RESEARCH MEMORANDUM

A LIMITED FLIGHT INVESTIGATION OF THE EFFECT OF DYNAMIC VIBRATION ABSORBERS ON THE RESPONSE OF AN AIRPLANE STRUCTURE DURING BUFFETING

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SUMMARY

Limited flight measurements have been made in order to investigate the effect of dynamic vibration absorbers on the structural response of a Lockheed F-80A airplane during buffeting. The absorbers were mounted on the wing tips and were tuned to the wing second bending mode. The results were obtained by comparison of data with and without the absorbers operating through use of electrical frequency-analysis techniques.

The results obtained showed that the dynamic vibration absorbers produced large changes in the buffeting response of the airplane but did not affect the total power of the wing tip accelerations appreciably. Operation of the absorber greatly reduced the amplitude of the principal response peak (which occurred in the tuned mode with the absorber not operating) at the expense of increased response at higher frequencies. The shifting of response to higher frequencies indicates that the device might be effective for relieving buffeting stresses.

The buffeting response in the tuned mode correlated with airplane normal-force coefficient but showed little consistent variation with Mach numbers within the range investigated. Operation of the absorbers reduced the root-mean-square acceleration in the tuned mode to about one-third its value at the same normal-force coefficient with damper not operating.

Approximate calculations indicated that for use as a buffet alleviator, an absorber installation weighing considerably less than that tested could produce a significant reduction in the structural response to buffeting in the tuned mode. The absorber also appears useful as a means for producing large changes in the response of aircraft structures to buffeting which would greatly facilitate much needed research on the nature of buffeting response, excitation, and damping and their effect on the pilot.

INTRODUCTION

The concentration of the buffeting response of airplanes in the natural vibratory modes of the structure which have been shown in the literature (for example, ref. 1) and the similarity of the response in each mode to that expected of a lightly damped resonant system subjected to random excitation (ref. 1) suggests that significant reductions in buffeting response might be realized if either the structural or aerodynamic damping (or both) could be increased appreciably. Although no practical means for obtaining large increases in the internal damping of structures or the aerodynamic damping of wings have yet been developed, the effective damping of a vibrating structure can be greatly increased within a narrow frequency range by means of a damped dynamic vibration absorber. Thus, dynamic absorbers operating on each of the modes in which appreciable buffeting response occurred might provide effective buffet alleviation.

Preliminary ground tests performed early in 1952 provided encouraging indications and accordingly damped dynamic vibration absorbers (hereinafter referred to as dampers) were designed and built in order to investigate their effectiveness in flight. Confirming evidence of the effectiveness of dampers as buffet alleviators was also obtained from flight tests performed by the Chance Vought Aircraft Division, United Aircraft Corporation late in 1952.

Inasmuch as the object of the flight tests reported herein was to study the effect of dampers on the buffeting response of the airplane rather than develop the optimum configuration for the test airplane, it was considered sufficient to provide dampers for one mode only. The second wing-bending mode (antisymmetric) was selected as, for the test airplane, this mode was shown in reference 1 to contain the principal buffeting response (in terms of wing tip acceleration) experienced in the high-speed low-lift buffeting region. The dampers were located at the points having the largest motion in the selected mode (the wing tips) in order that the maximum effectiveness would be obtained for a given amount of damper weight.

The dampers were designed according to the method of reference 2 which relates optimum values of the damper design parameters to the characteristics of the basic structure (the wing). The optimum values of reference 2 are those which minimize the amplitude response per unit force of an undamped single-degree-of-freedom system when fitted with a damper of given weight. Inasmuch as the design values may not be optimum for the actual aircraft structure, large damper weights were selected so that readily measurable effects would be obtained even if the dampers operated at non-optimum conditions.

Results are presented herein of limited flight tests of the dampers in the high-speed low-lift buffeting region at altitudes near 30,000 feet, in order to show the effect of dampers on the response of the airplane structure to buffeting. The results, in the form of accelerations of the structure and damper components, were analyzed by electrical frequency-analysis methods which differed from those used in reference 1 in several details which were intended to increase the convenience and accuracy of the method. The buffeting experienced and the effectiveness of the damper are presented as functions of the airplane normal-force coefficient and Mach number.

The implications of the results with regard to the nature of buffeting and of the buffeting response and with regard to the evaluation of dampers as practical buffet alleviators and as research instruments are also discussed.

EQUIPMENT AND INSTRUMENTATION

Airplane.- The airplane used in this investigation (Lockheed F-80A) was the same as that used in reference 1. A three-view drawing showing the location of the accelerometers and the principal characteristics of the airplane is presented as figure 1. The airplane was modified by the addition of the dampers which were mounted on the tip tank attachment points at the wing tips, and were covered by simple fairings. A photograph showing one of the fairings in place is presented as figure 2.

Dampers.- A photograph of one of the dampers installed on the airplane is presented as figure 3 and a schematic drawing as figure 4. As may be seen from these figures, the unit consists of a weight mounted on a rigid arm attached to the shaft of a rotary-vane-type damping cylinder and supported by a folded cantilever spring. The damper case was rigidly mounted to a stiff channel which also supported the damper spring. The channel was, in turn, attached to the wing tip in a position such that the damper spring attachment points and weight center of gravity were located under the elastic axis of the wing. A fitting was provided on the weight arm which engaged the front hook of the standard wing tip bomb shackle when the damper weight was forced upward to near the limit of its travel, compressing the spring. This fitting allowed the damper weight to be effectively fixed to the wing and to be released in flight by firing the bomb shackle.

The complete wing of the test airplane has a weight of about 4,200 pounds and a natural frequency in its second bending mode of about 17 cps. Addition of the fixed part of the damper assemblies (30 pounds at each tip) reduced the natural frequency to about 15.3 cps. The effective weight at the tip of each half of the wing vibrating in its second bending mode (including the effects of the fuselage and of the fixed part of the damper assembly) was computed by the method of reference 3 to be about 270 pounds. Thus, the total effective weight at the tips of the complete wing was about 540 pounds. The selected value of the damper moving weight (140 pounds, 70 pounds at each tip) is thus about one-fourth of the effective wing weight. For this weight ratio the method of reference 2 gives the optimum value of damping of the damper weight as 0.22 of critical and the optimum natural frequency of the damper as 12.2 cps. The damping ratios given in reference 2 are referred to the natural frequency of the wing. Hereinafter the damping ratios are referred to the damper natural frequency: in this form the optimum ratio is 0.275 of critical.

Preflight tests indicated that the natural frequencies of the dampers were between 11 and 12 cps and that the damping was about 0.10 of critical. The small value of damping was ascribed to the limited angular range used in the preflight tests. Thus, the dampers as constructed had less than optimum damping and were tuned to a slightly lower frequency than the optimum for the estimated mass ratio. It should be noted, however, that the optimum values given by reference 2 may not be optimum for the airplane for several reasons; for example, the method of reference 2 treats an undamped single-degree-of-freedom system and thus does not consider the effect of either the structural or aerodynamic damping of the wing or the presence of other modes. The uncertainties involved in the calculation of the effective weight of the vibrating wing (and thus the weight ratio) may also be of appreciable magnitude. Because of the limited nature of the investigation only the one damper configuration was used in flight tests.

Instrumentation.- The instrumentation used to measure the structural response of the airplane was similar to that used in reference 1 (i.e., heated, strain-gage-type accelerometers located on major structural members as shown in figure 1) with an additional accelerometer located on each damper weight. Time histories of the output of these accelerometers were recorded on an oscillograph together with the outputs of a control position transmitter located at the control horn of the right aileron. The frequency response characteristics (including the effect of the galvanometer element) of the accelerometers were flat within ±5 percent up to about 40 cps and that of the aileron position system up to about 60 cps.

The flight conditions (Mach number, normal-force coefficient, and pressure altitude) were obtained through use of standard NACA recording instruments synchronized with the oscillograph by means of a coded timing circuit. A calibrated airspeed system was used and the values of Mach number quoted are considered reliable within ±0.01.

Inasmuch as the structural response was to be analyzed by electrical means, the data were also recorded directly in electrical form. To this end an NACA seven-channel telemetering system was installed in the airplane and 6 heated, telemetering-type accelerometers were installed adjacent to the strain-gage accelerometers at the wing tips, damper weights, fuselage center of gravity and nose. The seventh telemetering channel carried the coded timing circuit.

Two simultaneous recordings of the telemetered signal were made at a ground station: one through a standard NACA telemetering station and oscillograph in time-history form; and the other, after beating the subcarrier frequencies to a convenient common value (3 kc), on an Ampex 7-channel tape recorder.

The conventional recording system was installed in the airplane in addition to the telemetering system in order to provide more channels than were then available in the tape recording equipment and to provide a check due to the experimental nature of the system. As the tape recordings proved completely satisfactory, the principal part of the analysis was made directly from the tapes.

The frequency-response characteristics of the telemetered accelerometer system were flat within ±10 percent up to about 65 cps for the wing tip accelerometers and up to about 130 cps for the damper weight accelerometers. As the major part of the subsequent analysis is confined to frequencies below about 50 cps, response corrections were not applied to the data.

Analysis equipment.- The analysis equipment consisted of a two-channel, variable filter width Automatic Harmonic Analyzer Model 510 manufactured by Davies Laboratories, Inc., Riverdale, Md., and associated play back and recording equipment. The device provides a reading of the mean square of the signal passed by the tunable filter with a specified accuracy of ±1/2 db. The absolute accuracy with which the center frequency of the filter is known is estimated to be about 1 cps. Frequencies obtained simultaneously on the two channels of the analyzer are comparable within somewhat smaller limits, however. A Western Electric Frequency Analyzer Model 3A was also used in connection with a Brush Pen Recorder to obtain time histories of amplitude and mean square amplitude of signals passed by the filter. An overall calibration check on each system was obtained before each use by recording the output of the system for a known sinusoidal input. The filter shape of both analyzers is nearly triangular when plotted as amplitude response squared against frequency.

TESTS AND RESULTS

Ground tests.- Measurements of the response at the instrumented points in the structure for sinusoidal excitation applied at one wing tip by means of a rotating unbalance shaker were made in the same manner as those reported in reference 1. The results obtained, in terms of normal acceleration per unit force as a function of forcing frequency, are presented in figure 5. Results are shown in figure 5 for the two wing tips (for the case of the damper weights locked to the tips) and are compared with similar results from reference 1 for the basic wing without damper. It is apparent from the figure that addition of 100 pounds to each wing tip reduced the frequency of the second wing bending mode from 17 to 13 cps, and reduced the response from about 0.022 to about 0.016g units per pound. The first wing bending frequency was reduced from about 8 to about 6.2 cps. The difference between the results for the two wing tips evident in the figure at frequencies above that of the first bending mode are thought to result from the use of single-point excitation as discussed in reference 1. Attempts to obtain response curves with the dampers operating were unsuccessful, owing, it is thought, to the inadequacy of the excitation equipment available.

Flight tests.- As the object of the tests was to determine the performance of the dampers for specified buffeting conditions, the flight program consisted of attempts to duplicate a specific maneuver several times with the dampers locked and with the dampers operating. The selected maneuver consisted of a slow entry to moderately heavy buffeting and maintenance of relatively constant flight conditions for as long as possible. Several runs were obtained during which the flight conditions were relatively constant (i.e., within a normal-force coefficient of ±0.10 and a Mach number of ±0.02) for periods of from 15 to 25 seconds. All of the test runs (and the ground response measurements) were made with the wing fuel tanks empty. The amount of fuel in the fuselage tank did not have a measurable effect on the wing frequencies.

Short samples of typical acceleration records obtained in the course of the flight tests are presented in figure 6. The time history shown in part (a) of the figure was obtained with the dampers locked at a Mach number of about 0.79, a normal-force coefficient of about 0.44, and an altitude of about 27,000 feet. That shown in part (b) of the figure was obtained with the dampers unlocked at approximately the same flight conditions.

The character of the wing tip acceleration traces with damper locked (fig. 6(a)) is similar to that obtained in other buffeting investigations (for example, ref. 1) and shows considerable variation in both amplitudes and apparent frequencies. It appears, however, that a large component is present near 13 cps, the second wing bending frequency for this condition. The traces for the unlocked case (fig. 6(b)) differs from those of figure 6(a) principally in that the second bending frequency appears to be less prominent and higher frequencies more prominent. The maximum peak-to-peak excursions of the tip accelerations are of the same order for both the locked and unlocked cases; however, because of the many vibratory components of different frequencies which are obviously present in the records, it is believed that detailed study of the effect of dampers should be based on the spectra of the motions.

The traces of the damper accelerometers in figure 6 show the expected results: in the locked case they reproduce the wing tip accelerations and in the unlocked case show a principal component at the damper tuned frequency of about 12 cps. Both the tip and damper traces show an appreciable component near 100 cps. It is believed that this vibration occurs due to a resonance in the damper attachments and could be eliminated by improved detail design.

Values of normal-force coefficient, at which the buffeting started and stopped for each of the runs obtained, are plotted against Mach number in figure 7 where they are compared with a buffet boundary taken from reference 4. The points which denote the start of buffeting fall slightly beyond the boundary of reference by an amount of the same order as the uncertainty in Mach number. The points at end of buffeting fall consistently below the boundary. This effect is similar to results shown in reference 5 of the effect of time in buffeting on the buffeting magnitude and on the end of buffeting. There appears to be no significant difference between the boundary with dampers locked and dampers unlocked. This result is to be expected as the damper should have no effect until after buffeting has started.

In the opinion of the pilot the buffeting encountered fell in the moderately heavy to heavy classification. Because of the difficulty in maintaining and repeating steady conditions, it was difficult for the pilot to judge; however, his overall opinion was that the damper produced no apparent change in the buffeting characteristics of the airplane. In general, little effect would be expected on the pilot as the damper was tuned to the second wing bending mode which has a node at the center line of the airplane.

Reference 6 shows that, for another airplane of the same type as that used herein, aileron buzz occurred at all flight conditions above the buffet boundary shown in figure 7. As discussed in reference 1, aileron buzz was not encountered in the subject airplane until a Mach number of 0.82 was exceeded. Operation of the dampers produced no apparent change in the aileron buzz characteristics of the subject airplane.

DISCUSSION

In order to delineate the operation of the dampers and their effect on the buffeting experienced by the airplane, two runs during which the flight conditions were maintained near the desired values for appreciable periods of time were selected from the data. The two selected runs (one with the dampers locked and one with the dampers unlocked) are considered typical of the results obtained and are presented and discussed qualitatively in terms of the average spectra of the wing tip accelerations. Time histories of the principal properties of all of the data obtained, however, are used in a quantitative discussion of the variation with flight condition of the buffeting experienced and the effect of the dampers on the airplane response. The operation of the dampers and possible application of dampers to buffeting problems are also discussed.

Qualitative discussion of effect of dampers on buffeting.- Sections of each of the typical runs 20 seconds long during which the normal-force coefficient and Mach number were most nearly constant were selected and accelerations at the right and left wing tips were transcribed from the master telemetered tape. The transcriptions were formed into loops and fed into the electrical frequency analyzer. The output of the analyzer is in the form of a variation with frequency of the average square acceleration passed by the filter as the filter is swept through the frequency range. This output divided by the filter area provides an estimate of the power spectral density of the acceleration time history averaged over the entire 20-second length of the record. The ordinate of the spectrum obtained in this manner (in units of g^2/cps) is referred to hereinafter as the power spectral density of the acceleration.

Spectra of the two selected runs obtained in the manner just described are presented in figure 8. A filter width of 1.4 cps measured at the 1/2 power point was used. The spectra for the locked case (fig. 8(a)) shows that the principal responses of the structure to buffeting occur in the first wing bending mode at 6.5 cps and in the second wing bending mode at 14 cps and are generally consistent with the results presented in reference 1. The spectra of the two wing tips differed by less than the estimated uncertainty of the measurement and therefore the single line presented is representative of both tips. The frequencies of maximum response differ from the ground shaking results presented in figure 5 by a maximum of about 1 cps, the estimated uncertainty of the frequency determinations. Although the differences between the two sets of data (both herein, in ref. 1 and in other similar papers) are small, the possibility that they may result from aerodynamic forces during buffeting should not be completely ignored. Differences could, of course, also result if the mode shapes obtained with single-point shaking were not representative of those occurring in flight.

The spectra of wing tip accelerations obtained with the dampers unlocked, which are shown in part (b) of figure 8, are markedly changed from those of the locked case presented in part (a) of the figure. It is immediately apparent that operation of the dampers greatly reduced the large resonant peak which occurred in the second wing bending mode with the damper locked, produced no significant changes in the first mode response, increased the response over a range of frequencies above that of the tuned mode, and destroyed the symmetry of response of the two wing tips at frequencies near that of the tuned mode. The difference between the response of the two wing tips with the dampers unlocked is believed to result from differences in the characteristics of the dampers and will be discussed in more detail subsequently in the section "Operation of Dampers."

Although the time average of the normal-force coefficient and Mach number during the two runs considered differed by only a small amount, the Mach numbers varied between extremes of 0.78 and 0.81 and the normal-force coefficients varied between 0.25 and 0.48 during the unlocked run and between 0.33 and 0.56 in the locked run. As previous buffeting results (for example, ref. 1 and 5) have shown that both the intensity and character of buffeting may change rapidly with small changes in normal-force coefficient and Mach number above the boundary, the effects of these large variations in flight condition must be considered and, therefore, direct comparison of the two spectra presented should be considered as qualitative only.

The area under a spectrum, usually referred to as the "total power," may be considered as a measure of the overall buffet intensity. In this connection it is of interest to note that for a single-degree-of-freedom system subjected to a flat spectrum of excitation the total power of acceleration is infinite. For the same system, however, the total power of velocity and of displacement have finite values which are functions of the damping. Thus, on theoretical grounds, the total power of displacement or of velocity would appear to be better measures of overall buffeting intensity than the total power of acceleration. It will be shown, however, that almost all of the power of the spectra of figure 8 occur at frequencies below about 40 cps. This result indicates that in this case the excitation is negligible above about 40 cps and thus the acceleration power may be used in the subject case as a measure of overall buffeting intensity. Accelerations were used in the subject tests as they could be measured conveniently and were adequate to describe the operation of the dampers. For other purposes, of course, the other measures might be more suitable. For example, buffeting stresses might best be studied through use of deflection measurements, damping through use of velocity, and effects on the pilot through use of acceleration.

The area under the spectra presented in figure 8, taken between frequencies of 4 and 40 cps, is for the locked case $0.75g^2$, and for the unlocked case about $0.60g^2$. The value presented for the unlocked case (in which the spectra of the two wing tip accelerations are different) was obtained by averaging the values for the two tips. Considering the slightly higher value of the average normal-force coefficient during the locked run, it appears from these values that the total power of the the acceleration is of the same order with the damper operating as with the damper not operating. The validity of this statement is, however, subject to the same qualifications due to the detailed variations in normal-force coefficients and Mach number within the runs as is the direct comparison of the spectra discussed above.

As a matter of interest, the acceleration spectra of figure 8 were converted to deflection spectra and the total power obtained. In terms of deflection appreciable power occurred only below 20 cps and the total power in the unlocked case was 70 percent of that for the locked case. This value may be compared with the acceleration power ratio of 80 percent presented above. Examination of the spectra of figure 8 reveals that although the total powers remain of the same order, an appreciable portion of the total power is shifted from the tuned mode to higher frequencies by operation of the dampers. Eliminating the effect of the first mode by integrating between 9 and 40 cps, it was found that the acceleration power in this range was affected to the same extent as the total power by operation of the dampers whereas the deflection power was reduced by a factor of about $2\frac{1}{2}$. This effect is believed significant from the point of view of possible stress relieving effects of dampers and will be discussed in more detail subsequently.

Quantitative discussion of effect of dampers on buffeting.- In view of the large variations of normal-force coefficient and Mach number within and between the various runs obtained and of the known variation of buffeting intensity with both normal-force coefficient and Mach number, it appears necessary that the results obtained be correlated with flight conditions before a quantitative evaluation of the effect of the damper can be made. Two quantities were chosen for this correlation: first, the total power of the wing tip acceleration, which, as discussed in the preceding section, appears to be a usable measure of the overall buffeting intensity without regard to frequency; and, second, the power in the mode to which the damper was tuned. The total power was obtained by feeding the acceleration signal into a thermocouple device which recorded its average square as a function of time. The power in the damper tuned mode was obtained in the same manner except that a filter centered on the second mode frequency was inserted into the circuit ahead of the thermocouple. In both cases the time histories were recorded directly from the master tape in order to avoid the effect of a splice which would occur if a loop was used. The response of the complete system used is flat within 10 percent between frequencies of about 3 and 65 cps. The pass band between the half-power points extended from about 1.5 to 80 cps. The lower limit results from the AC signal amplifier used and the upper limit from the accelerometer characteristic.

Figure 9 is presented in order to illustrate the operations performed on the data and the nature of the variations involved. The variations with time of the flight conditions, component accelerations, and average square accelerations are shown. The example presented is the locked case for which the spectrum was presented in figure 8(a) and a section of the basic record was presented in figure 6(a).

The measures of power obtained with the analysis equipment are subject to distortion due to the time constants of the equipment. The effect of the filter is shown in the center of the figure where time histories of the component of the basic record passed by the filter when tuned to the first and second bending mode frequencies are recorded. These time histories are similar to the amplitude time histories presented in reference 1. The time constant of the filter used is of the order of 1/2 second and its overall effect on the record is similar to a running 1/2 second average. The distortion due to this effect is believed to be small at the frequencies considered as the maximum rate of change of response of the structure (which is inversely proportional to the damping of the motion) is of the same order as that of the filter. The character of the amplitude time histories presented confirm the results of reference 1 in that they show that the buffeting response of the structure consists of intermittent bursts which do not appear to be directly related to the variations of normal-force coefficient and Mach number and which is consistent with the response expected of a lightly damped system subject to random excitation.

The thermocouple device used to obtain the average square of the data has a time constant of about $3\frac{1}{2}$ seconds. Thus, the device has the effect of a running $3\frac{1}{2}$-second average of the square of the input signal. Time histories of the thermocouple output for the total power and the power near the second bending mode are presented at the top of the figure. As the averaging process results in an apparent lag of the output, the power time histories have been shifted ahead in time to account for this effect. The values of power were averaged over a 2-second period and were compared with values of Mach number and lift coefficient averaged over the same 2-second interval.

The variation of the total power of the wing tip accelerations reduced in the manner just described is presented in figure 10 as the variation of the root-mean-square (rms) acceleration with airplane normal-force coefficient. Root-mean-square values are used instead of average squares as the data appear to plot linearly in this form. For the case with the dampers unlocked, where the total power at the two wing tips is different, the average of the two tips is presented. The points on the figure are coded to indicate the Mach number range and a straight line fairing of the locked data is shown in both parts of the figure to facilitate comparison. The points show considerable scatter; however, a marked trend of increasing rms acceleration with increasing normal-force coefficient and a tendency toward increased rms acceleration with increased Mach number are evident. It is apparent from the figure that operation of the dampers produced little change in the rms acceleration at the wing tips within the range of flight conditions investigated.

The points obtained by integration of the spectra of figure 8 are also plotted in figure 10 (large symbols). It is evident that these points are consistent with the remainder of the data indicating that almost all of the power of the motion at the wing tips is contained within the limits of integration used (4 to 40 cps).

In order to obtain a measure of the power in the second wing-bending mode to which the damper was tuned, the response in this mode was isolated by the use of a filter as previously described. As it was the intention to present a measure of all of the buffeting response near the tuned mode, a filter width of 3 cycles at the half-power point, which encompassed the principal part of the desired response, was used. For the locked case the filter was centered at 14 cps, the frequency of maximum response shown in figure 8(a). For the unlocked case the filter was centered on 12 cps, the damper tuned frequency. This frequency was chosen because reference 2 shows that for the optimum system there considered the principal responses are concentrated about this frequency. Inasmuch as the dampers did not operate under optimum conditions during the subject tests (discussed in more detail subsequently) and as reference 2 shows that the effect of nonoptimum conditions is, in general, to spread the response unequally about the tuned frequency, results obtained in the manner described may not give proper weight to some of the deleterious effects of nonoptimum conditions. Thus, the results are thought to be representative of the performance of dampers nearer optimum than those tested.

The correlation of the power near the second mode with normal-force coefficient and Mach number is presented in figure 11 in the same form as that used in figure 10. The rms acceleration values at the wing tip are those passed by the filter at the indicated frequencies and, as in the previous case, the unlocked values are the average of the results for the two wing tips. The correlation shows some scatter but a consistent effect of normal-force coefficient. The data are satisfactorily faired by straight lines which intersect the zero acceleration axis at about the same point thus confirming the expectation that the damper should have little effect on the buffet boundary. The effect of operating the damper is clearly shown and amounts to a reduction of the rms acceleration in the second mode by a factor of about three. Or, from another point of view, the airplane could be operated near a Mach number of 0.80 at a normal-force coefficient of about 0.50 with the dampers unlocked without exceeding the value of rms acceleration in the tuned mode which occurred with dampers locked at a normal-force coefficient of 0.20.

Operation of dampers.- It is of interest to examine the operation of the dampers in some detail in order to determine the operating conditions for comparison with the design conditions and to investigate the marked difference between the response of the two wings. The spectra of the two wing tips for the damper-unlocked case taken from figure 8(b) are reproduced in figure 12 where they are compared with the spectra for the damper weights during the same run. The spectrum of each wing and its damper were obtained simultaneously on the two channels of the analyzer in order that the frequency scales should be as comparable as possible. (See section entitled "Instrumentation.") It is evident from the figure that the peak responses of the two dampers occur near the tuned frequency (between 11 and 12 cps) and that the spectra agree more closely than do those of the wing tips.

The variation with frequency of the ratio of the absolute motion of each damper weight to that of its wing tip (the square root of the ratio of the spectra of figure 12) is compared in figure 13 with theoretical values computed from the relations of reference 2 for appropriate values of damping, and with vibration table test results. It is apparent that the flight test curves agree satisfactorily with the theoretical curves computed for a damper tuned frequency of 12 cps; the left damper (part (a) of figure) having damping of the damper weight of about 0.125 critical and the right damper (part (b) of figure) having a damping of about 0.20 critical. Data from other runs showed results in agreement with those presented within the uncertainty of the measurements for the left damper, but showed a considerably greater variation for the right damper. Thus, in flight the left damper operated consistently but had only 45 percent of the desired damping (0.275 of critical), whereas the right damper had 73 percent of the desired damping but appeared to operate inconsistently.

Because of the above results, additional measurements of the damper response were made at the completion of the flight tests. The dampers were mounted on a vibrating table and accelerometers were placed both on the table and damper weight; thus, the motion of the table was analogous to the motion of the wing in flight. Response curves were obtained for steady oscillations at amplitudes representative of those obtained in flight both at room temperature and at a temperature near that encountered in flight (-30° F) and at a reduced amplitude at room temperature. The results obtained for the case of low temperature and the amplitude representative of that encountered in flight are presented in figure 13. The curve for the left damper is in resonably good agreement with that of the flight data; however, that for the right damper differs markedly. The shape of the curve for the right damper (particularly the low value almost up to the frequency of maximum response and the abrupt increase to the frequency of maximum response) is similar to that which might be expected if an appreciable amount of friction was present in the damper. This result, together with other results not presented, indicates the presence of friction to be the most probable cause of the relative inconsistency of operation and the higher apparent damping of the right damper.

Computations from the relations of reference 2 for the flight determined values of tuning and damping, combined with the assumption that the input was unchanged by the operation of the dampers (i.e., the spectrum measured with dampers locked times the ratio of the response curve computed from reference 2 to that of a single-degree-of-freedom system) provided resonably satisfactory estimates, both in shape and magitude, of the spectra measured in flight with the dampers unlocked. Although the spectra with dampers locked were the same at the two tips, the spectrum at each tip with dampers unlocked reflected the characteristics of its damper independent of the other damper. The symmetry of the response measured at the two wing tips in the locked case extends not only to the spectra (fig. 8) but to the individual bursts which are characteristic of the buffeting response. Comparison of amplitude time histories similar to those shown in figure 9 shows that the time variations of the response at the two tips agree almost burst for burst in the locked case. In the unlocked case, however, the amplitude time histories of the response at the wing tips do not appear to be related. The time history of each damper response, of course, follows the response of its wing tip burst for burst as expected. The principal effect of the low damping (45 percent of optimum) of the left damper compared to that of the right damper (73 percent of optimum damping) is shown by both the computations and experimental results to be the increased response of the left tip near 16 cps evident in figure 12.

Possible applications of dampers.- Two possible applications of dynamic vibration absorbers to aircraft buffeting appear practical in view of the material which has been presented: first, as a device to alleviate buffeting, and second, as a research instrument (a means for producing large changes in the response of the aircraft structure) which would greatly facilitate study of the factors which affect the pilot's appreciation of buffeting and the nature of buffeting response, excitation, and damping.

For possible use of the device as a buffet alleviator the first consideration is the weight which would be added to the structure. The total weight of the experimental damper installation tested was 200 pounds, about 5 percent of the wing weight. As this weight might be considered excessive for practical use, calculations were performed by the method referred to in the previous section in order to provide an indication of the performance capabilities of lighter weight dampers. The calculations indicated that dampers having moving weights of only 10 pounds (total weight of about 0.7 percent of the wing weight) would reduce the peak response almost as much as did the 70-pound weights but would not spread the response over as wide a range of frequencies. The calculations also indicated that with a damper installation somewhat heavier than that with 10-pound-moving weights and having components tuned to both the first and second wing-bending mode frequencies, the response to buffeting of the test airplane could be made nearly flat throughout the investigated frequency range.

A difficulty which might be encountered in practical application of dampers as buffet alleviators results from the fact that a change in the natural frequency of the buffeting mode would change the tuning ratio (and therefore the effectiveness) of the damper. The principal cause of changes of the wing natural frequencies in flight is the use of fuel stored in the wings; thus, the dampers could be tuned only for the most critical buffeting condition, or, alternately, the additional complication of automatic tuning could be accepted. The weight penalties associated with damper installations might be minimized by novel design features, such as the use of rotating elements or certain items of fixed equipment as the sprung mass.

The results presented herein provide an indication that large changes in the character of the spectra of the buffeting response of an airplane can be made by use of a tuned damper and that, within practical limits, almost any desired type of spectra can be produced by suitable combinations of dampers. The problem thus arises as to what is the least objectionable type of buffeting response spectra which could be desired. Obviously the characteristics desired for the spectra would depend on the principal purpose; for example, the reduction of wing stresses due to buffeting, reduction of buffeting felt by the pilot, and so forth.

The total spanwise variation of the wing stress due to buffeting may be considered as the vector sum of components in each mode, the stress in each mode being a different function of the tip deflection. For a simple system (i.e., a single mode) the probability of occurrence of oscillating stresses greater than a given level is reduced if the total power of the motion is reduced. The results presented herein show that although the dampers do not reduce the total power of the tip accelerations, they reduce the power markedly in the tuned mode and shift it to higher frequencies. Thus, for cases in which the maximum buffeting stress results principally from one mode, a significant reduction in maximum stress might result from distributing the power of the principal mode to higher modes in which the stress levels were not critical or in which the maximums occurred at different spanwise stations. From these considerations it appears that dampers might be used to reduce maximum buffeting stresses or reduce structural weight by allowing more efficient use of the structural material. The gains realized would depend both on the buffeting experienced and on the details of the structure and an analysis much more detailed than the previous remarks would be necessary before strict conclusions could be reached for any particular case.

In order to reduce the buffeting felt by the pilot, it is, of course, necessary to know how his appreciation of buffeting is related to the spectrum to which he is subjected. Very little information is available on this subject and research along these lines is both desirable and necessary. As indicated previously, the present results show that use of dampers to alter the spectrum affords an excellent research tool for this purpose. It is also believed that such work would provide much needed information on the nature and mechanism of buffeting response, excitation, and damping.

CONCLUDING REMARKS

Limited flight measurements have been made in order to investigate the effect of dynamic vibration absorbers on the structural response of a Lockheed F-80A airplane during buffeting. The absorbers were mounted on the wing tips and were tuned to the second wing-bending mode. The results were obtained by comparison of runs with and without the absorbers operating through use of electrical frequency-analysis techniques.

Operation of the dynamic vibration absorbers produced large changes in the response of the structure, greatly reducing the amplitude of the principal response peak of the wing tip acceleration spectra (which occurred in the second mode with damper not operating) at the expense of increased response at higher frequencies. The total power of the wing tip accelerations during buffeting was not appreciably affected by operation of the absorbers; however, a large part of the total power was shifted from the second mode to higher frequencies. This shift indicates that the device might be effective for relieving buffeting stresses.

The part of the rms acceleration of the wing tip during buffeting at frequencies near the second wing-bending mode correlated with airplane normal-force coefficient but showed little consistent variation with Mach number within the region investigated. Operation of the absorbers reduced the rms acceleration in the tuned mode to about one-third its value at the same normal-force coefficient with damper not operating.

Approximate calculations indicated that for use as a buffet alleviator, an absorber installation weighing considerably less than that tested could produce a significant reduction in the structural response to buffeting of the tuned mode. The absorber also appears useful as a means for producing large changes in the response of aircraft structures to buffeting which would greatly facilitate much needed research on the nature of buffeting response, excitation, and damping and their effect on the pilot.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., October 20, 1954.

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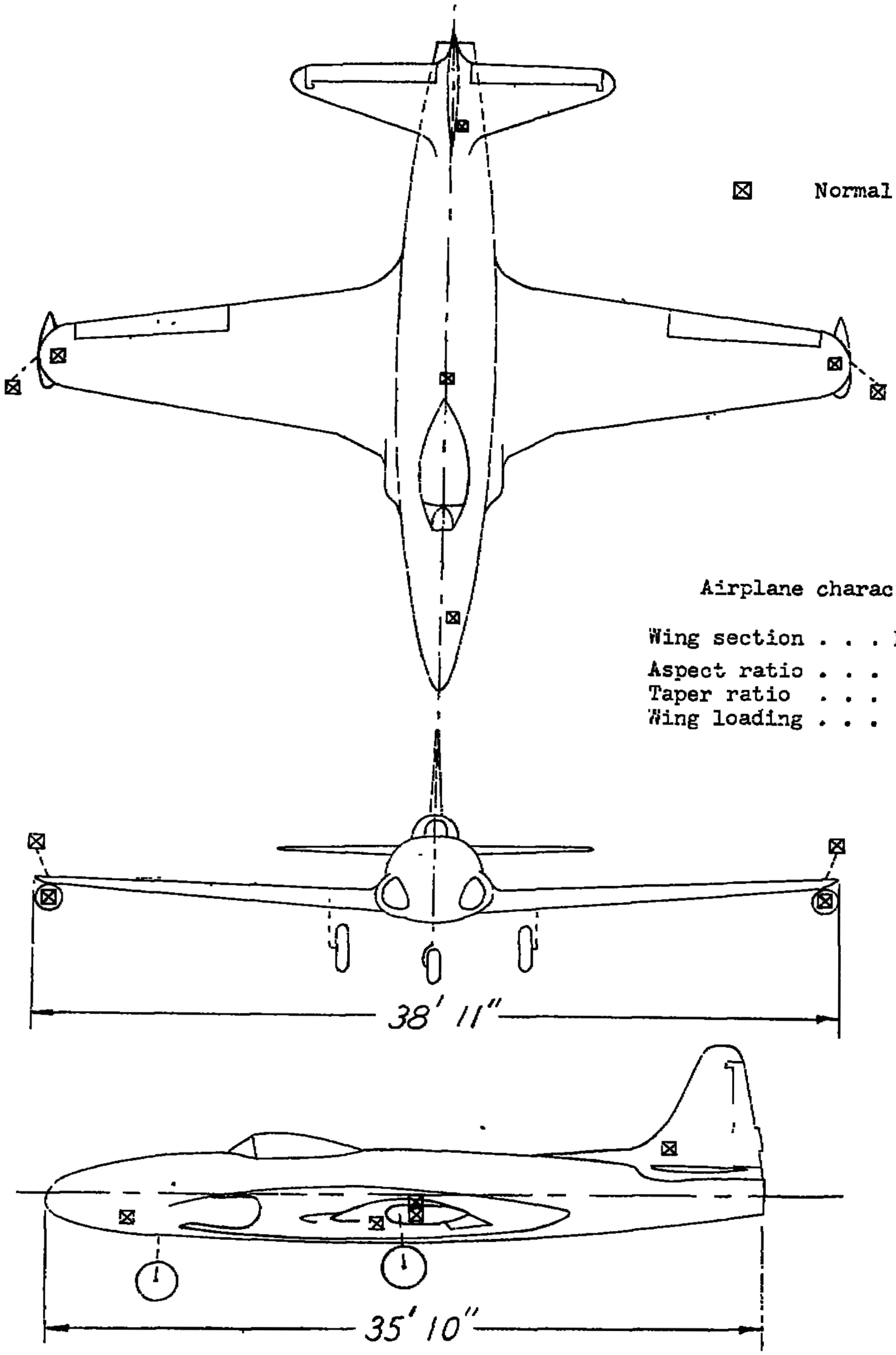

⊠ Normal accelerometers

Airplane characteristics

Wing section . . .	NACA $65_{(12)}$-213
Aspect ratio	6.39
Taper ratio	0.42
Wing loading	45 lb/sq ft

Figure 1.- Three-view drawing of test airplane (Lockheed F-80A) showing location of accelerometers and damper fairings.

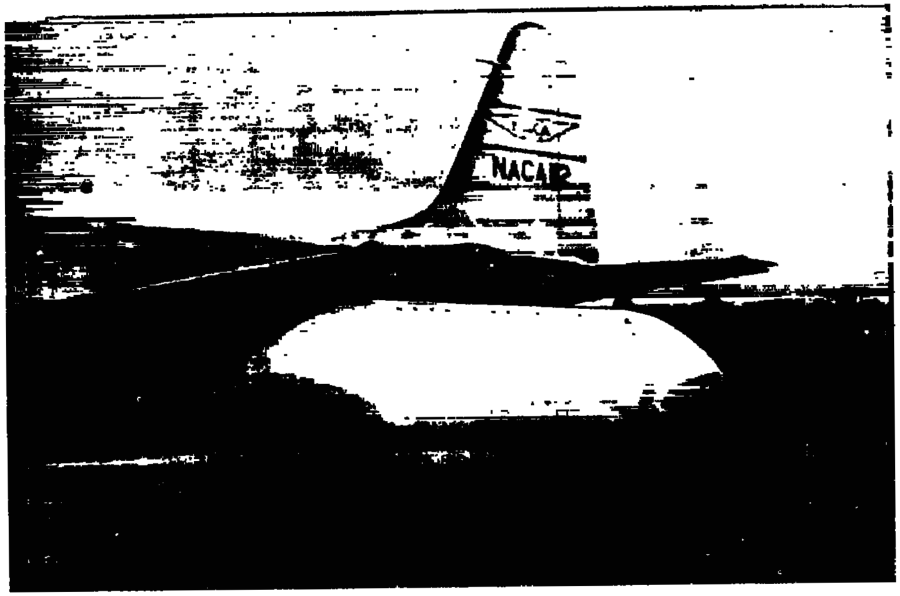

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Figure 2.- Photograph of test airplane showing damper fairing mounted on the left wing tip.

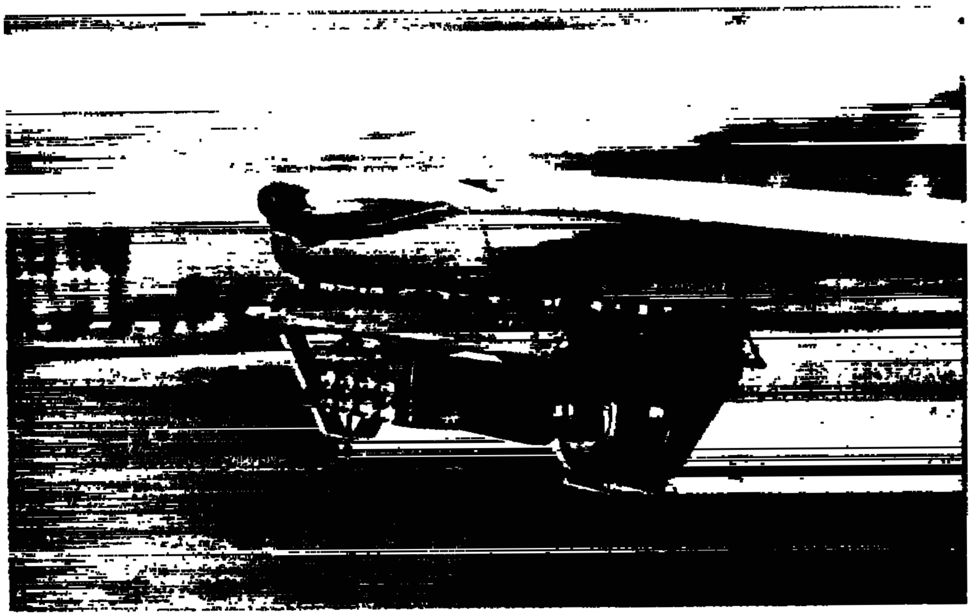

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Figure 3.- Photograph showing damper mounted on left wing tip of test airplane with fairing removed.

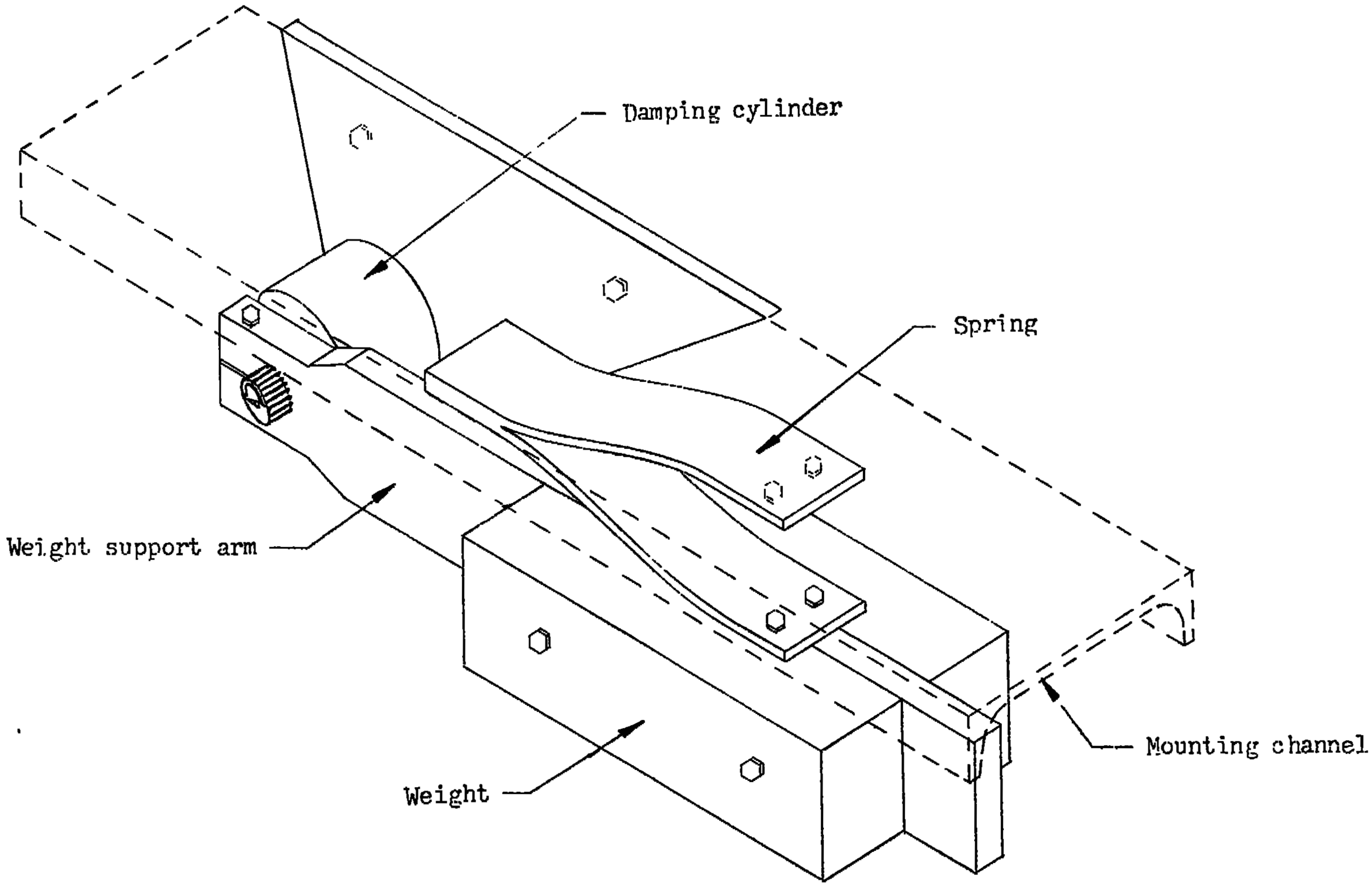


Figure 4.- Schematic drawing of damper.

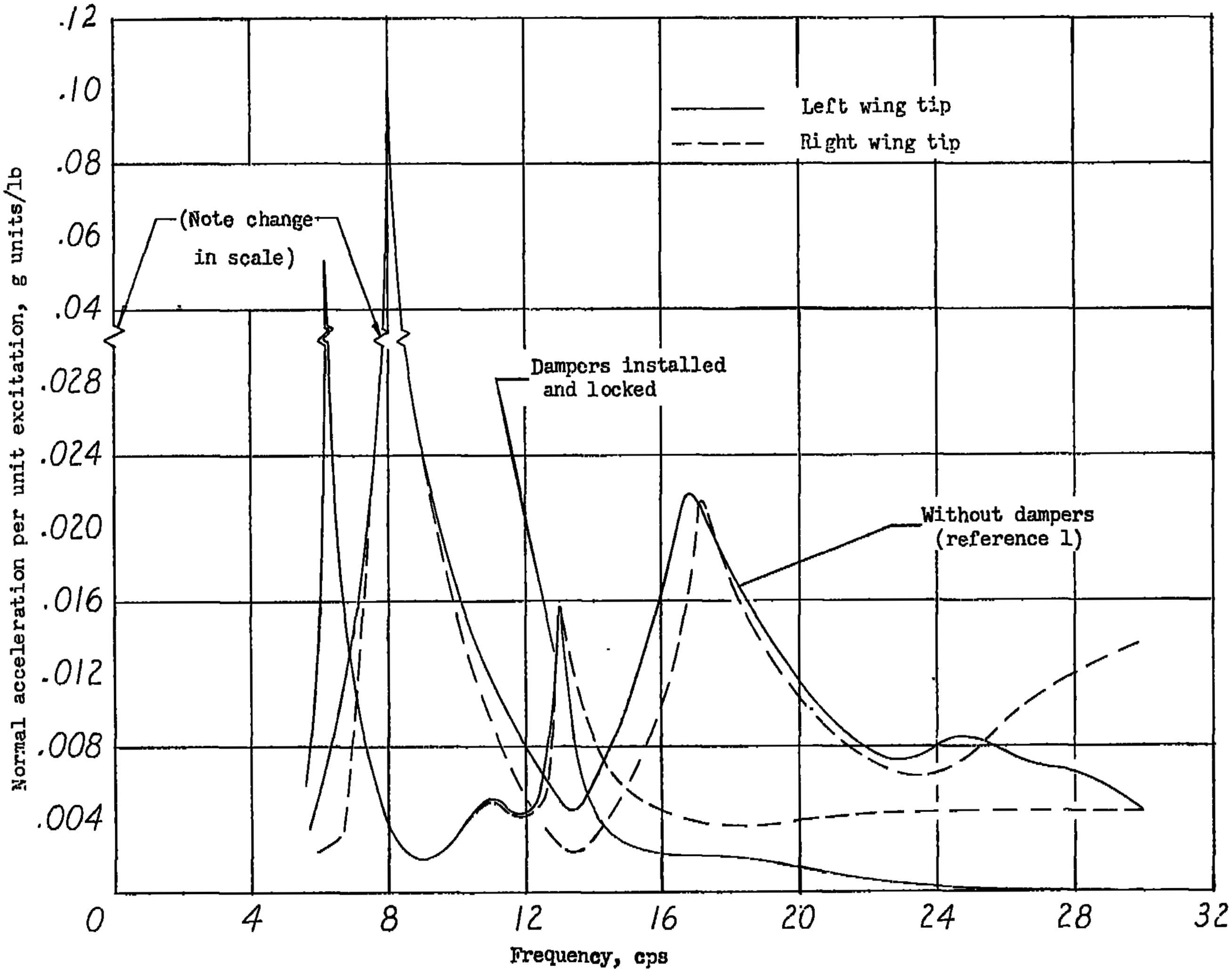
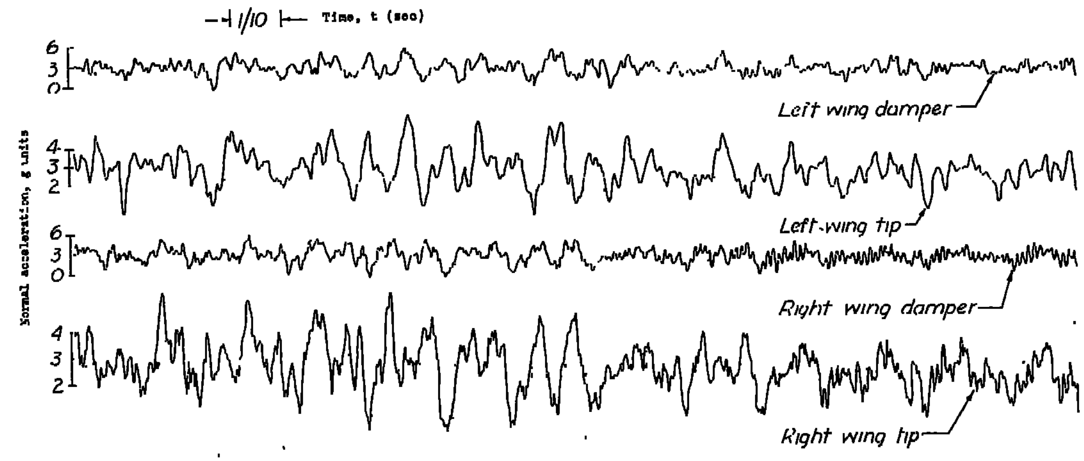
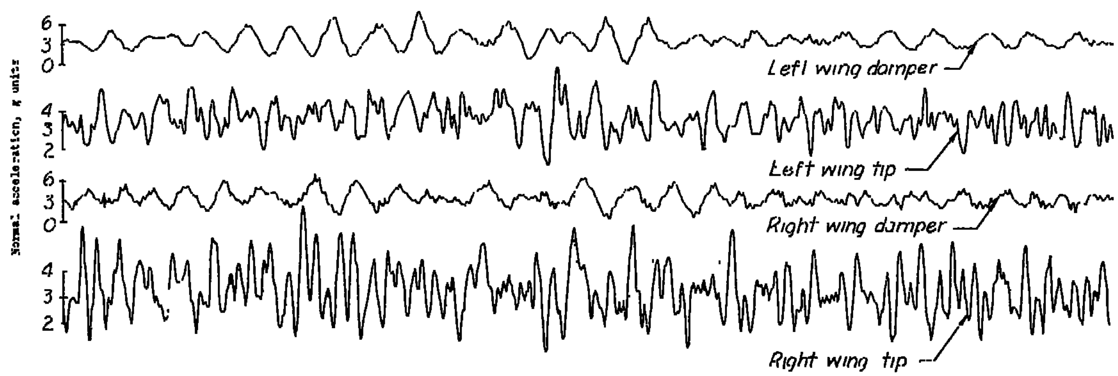


Figure 5.- Response of airplane structure to sinusoidal excitation applied at the right wing tip with and without dampers installed.



(a) Dampers locked.



(b) Dampers unlocked.

Figure 6.- Tracings of parts of the acceleration records obtained during buffeting with tuned vibration absorbers locked and unlocked at a Mach number of about 0.79, a normal-force coefficient of about 0.44, and an altitude of about 27,000 feet.

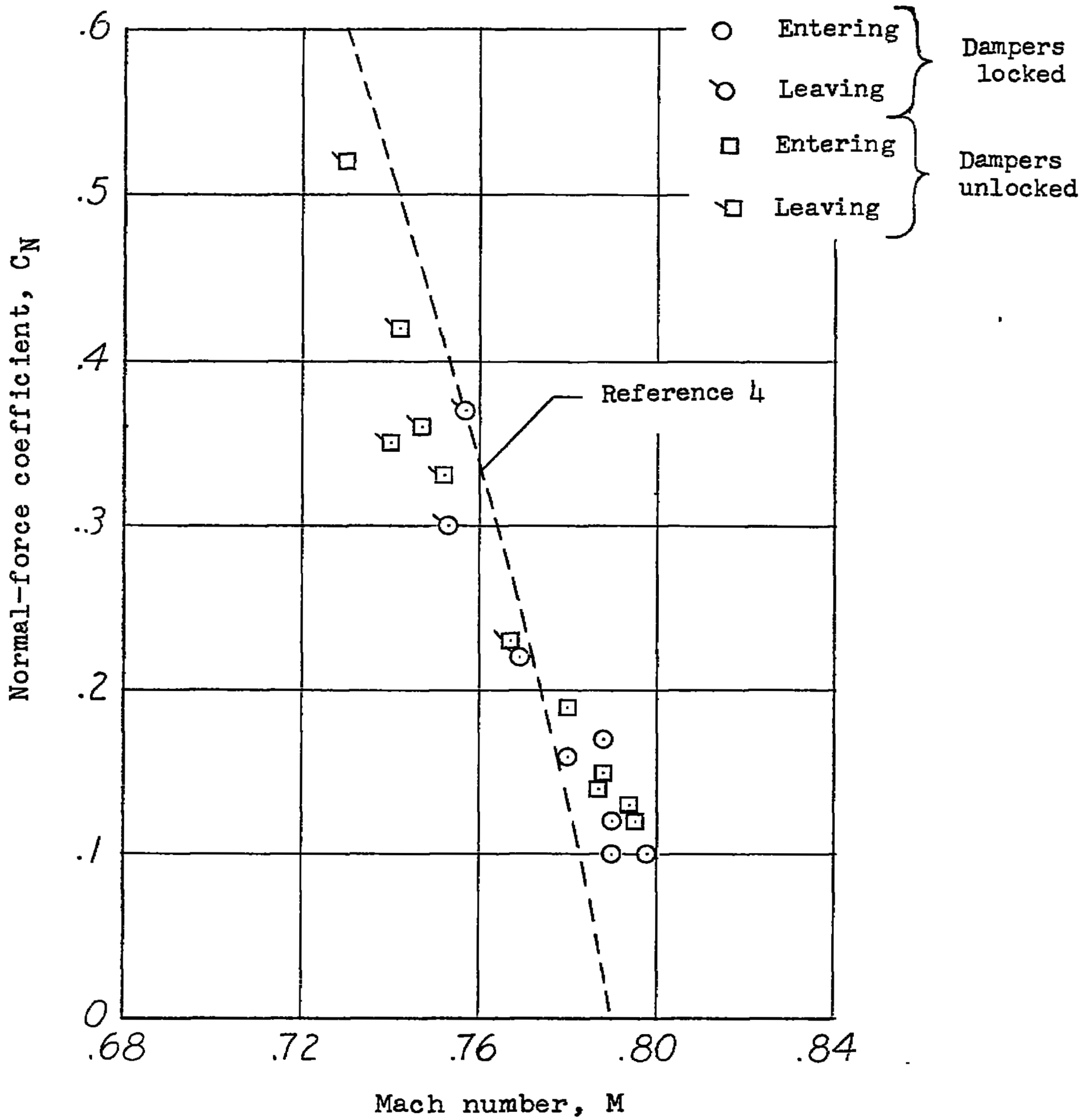
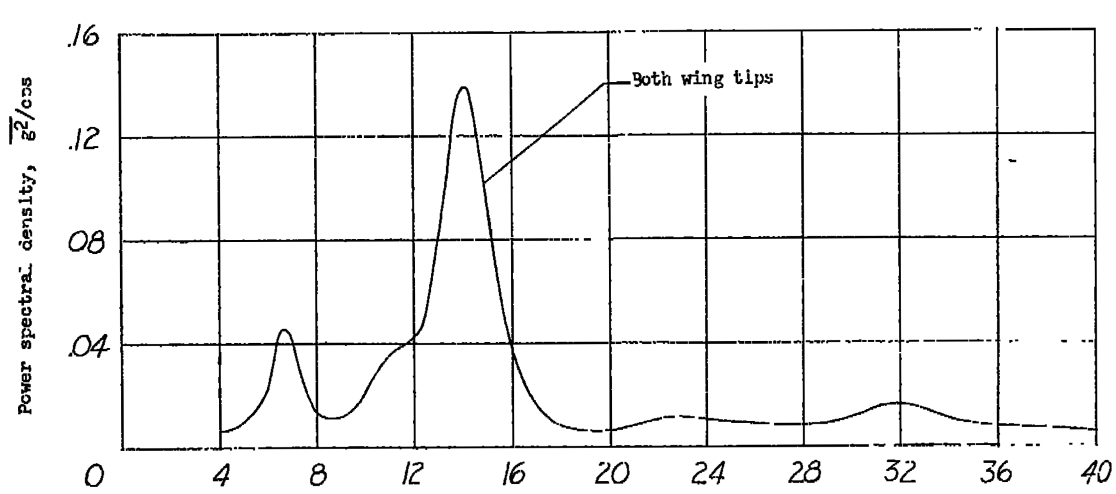
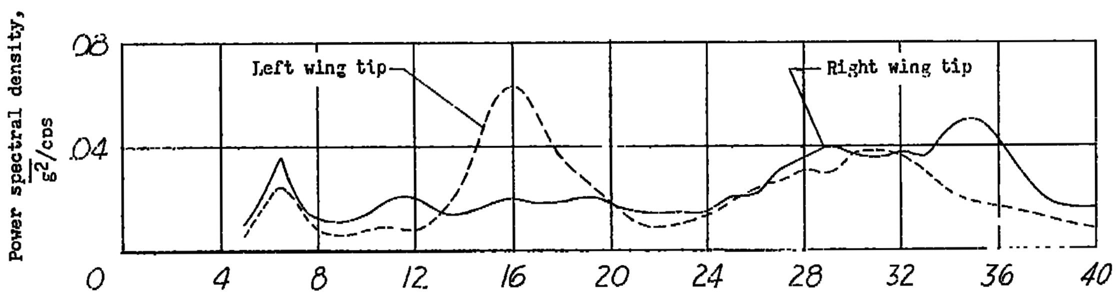


Figure 7.- Buffet boundary data for the test airplane with tuned vibration absorbers installed.

[redacted]



(a) Dampers locked. Average Mach number 0.79; average normal force coefficient 0.46.



(b) Dampers unlocked. Average Mach number 0.79; average normal force coefficient 0.40.

Figure 8.- Spectra of normal accelerations at the wing tips during 20-second sections of two typical buffeting runs, one with dampers locked and one with dampers unlocked. Filter band width at half-power point, 1.4 cps.

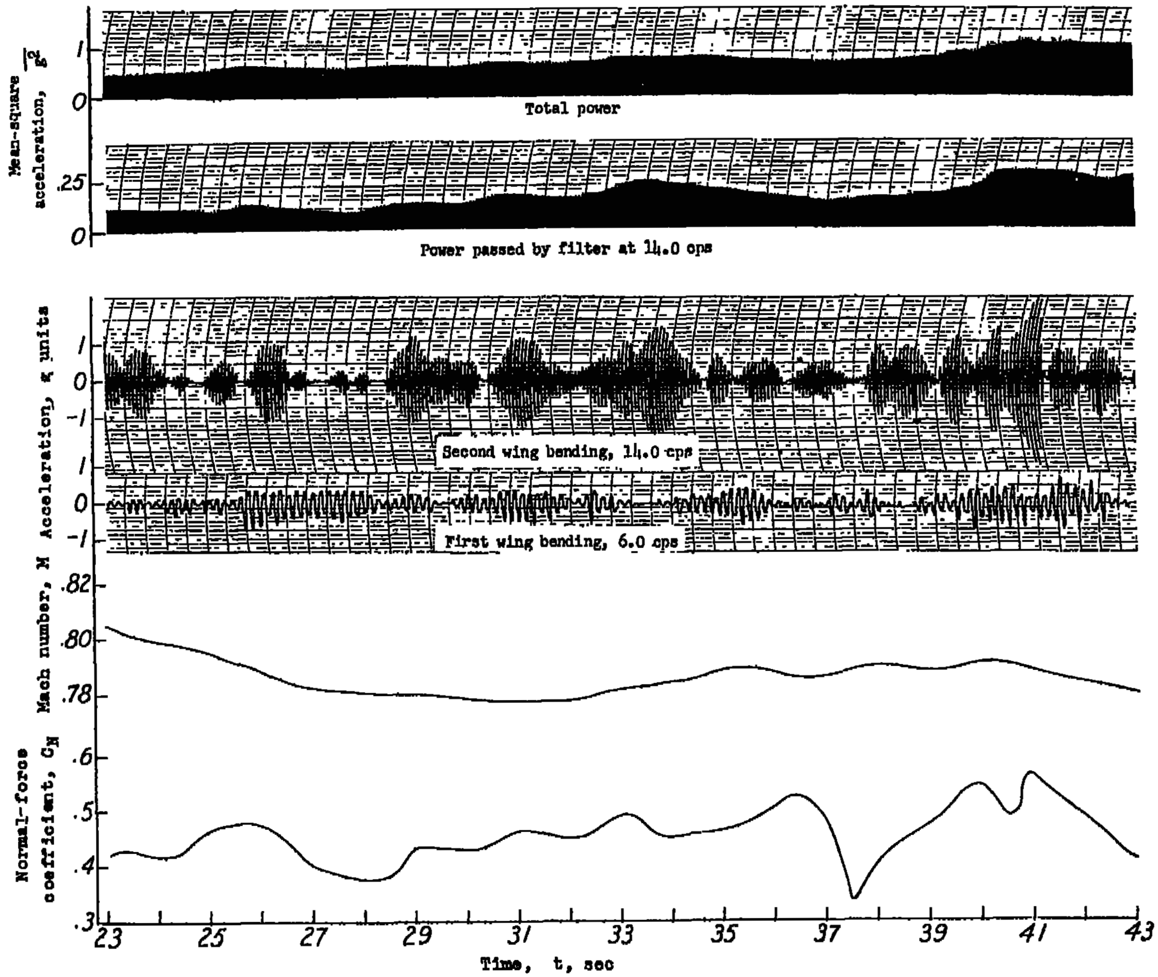


Figure 9.- Time histories of flight conditions, component accelerations, and total and component average square accelerations for the left wing tip during typical buffeting run with dampers locked. The power time histories have been shifted to account for the apparent lag of the thermocouple.

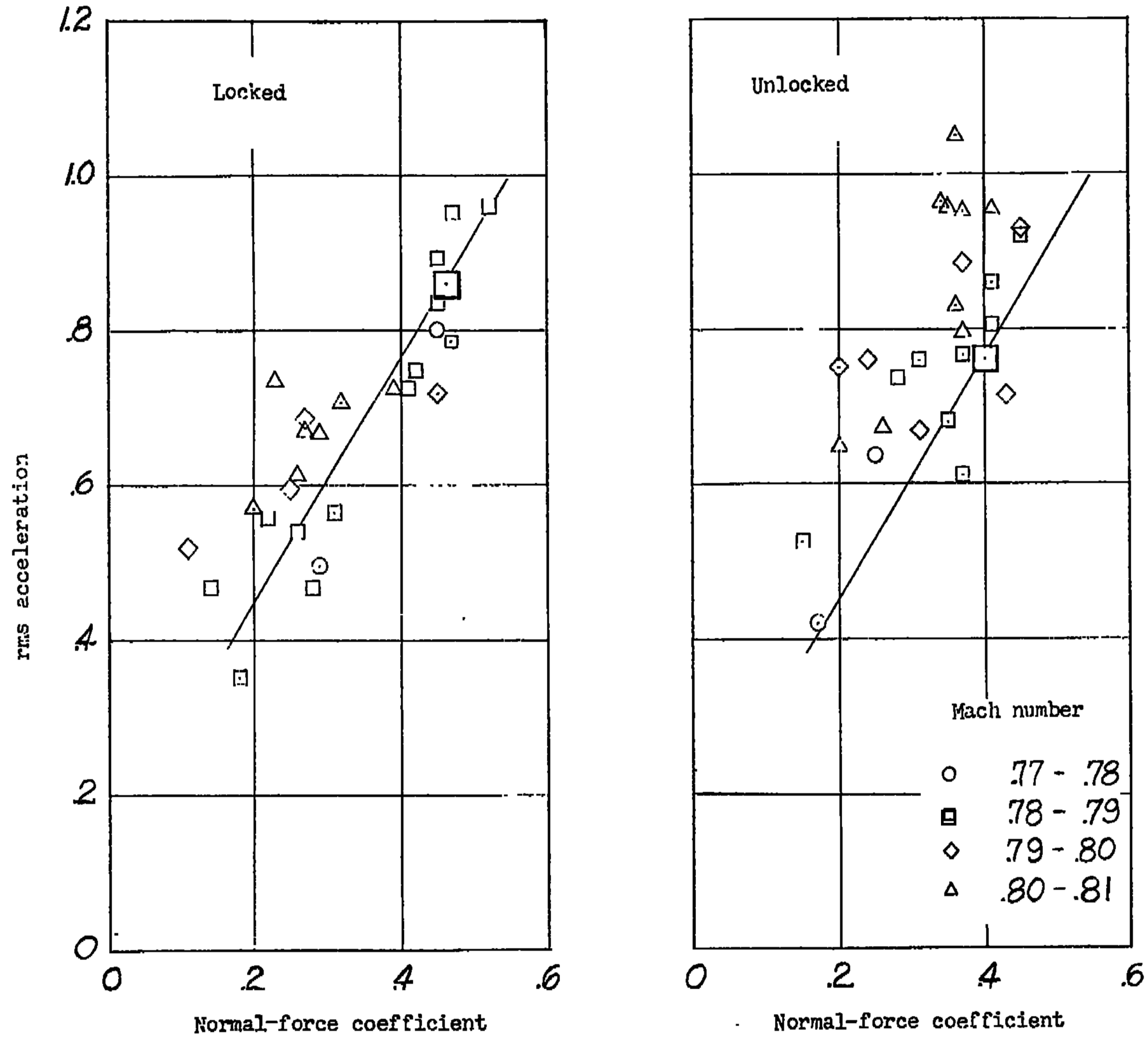


Figure 10.- Correlation with flight condition of total rms acceleration at the wing tips during buffeting for dampers locked and unlocked cases.

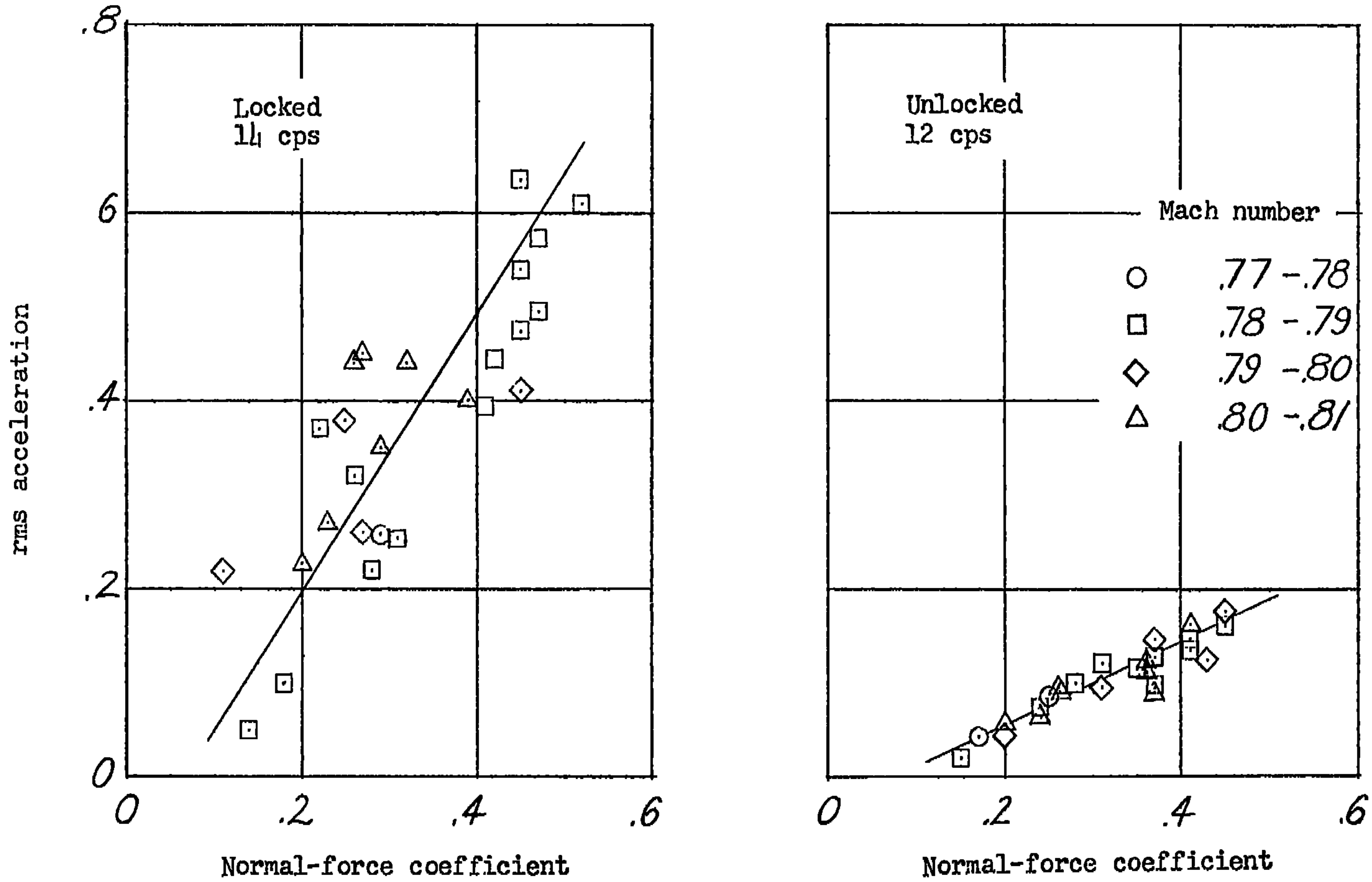


Figure 11.- Correlation with flight condition of rms acceleration passed by filter of 3 cps band width centered on frequency of second bending mode.

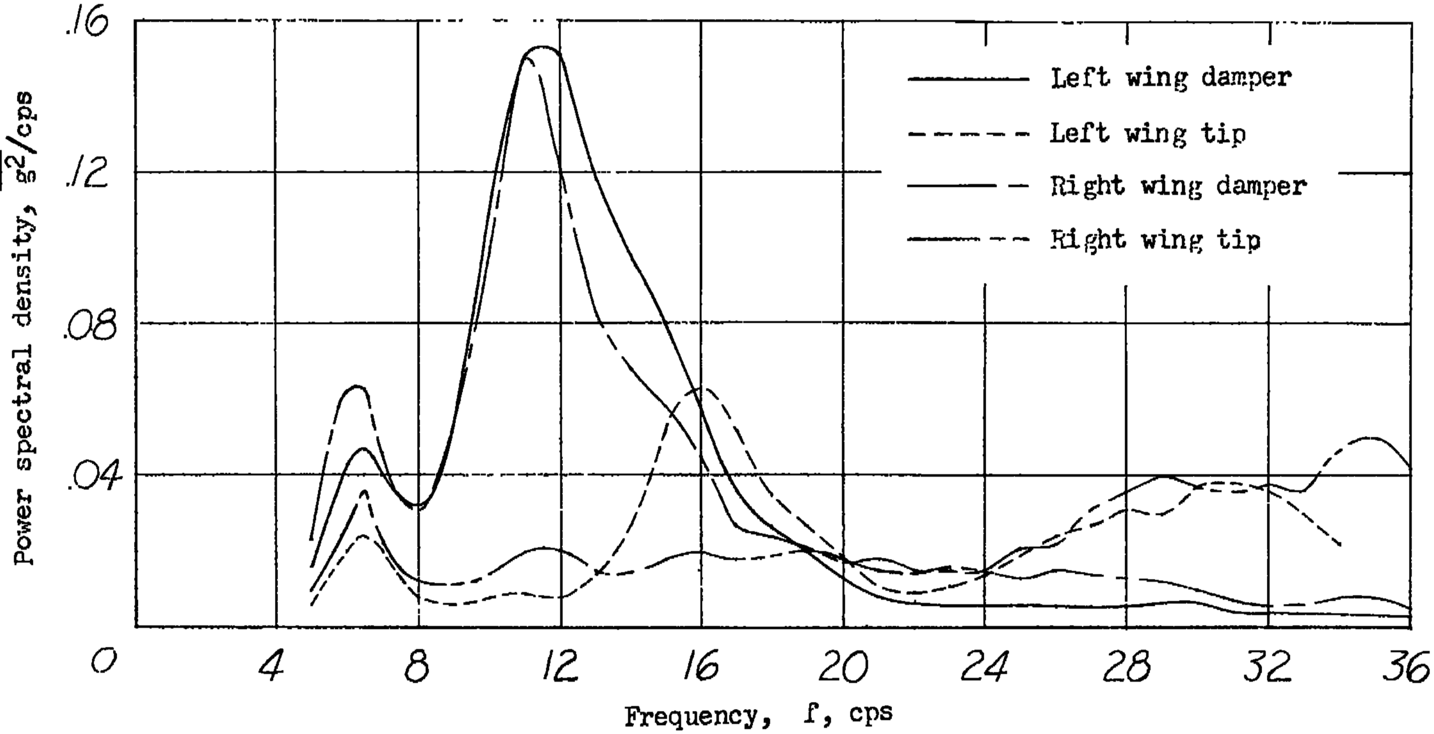
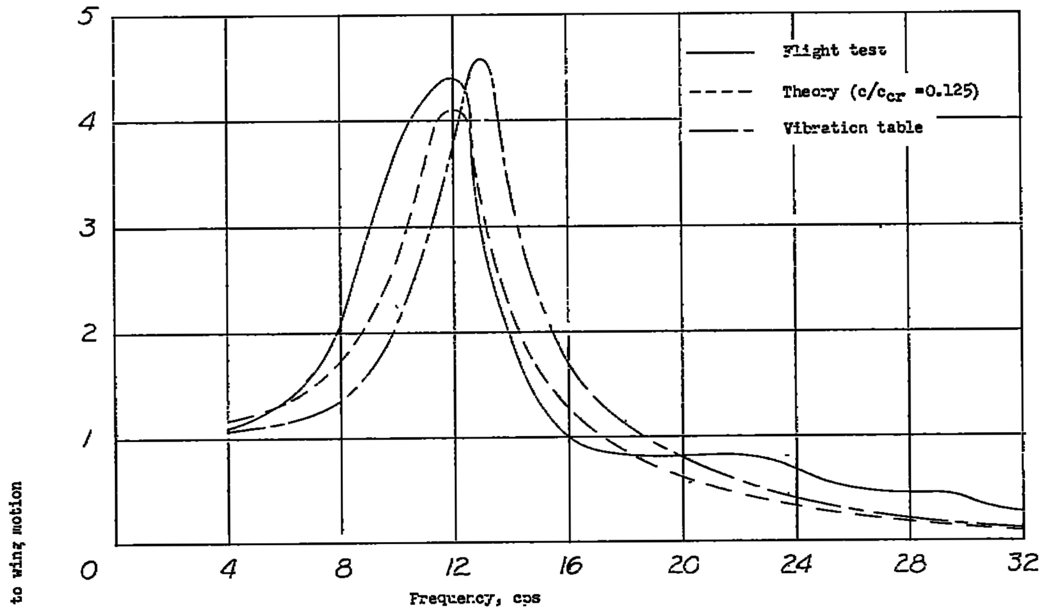
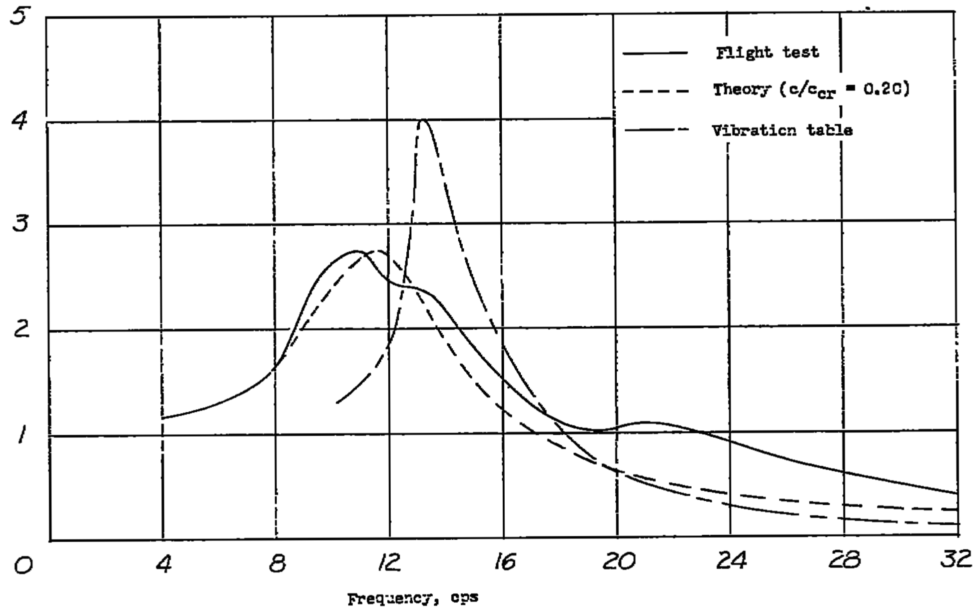


Figure 12.- Spectra of damper accelerations during buffeting compared with spectra of wing tip accelerations reproduced from figure 8(b).



(a) Left damper.



(b) Right damper.

Figure 13.- Variation with frequency of the ratio of damper motion to wing motion obtained for each damper during flight tests. Vibration table test results and theoretical curves are included for comparison.