Bernard, and Mayers, J.: Influence of Aerodynamic Heating on the Effective Torsional Stiffness of Thin Wings. Jour. Aero. Sci., vol. 23, no. 12, Dec. 1956, pp. 1081-1093, 1108.

MODEL CONFIGURATIONS

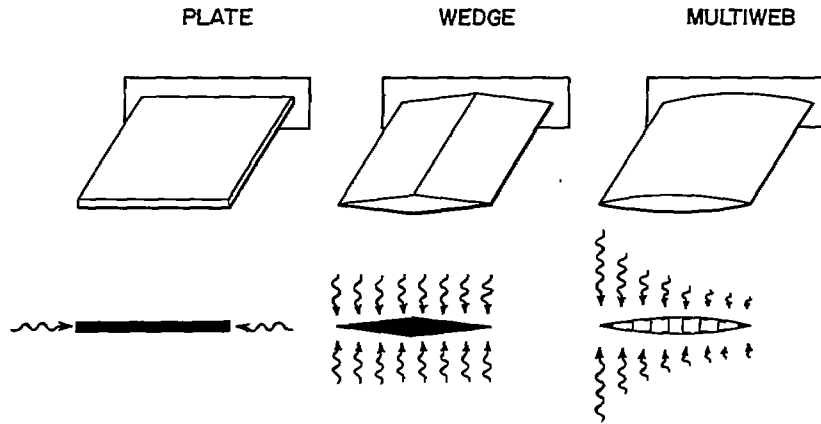


Figure 1

RESONANCE-FOLLOWING SYSTEM

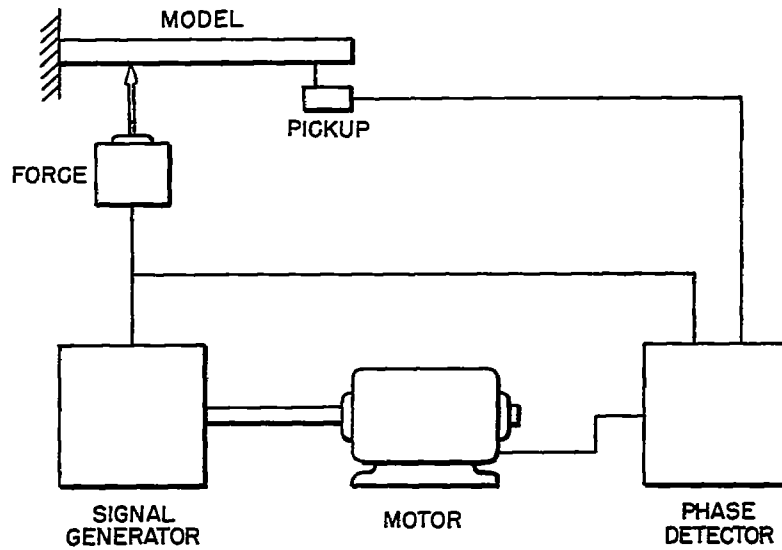


Figure 2

FREQUENCY HISTORIES
CANTILEVER PLATE

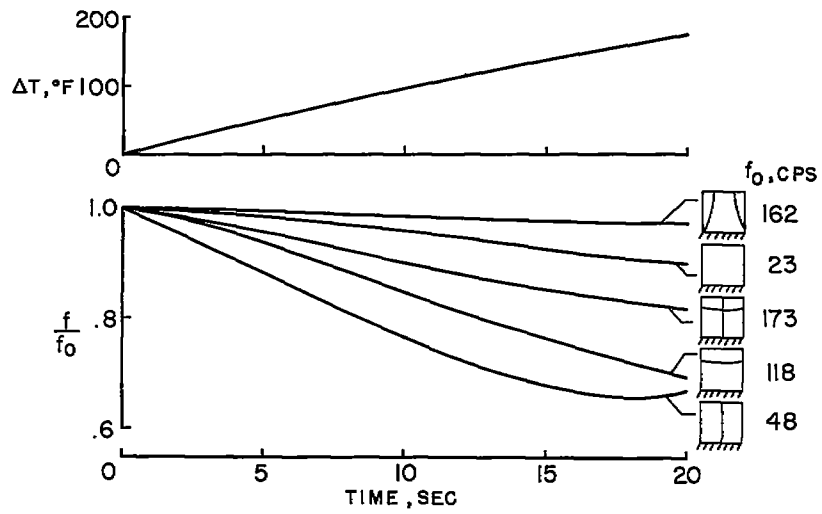


Figure 3

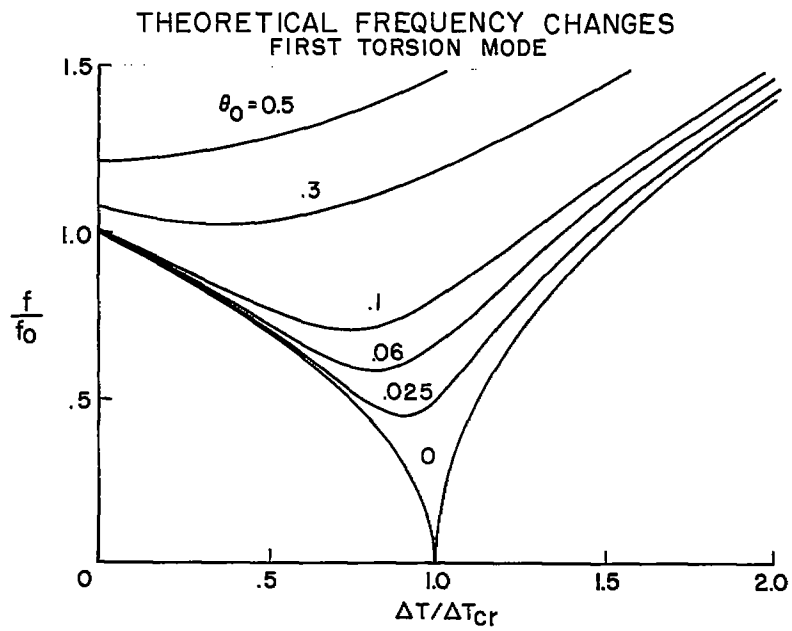


Figure 4

COMPARISON OF FREQUENCY HISTORIES
FIRST TORSION MODE

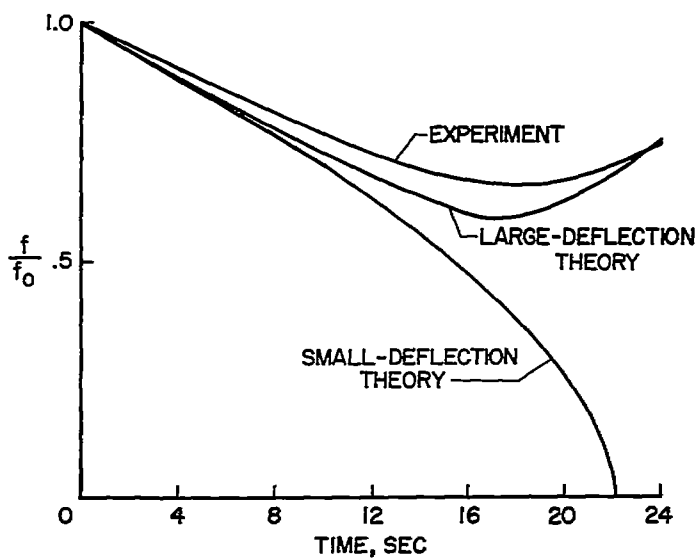


Figure 5

FREQUENCY HISTORIES
DOUBLE WEDGE

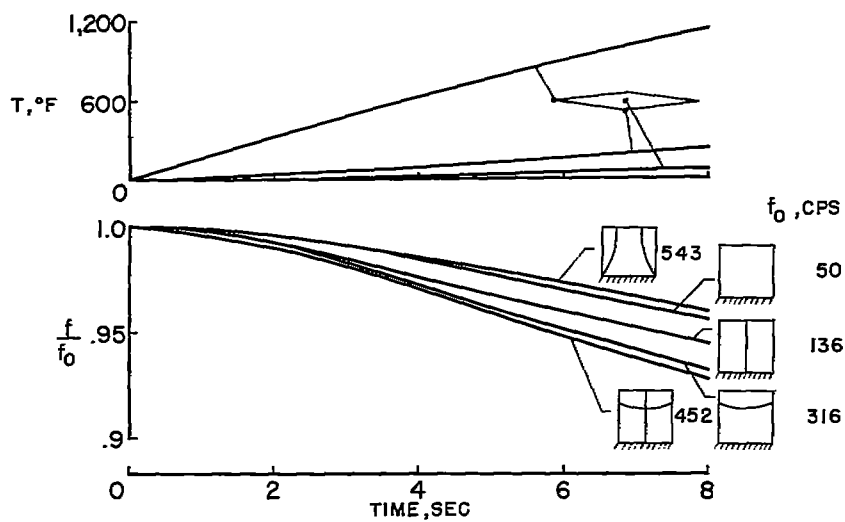


Figure 6

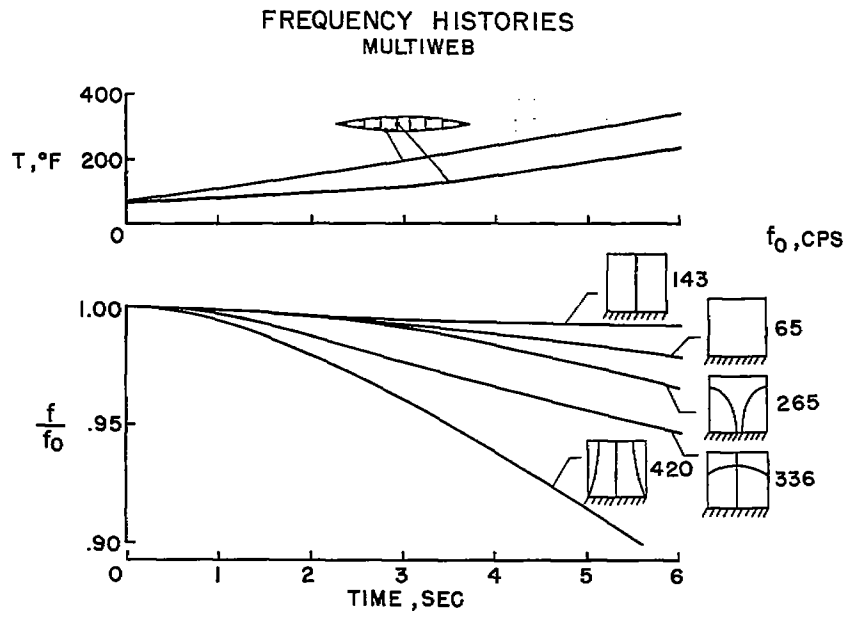


Figure 7