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RESEARCH MEMORANDUM

A PRELIMINARY STUDY BY MEANS OF ELECTRICAL FREQUENCY-ANALYSIS TECHNIQUES OF THE RESPONSE OF AN AIRPLANE STRUCTURE DURING BUFFETING

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SUMMARY

As part of the National Advisory Committee for Aeronautics program of buffeting research, a flight investigation has been performed to study in detail the response of an airplane structure during buffeting. Measurements of the acceleration at selected points on the structure were made during buffeting for two different conditions of lift coefficient and Mach number and the resulting time histories of acceleration were studied by means of electrical frequency-analysis techniques.

It was found that buffeting occurred principally at frequencies of the lower natural modes of the structure and that the complicated response measured at any point could be approximated by superposition of the lower natural modes as determined by ground response measurements. The relative amplitude of the several modes varied with flight condition, the higher frequency modes being the largest at high speeds, and the lowest frequency mode being the largest at lower speeds and high lift. The response in a given mode during buffeting was not steady but consisted of a series of "bursts" at apparently random intervals.

The method of electrical frequency analysis used was found to be a useful tool in the study of flight buffeting records.

INTRODUCTION

Buffeting is often considered to be the response of the airplane structure to the excitation forces associated with separated flow. The occurrence of an amount of separated flow on an airplane sufficient to produce buffeting is generally limited at low Mach numbers to a region near maximum lift, but at high subsonic Mach numbers, due to the influence of compressibility and the presence of shock waves, a sufficient amount of separation to cause buffeting occurs at values of lift appreciably below maximum lift. The amount of separation present (and the buffeting amplitude) in general increases with an increase in the lift beyond the buffet boundary and, inasmuch as the buffeting is disturbing to the pilot, in some cases limits the usable amount of lift of the airplane to a value considerably below the maximum obtainable. In addition to this severe performance penalty, buffeting reduces the effectiveness of the airplane as a gun platform and may cause structural loads in excess of those for which the airplane is designed.

As part of the program of buffeting research of the National Advisory Committee for Aeronautics, a flight investigation has been performed to study in detail the response of an airplane structure during buffeting. Previous flight buffeting studies (for example, refs. 1 and 2) have provided adequate information on the onset of buffeting and have indicated that buffeting occurred principally at the natural frequencies of the structure; however, the complicated and apparently time-varying character of the records obtained indicated that more detailed measurements and analysis of the responses of an airplane structure during buffeting would be profitable.

In the investigation reported herein, efforts were made to define in detail the motions of the structure during buffeting through use of high-frequency accelerometers located at several points in the structure, through measurements of the ground response characteristics of the structure, and through use of electrical-frequency-analysis techniques to study the complex buffeting records. Results obtained from a preliminary application of this analysis method to buffeting records for two examples of moderately heavy buffeting, one near maximum lift and one in the high-speed low-lift buffeting region, are presented. Some of the implications of the results concerning the nature of the buffeting response are discussed.

AIRPLANE INSTRUMENTATION

A three-view drawing of the airplane used in the investigation (Lockheed F-80A) showing the location of the accelerometers and the principal characteristics of the airplane is presented as figure 1. The motions of the airplane structure perpendicular to the plane of the wing were measured by means of electrical strain-gage accelerometers (maintained at constant temperature by a thermostatically controlled heating system) located on major structural members at the wing tips, the center of gravity, the fuselage nose, and the rear engine attachment point. Time histories of the outputs of these accelerometers were recorded by an oscillograph. The accelerometer-galvanometer combinations were adjusted to have a frequency-response flat within ±5 percent to 37 cps so that the motions thought to be of major interest (the lower principal modes of the complete structure) would not be obscured by local or engine-excited high-frequency vibrations. The response of the accelerometer-galvanometer combination to sinusoidal forcing is shown in figure 2. As the subsequent analysis is confined to frequencies below about 45 cps, dynamic-response corrections have not been applied. The angular position of the right aileron with respect to the wing was recorded by means of a direct-linked strain-gage type of device, the response of which was flat to at least 50 cps.

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

TESTS AND RESULTS

Ground response measurements.- In order to determine the natural frequencies of the lower principal modes, the response of the airplane structure at the five accelerometer locations was measured for sinusoidally varying forces applied at the right wing tip and at the center of gravity. The sinusoidally varying force was applied by means of a rotating unbalance-type shaker and its frequency was varied between about 6 and 45 cps in small increments. During these measurements the airplane was fueled to a weight condition representative of that obtained in the flight tests and was supported on the landing gear. The tire pressure was reduced about 50 percent with the result that the natural frequency of the airplane as a whole on the tires was between 1 and 2 cps.

The response of each of the instrumented points of the structure in terms of normal acceleration per unit force as a function of the forcing frequency is shown in figure 3(a) for forcing at the wing tip and in figure 3(b) for forcing at the center of gravity. The excitation force available from the rotating unbalance shaker increases in proportion to the square of the frequency and, as the sensitivity of the accelerometers is constant, the uncertainty of the values of normal acceleration per unit force decreases with increase in frequency. Values of the estimated maximum uncertainties of the results presented in figure 3 are given in table I.

The results for excitation at the wing tip shown in figure 3(a) clearly reveal the first two wing bending modes. The first wing bending mode (in which the wing tips move together and the center of gravity in the opposite phase) occurs at 8 cps and the ratio of wing tip to center-of-gravity acceleration is about 12 to 1. The second wing bending mode (asymmetric, tips moving in opposite directions with a node at the center of gravity) occurs at 17 cps. The third wing bending mode (which occurs at 26 cps and is discussed subsequently) and higher modes are not clearly shown in the figure.

The results for excitation at the center of gravity presented in figure 3(b) were not extended to a low enough frequency to excite the first wing bending mode. The fuselage bending mode which occurs at 15 cps is characterized by the tail and nose moving together in opposition to the center of gravity. The wing tips also move together in opposition to the center of gravity indicating that the wing is being forced in its first bending mode. The third wing bending mode (wing tips and center of gravity all moving together) occurs at 26 cps and is clearly defined at the wing tips. No clear peak is apparent at the center of gravity, however, possibly because of the presence of several unidentified modes which occur at frequencies above 26 cps. The small peak near 36 cps in the wing-tip response curves is thought to be the first wing torsion mode on the basis of results presented in reference 3.

A measurement of the structural damping was obtained under the same conditions as the ground response tests by recording the transient vibrations which occurred after the sudden release of 1,000-pound weights from the wing tips. The vibration decayed in the first wing bending mode (approx. 8 cps) and the equivalent viscous damping was found to be 0.028 of critical damping.

Response to buffeting excitation.- The flight program consisted of wind-up turns which penetrated the buffet boundary to the extent that, in the pilot's opinion, moderate-to-heavy buffeting was obtained. The maximum emphasis was placed on obtaining slow, smooth penetrations of the boundary and on maintaining constant lift coefficient and Mach number for as long as possible during buffeting. For the application of the method of analysis presented herein two typical cases tested at altitudes near 33,000 feet were selected during both of which the lift coefficient and Mach number were maintained constant within 0.1 and 0.04, respectively, for a period of about 4 seconds. The two selected cases are compared with the buffet boundary and the maximum-lift line in figure 4. The maximum-lift line was obtained from wind-tunnel data presented in reference 4 and appears to be slightly lower than the values of maximum normal-force coefficient attained in flight.

The first case chosen, at a Mach number near 0.60, is considered typical of the buffeting encountered when the buffet boundary approaches the maximum-lift line and will be referred to as the "stall" case. The second case, at Mach numbers near 0.78 and at moderate lift coefficients, is considered typical of the buffeting encountered in the region beyond the point where the buffet boundary abruptly diverges from the maximum-lift line and will be referred to as the "high-speed" case. The analyzed portion of the second run is 8 seconds long and includes the pull-up into moderate buffeting as well as the 4-second period of relatively constant flight conditions.

Tracings of parts of the oscillograph records of the stall case and of the high-speed case are presented as figure 5 to illustrate the nature of the data obtained. It is apparent from figure 5(a) (the stall case) that the principal mode evident at the wing tips is first wing bending (approx. 8 cps, see also fig. 3) but it is also apparent from the character of the wave shape that other frequencies are superimposed upon it. In figure 5(b) (the high-speed case) it is not immediately evident which frequency is predominant. The complicated and apparently time-varying character of the center of gravity and nose traces, as well as that of the wing traces, emphasizes the desirability of separating the several modes for individual study.

The trace of the rear accelerometer in figure 5 shows a principal frequency of the order of 100 cps. This high-frequency vibration is thought to be of local or engine-induced origin and, inasmuch as this frequency is beyond the capabilities of the equipment used, the analysis will be confined to the results obtained from the other four accelerometers.

METHOD OF FREQUENCY ANALYSIS

The method chosen for separating the several modes which were thought to be present in the buffeting records and for evaluating their relative importance consisted of transcribing the oscillograph record into an electrical signal and feeding the alternating part of this signal through a tuneable narrow-band-pass filter to a suitable recording system. The transcription process was accomplished by manually tracing the record (which was moving at a speed of one-seventy-second of the speed at which it was originally recorded) with a device which controlled the ribbon shutter of a Mirragraph recorder operating at a slow film speed. The Mirragraph record, which is similar to a moving-picture sound track, was then played back through a reproducer at a fast speed so that the buffeting frequencies were within the range of the filter. For the filter used the playback speed chosen was 1.7 times the original recording speed.

The recording and reproduction equipment consisted of a Western Electric Mirragraph Recorder, model number RA-1132-C, and the companion reproducer model number RA-1129-B. The over-all signal-to-noise ratio of the Mirragraph recording and reproducing system is about 35 decibels, and the frequency response is flat within $\pm 1/2$ decibel from 2 to 2,000 cps. The harmonic distortion is of the order of 1 percent. The filter and output recording equipment was a Western Electric Frequency Analyzer (model 3A) and a Level Recorder (model 4A), respectively. The uncertainty of the tuned frequency of the filter is considered to be about ± 2 cps and the output level is considered to be uncertain within about ± 1 decibel.

The shape of the filter in terms of frequencies based on the original recording speed is given in figure 6. The band width of the filter, defined at the half-power (0.7 amplitude) points is about 2.3 cps and does not vary with filter setting throughout the frequency range investigated. It is shown in reference 5 that the response of a filter of this type to an abrupt change in amplitude of a sinusoidal variation consists of a delay period during which the output oscillates slightly about its previous value and a buildup period during which the output changes to the new value. For the filter used, reference 5 indicates that both of these quantities should be independent of the tuned frequency and that the buildup time should be about 0.43 second. Measurements of the response of the filter to step functions have verified the order of magnitude of the buildup time and indicated that the delay time is considerably smaller than the buildup time. Thus, the filter output would be expected to show the true magnitude of an abrupt change in input after a delay of about 1/2 second.

The output of the filter for each frequency setting was recorded in two ways: first, the average amplitude of the entire length of record by feeding the output into the model 4A Level Recorder and second, as a time history of the amplitude by feeding the output into a Brush (model BL 902A) Recorder having a time constant much less than the buildup time of the filter. The unfiltered output could also be recorded directly on the Brush Recorder (which had a frequency-response flat to 100 cps) for comparison with the original record. The entire system was calibrated by tracing sine waves (and combinations of sine waves) of known amplitude and determining the ratio of input to output as a function of the gain control settings. The averaging process of the model 4A Level Recorder was checked by comparison of its indication with the numerical average of the acceleration values recorded in time-history form by the Brush Recorder. This comparison was made at several filter tunings and satisfactory agreement was obtained.

It should be noted that the Mirragraph records will necessarily begin and end with a step function in signal. It was found that this step function could be materially reduced from that found in initial experiments if the unexposed and overexposed sections at the ends of the run were carefully trimmed off and the ends joined forming a loop. However, a moderate disturbance still remains and for this reason the first 1/2 second of the time histories of component amplitude must be disregarded.

Each of the accelerometer records had to be traced separately and, because of slight variations in the transcription and recording speeds, the component time histories differed slightly in length. The maximum discrepancy was about 1/4 second in a record 8 seconds long. The components of different accelerometers were synchronized by means of a mark placed a short distance from the beginning of each Mirragraph record which was arranged to appear as a pulse on an auxiliary recording channel. Thus, the synchronization of components of different accelerometers may be in error by as much as 1/4 second near the end of the records, but the average uncertainty is considered to be less than half this value. The synchronization between different frequency components of one accelerometer is more exact, however.

DISCUSSION

Verification of Transcription Procedure

Time histories of the acceleration amplitudes recorded by the accelerometers at the nose, center of gravity, and left and right wing tips during the stall buffeting case as reproduced from the unfiltered Mirragraph records are presented in figure 7, together with the accompanying time variations of lift coefficient and Mach number. The abrupt disturbance at the extreme left side of the figure is the effect of the splice discussed in the previous section, and the slow change in level which is particularly evident in the first half of the nose acceleration trace is introduced by the characteristics of the amplifiers used. The frequencies of the slow change in level are below the frequency range of interest. Although much of the higher-frequency detail of the acceleration records is obscured because of the compressed time scale, comparison of these traces recorded on an expanded time scale with the original oscillograph traces have shown that the salient features are satisfactorily represented. As a further check one accelerometer record was traced twice. The filtered component at 14.1 cps of these two separate transcriptions of the same record are compared in figure 8. It is apparent that the envelopes of the curves differ only slightly in shape and that the repeatability of the process is good. (Tracing 2 was recorded at a smaller gain setting than tracing 1; note 20-percent difference in scales.)

Stall Buffeting Case

Separation of buffeting modes in left-wing-tip acceleration.- In order to illustrate the separation of the acceleration records shown in figure 7 into components, the frequency analysis of the left-wing-tip record will be shown in detail.

First, the average spectrum over the entire 4-second record is shown in figure 9 as the variation of amplitude with frequency. Comparison with the ground response results of figure 3 shows that the largest peak, at 8 cps, is the response at the first wing bending mode. The amplitude of the second peak, at 16.5 cps, is about 75 percent of the first and occurs between the second wing bending mode at 17 cps and the fuselage bending mode at 15.5 cps. The third wing bending response peak appears at 27.5 cps with an amplitude of about 30 percent of that of the first peak. Superposition of the filter shape (fig. 6) on the first peak (shown dashed in fig. 9) shows that the response is only slightly greater than that which would have been obtained from sinusoidal input at 8 cps. Superposition of the filter shape on the second peak, however, shows that the response at adjacent frequencies is appreciably greater than would be expected from a sinusoidal input at 16 cps. This condition could result from the presence of a pure wing bending mode with the fuselage bending mode (of smaller amplitude) superimposed upon it. This possible explanation of the observed phenomena appears logical as the natural frequencies of the second wing bending and fuselage bending modes do not differ by an amount sufficient for the filter to discriminate between them. The ground response results presented in figure 3 showed that the second and third response peaks were appreciably wider than the first peak. Thus, the greater width of the second and third peaks compared with that of the first peak observed in figure 9 could have resulted if the excitation in the vicinity of each of the peaks had had a relatively flat spectrum (i.e., not concentrated at a fixed frequency) and if the breadth of the peaks indicated by the ground response results was not markedly changed by the aerodynamic damping present in flight.

Second, time histories of the components are presented in figure 10. It is immediately apparent that the amplitude of each component varies widely even though the lift coefficient and Mach number remain relatively constant. It should be noted, however, that the angle of attack, which was not measured, might have varied as the flight condition is approaching that of maximum lift.

Detailed examination of figure 10 reveals that each of the component time histories consists of periods of small amplitude ("dwells") followed by periods of large amplitude ("bursts"). The spacing of the bursts is irregular; a greater number of distinct bursts occur in the higher-frequency components than in those at low frequencies. Some of the bursts also appear to have been superimposed on the decay of the preceding burst. The buildup and decay of the bursts appear to become more abrupt at the higher frequencies. This effect can be predicted from the filter characteristics presented in the section entitled "Method of Frequency Analysis" and the damping characteristics of the structure. Inasmuch as the buildup (and die-down) time of the filter does not vary with frequency, it is evident that variations in any of the components of acceleration which occurred faster than this time would appear as the filter buildup time whereas variations which occurred appreciably slower than the buildup time would appear only slightly modified from their true shape. The damping of the wing controls the rate of change of acceleration of the wing; for example, the structural damping (0.028) corresponds to a decrease to one-half amplitude in about 4 cycles. If the decay occurred at this rate in the first mode (near 8 cps), the change to half amplitude would require 1/2 second and in the second mode (near 16 cps), 1/4 second. The presence of aerodynamic damping in flight might, of course, reduce the times to half amplitude from the values given. In view of the preceding observations, it appears that the buildups and decays evident in the components at the lowest frequencies reflect, to some extent, the true motion of the structure; whereas, at the higher frequencies, the buildup and decay rates are those of the filter. It should be noted that, because the buildup and die-down phenomena of the filter are equal and opposite, the area of the burst correctly indicates the area of the motion burst which caused it even though the true shape of the burst is distorted by the filter. The length of the dwells, the periods of small amplitude between bursts, indicates that during the corresponding time period there was no appreciable motion of the wing and presumably no appreciable excitation on the wing at the frequency of the component showing the dwell.

The wide variations with time of the amplitude of the filtered components shown in figure 10 are usually considered characteristic of the response of a resonant system to random excitation. Although some of the component traces have a superficial resemblance to the response of a lightly damped vibrating system to random impacts, it is evident that the excitation is not of that type because if it were the bursts would necessarily occur at the same time in all of the component traces.

The average amplitude of each of the component time histories is a maximum at frequencies which differ from those of peak response shown in figure 3 by amounts less than the uncertainties of the frequency measurements. Both the frequencies noted for the component time histories and those of figure 9 depend on the calibration of the filter tuning system and are uncertain within about ±1.5 cps.

For ease in comparison, the traces of figure 10 which have maximum amplitudes and which correspond to the three frequencies of maximum response (7.1, 15.3, and 27.7 cps) are reproduced in figure 11 where they are compared with the unfiltered record and the flight conditions. The motion of the left wing tip during the stall buffeting case is shown in figure 11 to consist of the following: a combined second wing bending—fuselage bending mode (15.3 cps) which consists of a series of closely spaced bursts having amplitudes which increase regularly throughout the test; a first wing bending mode (7.1 cps) consisting of a single large burst near the middle of the test; and a much smaller third wing bending mode (27.7 cps) consisting of several bursts which increase slowly and then appear to decrease in amplitude. This result is consistent with the concept that the complicated motion of the airplane structure during buffeting consists of the superposition of the natural modes of the structure which respond and decay in accordance with the apparently random excitation induced by flow separation. It may be significant that the peak responses of the different modes frequently occur at different times and usually appear to occur at minimums of the other responses.

Comparison of response at four points in the structure.- The basic records presented in figure 7 for the three accelerometer locations other than the left wing tip were analyzed in the manner described in the preceding paragraphs and similar results were obtained. Component time histories at the three frequencies of maximum response are compared in figure 12 in order to provide as complete a picture as possible of the buffeting encountered. At the first frequency (7.1 cps) the traces for the two wing tips differ only in detail as would be expected for the first bending mode. The center-of-gravity trace responds at about the same time as the maximum response of the tips, but at a much smaller amplitude, the ratio of the tip to center-of-gravity accelerations being of the same order as that measured in the ground response tests. The response of the fuselage nose trace is of the same order as that of the center of gravity indicating that at this frequency (if they were in phase as was found in the ground response measurements) the fuselage acts as a rigid body (i.e., no appreciable fuselage bending occurs).

At the second peak response frequency (15.3 cps) the large amplitude and similar character of the nose accelerometer trace compared with that of the center of gravity shows that an appreciable amount of fuselage bending mode was excited. As the second wing bending mode is asymmetric, the motion of the center of gravity in the fuselage bending mode would tend toward an alternate increase and reduction of the amplitude of the wing tips, destroying the symmetry (of amplitude) of the pure asymmetric mode. The traces shown here are, in general, consistent with this picture (i.e., near 22 seconds the amplitude of the center-of-gravity traces is zero and the bursts in the two wing traces are about of equal magnitudes, whereas at 24.5 seconds the center-of-gravity trace has an appreciable amplitude and the wing trace amplitudes are markedly different). The traces presented are not completely consistent with the foregoing explanation; however, it should be noted that because of the small amplitude of the center-of-gravity accelerations, a high degree of amplification was necessary and therefore the signal-to-noise ratio in the electrical equipment was poor.

The third peak response frequency presented in figure 12 (27.7 cps) corresponds to the third wing bending mode. Although the amplitude was small, the bursts in the nose trace and the corresponding but much smaller bursts in the center-of-gravity trace may indicate the presence of a fuselage bending mode of higher natural frequency than that previously discussed. The wing-tip accelerations show small bursts which appear to correlate in time but not in amplitude.

High-Speed Buffeting Case

Basic records and separation of modes in the left-wing-tip acceleration.- The accelerations measured during the high-speed buffeting case were analyzed in the same manner as those of the stall case, and, except for certain differences which are discussed subsequently, the character of the filtered traces and the results obtained are similar to those presented for the stall case.

The time histories of the unfiltered accelerations measured at the left and right wing tips and at the fuselage nose are presented in figure 13 together with the time variations of normal-force coefficient and Mach number. The center-of-gravity trace was used in the subsequent analysis but was not recorded in a form suitable for reproduction in this figure. The slow transients referred to previously are particularly evident in the right wing and nose traces.

The amplitude spectrum of the left wing tip averaged over the entire 8 seconds of record is presented in figure 14. The character of the spectrum differs from that found in the stall case, principally in that the second peak is larger than the first. The second peak (14 cps) is 30 percent greater than the first peak (7.5 cps) and the third peak (24 cps) is about 10 percent greater than the first peak. The frequencies of the peaks differ from those found in the stall case, the peaks of the lower two modes by an amount smaller than the estimated uncertainty of the frequency and that of the third mode by an amount slightly greater than the estimated uncertainty. The greater breadth of the peaks compared with that of the filter shape probably results from the same effects discussed for the stall case. The average amplitude of the spectrum is somewhat reduced because of the fact that during the first 4 seconds the lift coefficient (and the buffeting intensity) are increasing; only in the last 4 seconds of the test is the lift coefficient relatively constant. Since wind-tunnel results for the aircraft configuration presented in reference 4 show that in the lift-coefficient range of interest the steady lift curve has an appreciable positive slope, it is considered probable that the angle of attack did not change appreciably during the last 4 seconds of the test.

Time histories of the filtered components of the left-wing-tip acceleration are presented in figure 15 for a number of filter tunings. The character of the traces presented is similar to those presented in the stall case; that is, the traces appear to consist of a series of bursts at more or less irregular time intervals, and the maximum average amplitudes correspond to the peaks in the spectrum presented in figure 14. As before, the component time histories corresponding to the maximum average amplitudes are reproduced in a separate figure (fig. 16). The unfiltered record and the flight conditions are included in figure 16 in order to present a convenient summary of the results for the left-wing-tip accelerations. Although the frequencies of peak response are all lower than the natural frequencies encountered in the ground response tests by an amount of the same order as the estimated uncertainty of the frequency measurement, it is believed that the modes represented are the same. The average amplitudes of all three modes appear to increase slowly during the first part of the record during which the normal-force coefficient was increasing. Near 27 seconds the bursts abruptly became larger and appear to remain of similar size throughout the remainder of the record at nearly constant normal-force coefficient.

Comparison of response at four points in the structure.- The filtered components of each of the four measured points are compared at the peak response frequencies in figure 17. The traces are consistent with the results presented for the stall case in that they indicate that the buffeting response could be approximated by superposition of the lower natural modes of the structure.

Effect of Flight Condition on Buffeting

The limited amount of information presented herein shows that definite differences exist in the buffeting characteristics of the airplane at the two flight conditions investigated. Although the modes excited appear to be the same, their relative amplitude changes drastically. For example, comparison of the filtered traces of figure 17 with those of figure 12 for the constant normal-force-coefficient part of the two records shows that for the first mode the wing-tip accelerations reach a maximum of $\pm 4g$ for the stall case and only $\pm 1.5g$ for the high-speed case. The average differs by a somewhat smaller but still appreciable amount. For the second mode the maximum (about $\pm 2.5g$) and the average accelerations are about the same magnitude for the two conditions. In the third mode the maximum wing-tip accelerations are $\pm 1g$ for the stall case and $\pm 2.5g$ for the high-speed case. The average value of the third mode tip accelerations shows an even greater change. Thus, the differences in the buffeting experienced in going from the stall condition to the high-speed condition can be summarized as a large reduction in the response at the first mode, no appreciable change in the second mode, and a large increase in the response at the third mode. The responses at the center of gravity appear to show changes similar to those observed at the wing tips as would be expected from the concept of superimposed pure modes. The effects at the center of gravity are poorly defined because of the small amplitude of these traces compared to the sensitivity of the equipment as discussed previously, but the ratios of center-of-gravity to wing-tip acceleration appear to be of the same order as that determined in the ground response tests for each mode.

The principal effect of flight condition observed in the results presented is the shifting of the maximum buffeting response from the wing first bending mode in the stall case to the higher modes in the high-speed case. Two possible explanations of this phenomenon can be advanced; first, that the exciting spectrum has a peak of fixed wave length which would therefore increase in frequency as the speed increased, or second, if the location of the area of separated flow (and therefore the oscillating span loading) changed with increase in speed in such a manner that it became concentrated near a node of the lower mode. Additional information is needed to resolve this problem.

Results of other tests of airplanes of the type here considered have shown the occurrence of a low-amplitude aileron oscillation known as "aileron buzz." For example, reference 6 shows that aileron oscillations of about $\pm 1^{\circ}$ occurred near 28 cps at flight conditions beyond a boundary in close agreement with the buffet boundary presented in figure 4. Although the aileron-position records for the data presented herein did show occasional oscillations near 33 cps, the amplitude did not exceed $\pm 0.2^{\circ}$. The ailerons of the subject airplane were rigged to a greater tension than those of reference 6, which might be expected to cause a change in the buzz characteristics in the direction indicated. Inasmuch as the small aileron oscillations which did occur had frequencies near 33 cps, the results presented near this frequency may represent combined effects of buffeting and aileron buzz. The amplitudes shown in figures 9, 10, 14, and 15 for frequencies near 33 cps are considerably smaller than those at the lower natural modes of the structure.

Pilot's Observation of Buffeting

It is of interest to note that the pilot described the buffeting encountered in both of the cases here considered as "moderate to heavy buffeting." The center-of-gravity acceleration records are probably the most representative of the data available for determining the excitation to which the pilot was subjected. It was estimated from the time histories and ground response measurements that during the stall run the maximum values of acceleration at the center of gravity were about $\pm 0.25g$ at both 8 cps and 15 cps. In the high-speed run it was estimated that the values were about $\pm 0.1g$, $\pm 0.4g$, and $\pm 0.2g$ at frequencies of 8, 15, and 24 cps, respectively. The ground response measurements showed that at 8 and 24 cps the motion at the cockpit should approximate closely the motion at the center of gravity. At 15 cps, however, the principal part of the center-of-gravity motion results from a fuselage bending mode with the nose and center of gravity out of phase. Thus, a node must exist between the two accelerometers, possibly in the vicinity of the cockpit, and the cockpit acceleration would be expected to be smaller than that at the center of gravity.

Information on the tolerable limits of human subjects to vibration presented in figure 48-1 of reference 7 indicates that for the frequency range of interest equal response or perception is observed for roughly constant values of acceleration. Reference 7 divides the response of human subjects into the following classes: Accelerations below about 0.003g are "imperceptible," between 0.003 and 0.04g are "perceptible to distinctly perceptible," between 0.04 and 0.1g are "unpleasant and annoying," and accelerations above about 0.10g are "painful to unbearable." The pilot considered that the buffeting he experienced fell into the "unpleasant and annoying" catagory. The large difference between the values assigned to this catagory in reference 8 and the values experienced in flight provide some indication that either the seat mounting and cushion attenuate the motion before it reaches the pilot or that the assigned values are not directly applicable to the condition encountered.

As the foregoing material is by no means conclusive, it appears profitable to investigate the means by which the pilot appreciates buffeting. Besides the obvious means of sight and hearing, a third possibility is suggested. As a seated pilot has a very low natural frequency in the normal direction, his response to high frequency excitation would be greatly attenuated compared with that at low frequencies. If any nonlinearities are present in the pilot's support (seat, cushion, etc.) his motion would tend toward the envelope of the exciting wave shape because of the rectifying property of nonlinear systems. Since it is shown herein that the excitation to which he is subjected consists of an irregular series of bursts of high-frequency excitation, the pilot would therefore tend to feel the bumps rather than the high frequency itself. Further work along these lines might lead to a better understanding of the pilot's appreciation of buffeting.

Evaluation of Method of Analysis

It is believed that the results presented have demonstrated the usefulness of electrical-frequency-analysis techniques in the study of buffeting. Analysis of data by the method described herein can be economically performed in a small fraction of the time required by other techniques. Use of the method has revealed features of buffeting which have not been shown by other methods (i.e., the relative importance of the various modes as influenced by flight condition and the intermittent nature of the response of the structure at each mode) and has contributed to an understanding of the structural motions during buffeting.

The arduous task of tracing the records manually, and the errors attendant to such a process, can be eliminated by recording the data directly in a form suitable for electrical reproduction. By use of a recording system different from that used herein, accurate values of the square of the recorded quantity averaged over any desired time period and for all or any part of the frequency spectrum can be easily and directly obtained. An appreciable body of mathematical theory has been developed (e.g., refs. 8 and 9) which relates the average square quantity to various statistical properties of the system and which has proved to be a powerful tool for the study of random processes. The intermittent nature of the time histories presented herein provides an indication of the times which should be used in order that representative average values may be obtained.

CONCLUDING REMARKS

As part of a program for buffeting research, a preliminary study of flight buffeting records by means of electrical frequency-analysis techniques has been made. The object of the study was to investigate in detail the response of the airplane structure during buffeting.

The results of the investigation indicated that buffeting occurred principally at frequencies of the lower natural modes of the airplane structure and that the complicated response measured at any point of the structure could be approximated by superposition of the lower modes as determined by ground response measurements. The relative amplitude to which each mode was excited during buffeting was found to depend on the flight conditions: for the airplane used, buffeting in the region where the buffet boundary approaches the maximum lift line occurred principally in the first wing bending mode whereas at high speeds where buffeting was encountered far below maximum lift, the buffeting occurred principally in the second and third wing bending modes.

Time histories of the response in each natural mode of the structure during buffeting indicated that the response was not constant for relatively steady conditions of lift coefficient and Mach number but consisted of a series of bursts. These bursts occurred at apparently random intervals. The average amplitude of the bursts may be a useful measure of the severity of the buffeting.

The method of electrical frequency analysis used in the study is particularly suited to the study of buffeting and should prove to be a useful tool in further buffeting investigations.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 10, 1953.

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TABLE I.- VALUES OF ESTIMATED UNCERTAINTY OF

GROUND RESPONSE MEASUREMENTS

Location	Estimated uncertainty, g units/lb (a)		
	8 cps	16 cps	32 cps
Excitation at Wing Tip (fig. 3(a))			
Right tip	±0.0030	±0.0007	±0.0003
Left tip	±.0030	±.0007	±.0003
Center of gravity	±.0013	±.0003	±.00008
Nose	±.0013	±.0003	±.00008
Rear	±.0013	±.0003	±.00008
Excitation at Center of Gravity (fig. 3(b))			
Right tip	±0.0003	±0.00007	±0.00003
Left tip	±.0030	±.0005	±.00013
Center of gravity	±.0003	±.00007	±.00002
Nose	±.0013	±.0003	±.00008
Rear	±.0013	±.0003	±.00008

[a]Estimated uncertainty values do not include dynamic response corrections.

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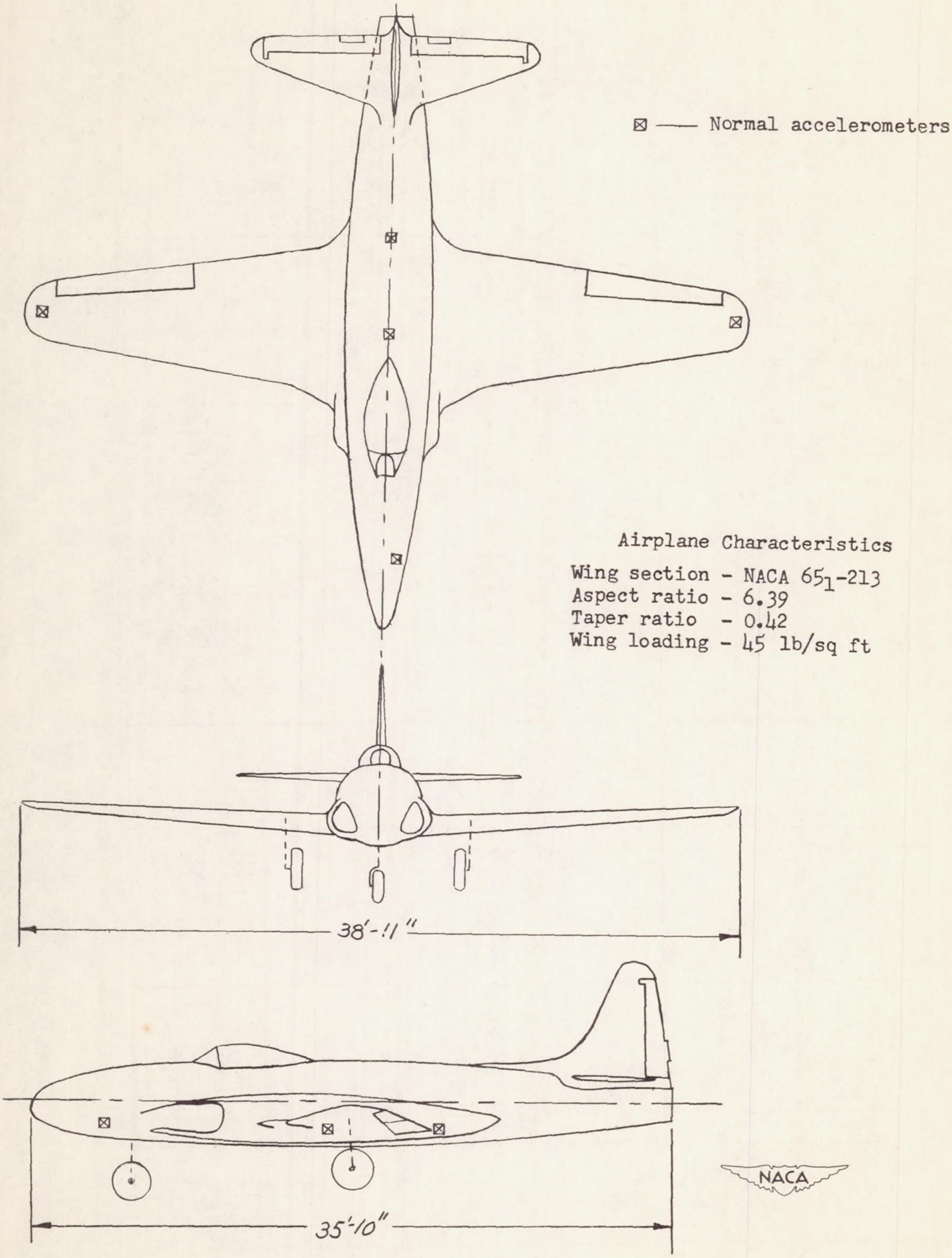


Figure 1.- Three-view drawing of test airplane (Lockheed F-80A) showing location of accelerometers.

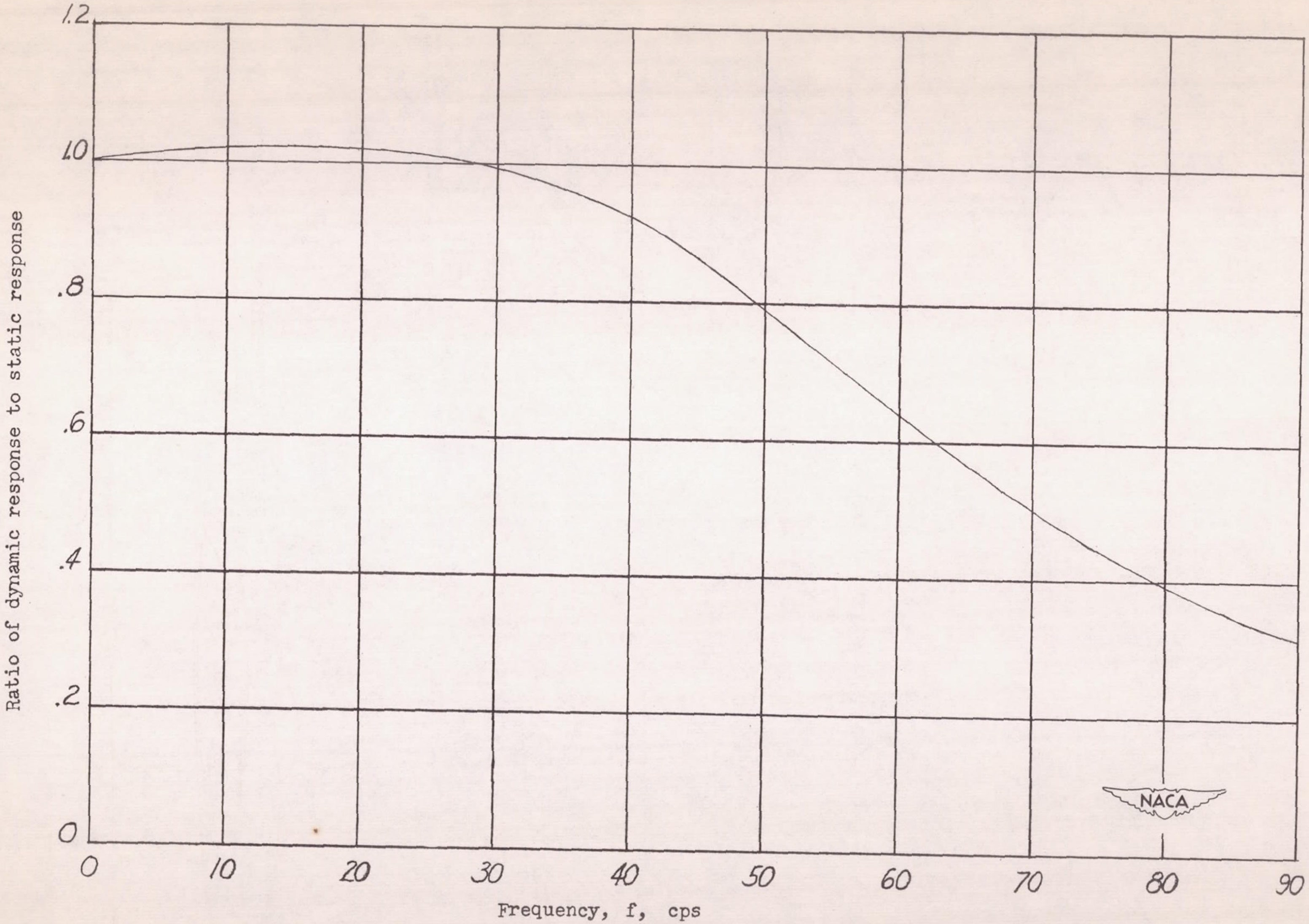
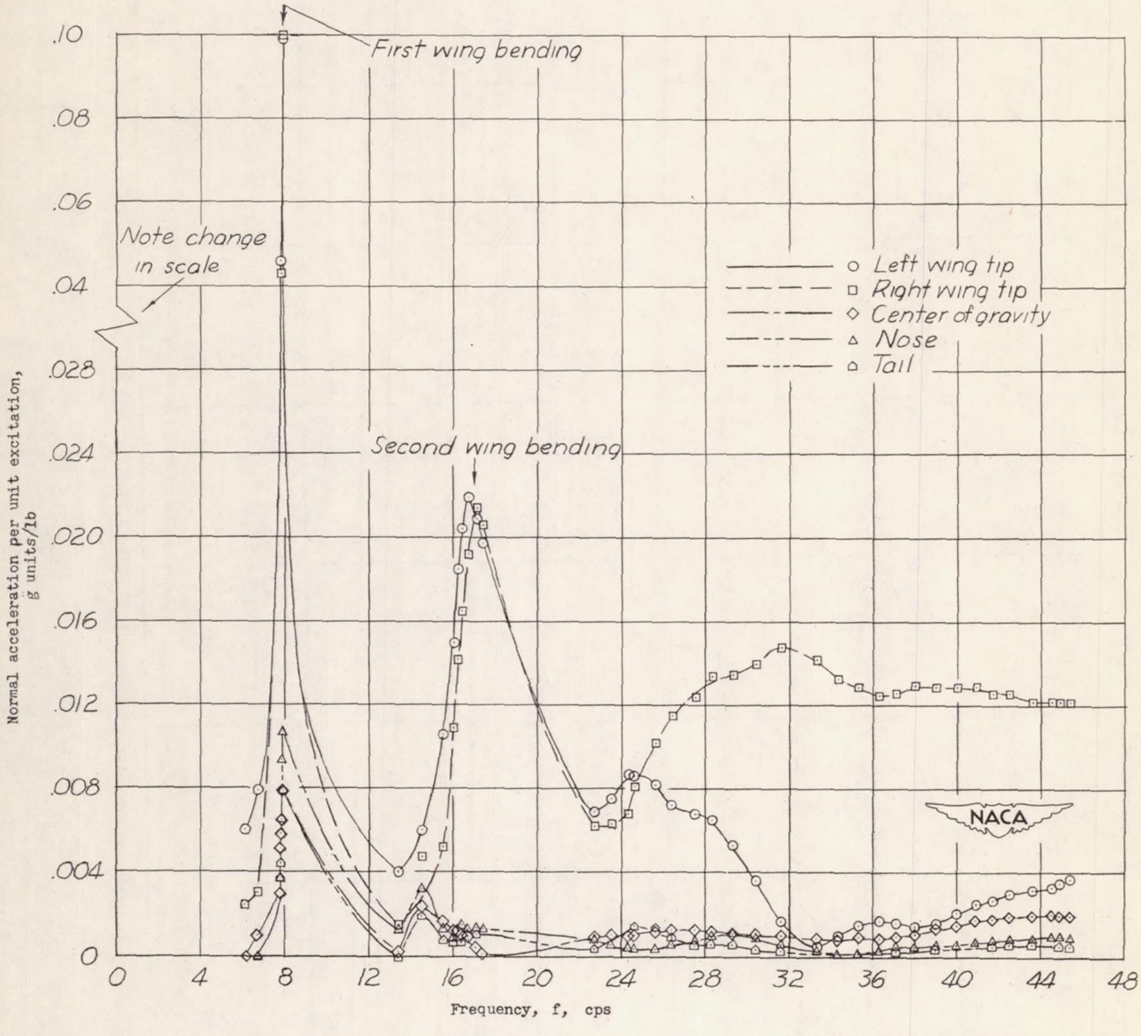


Figure 2.- Response curve for accelerometer-galvanometer combination used.



(a) Excitation applied at right wing tip.

Figure 3.- Response of airplane structure to sinusoidal excitation.

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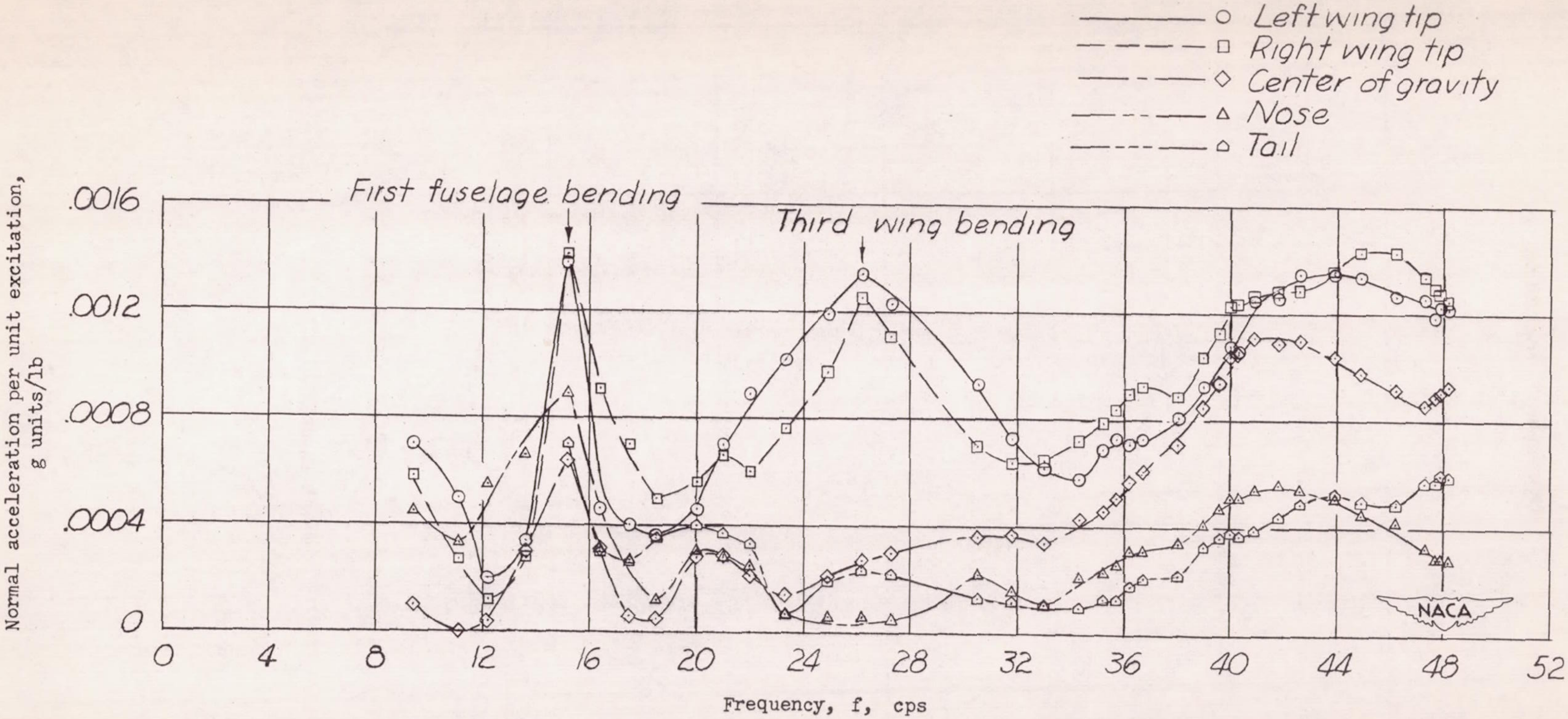

(b) Excitation applied at center of gravity.

Figure 3.- Concluded.

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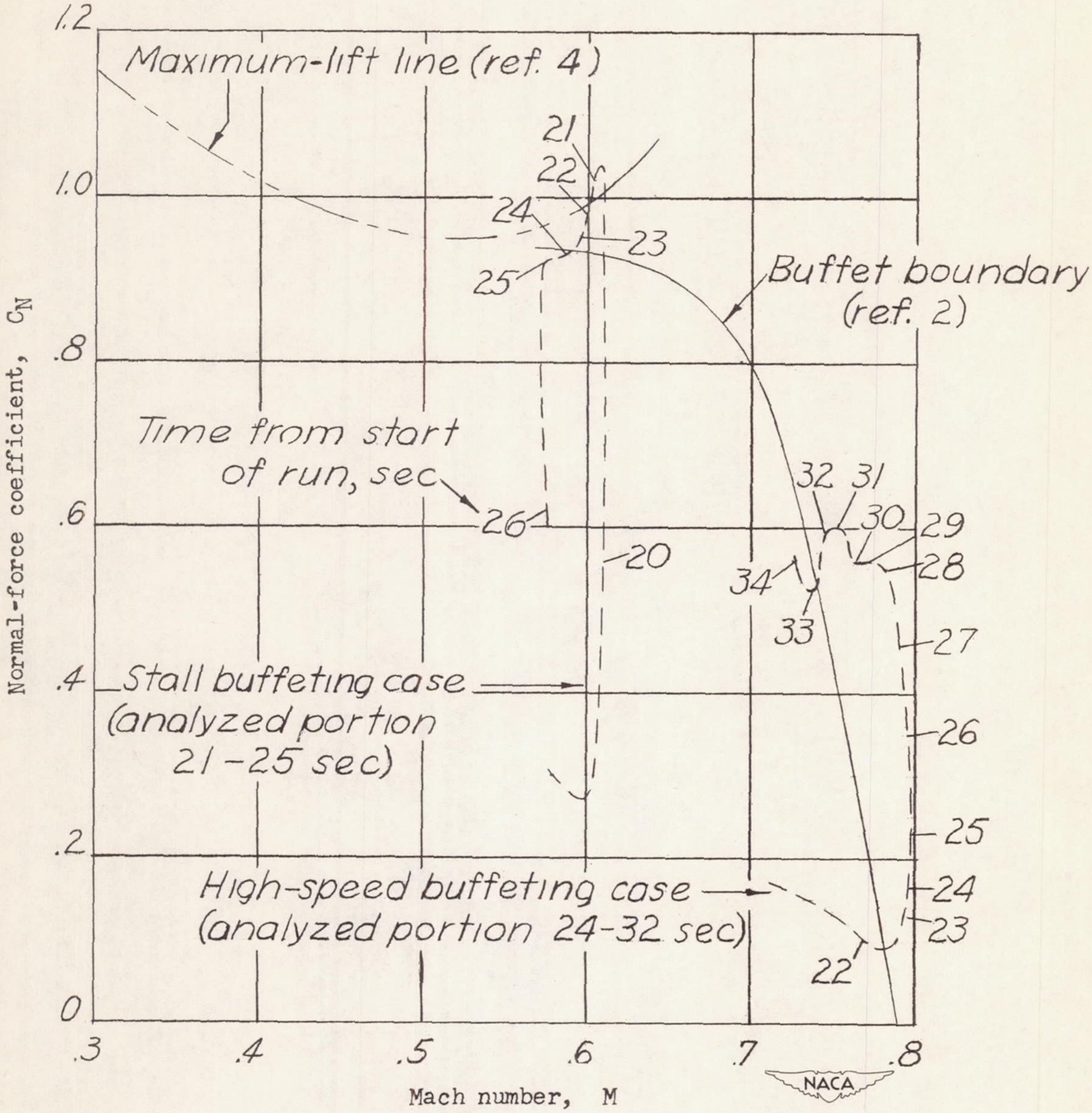

Figure 4.- Buffet boundary for test airplane showing the two entries into buffeting that are presented in this paper.

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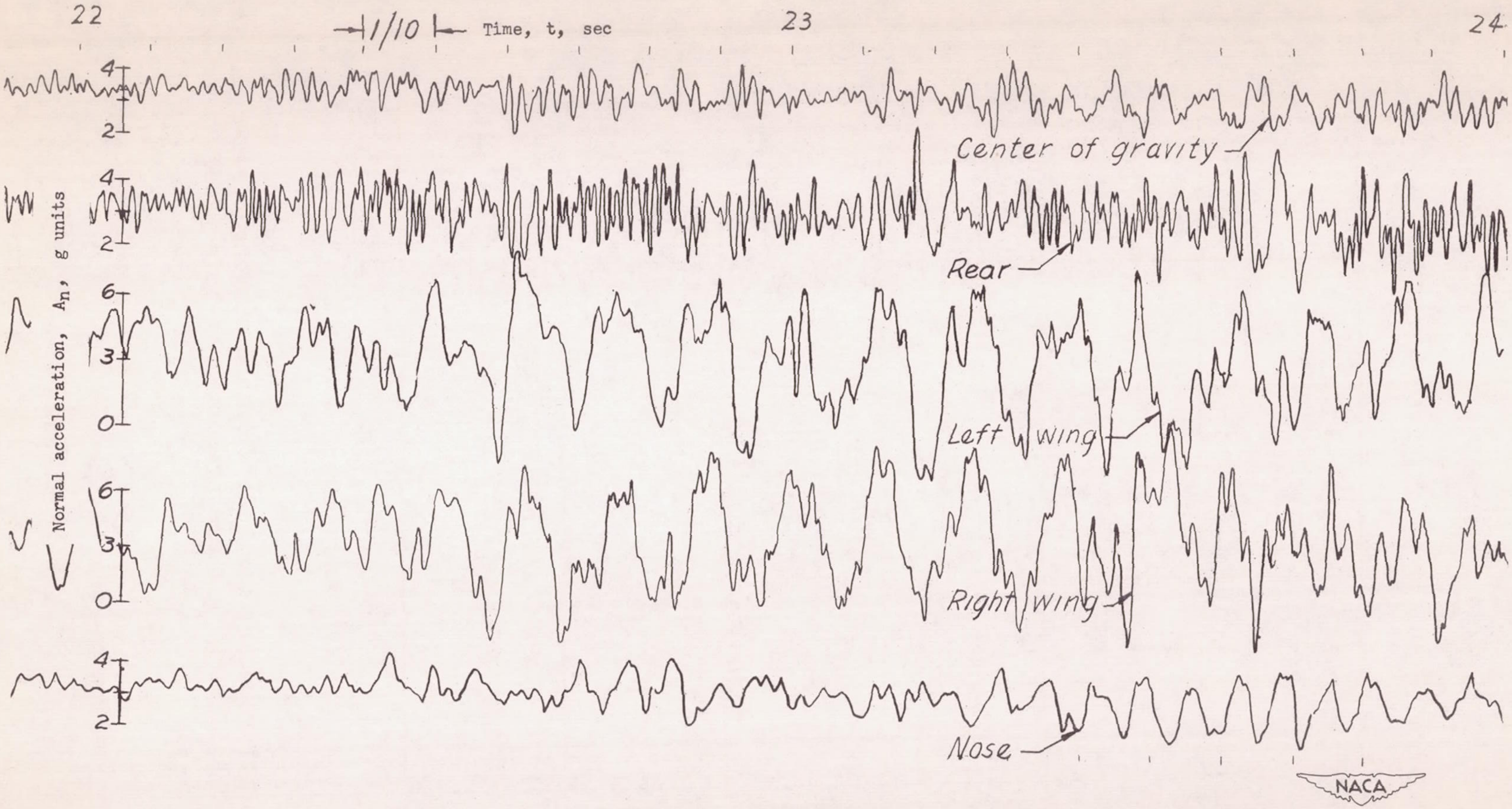

(a) Stall buffeting case.

Figure 5.- Tracings of parts of the acceleration records obtained during buffeting.

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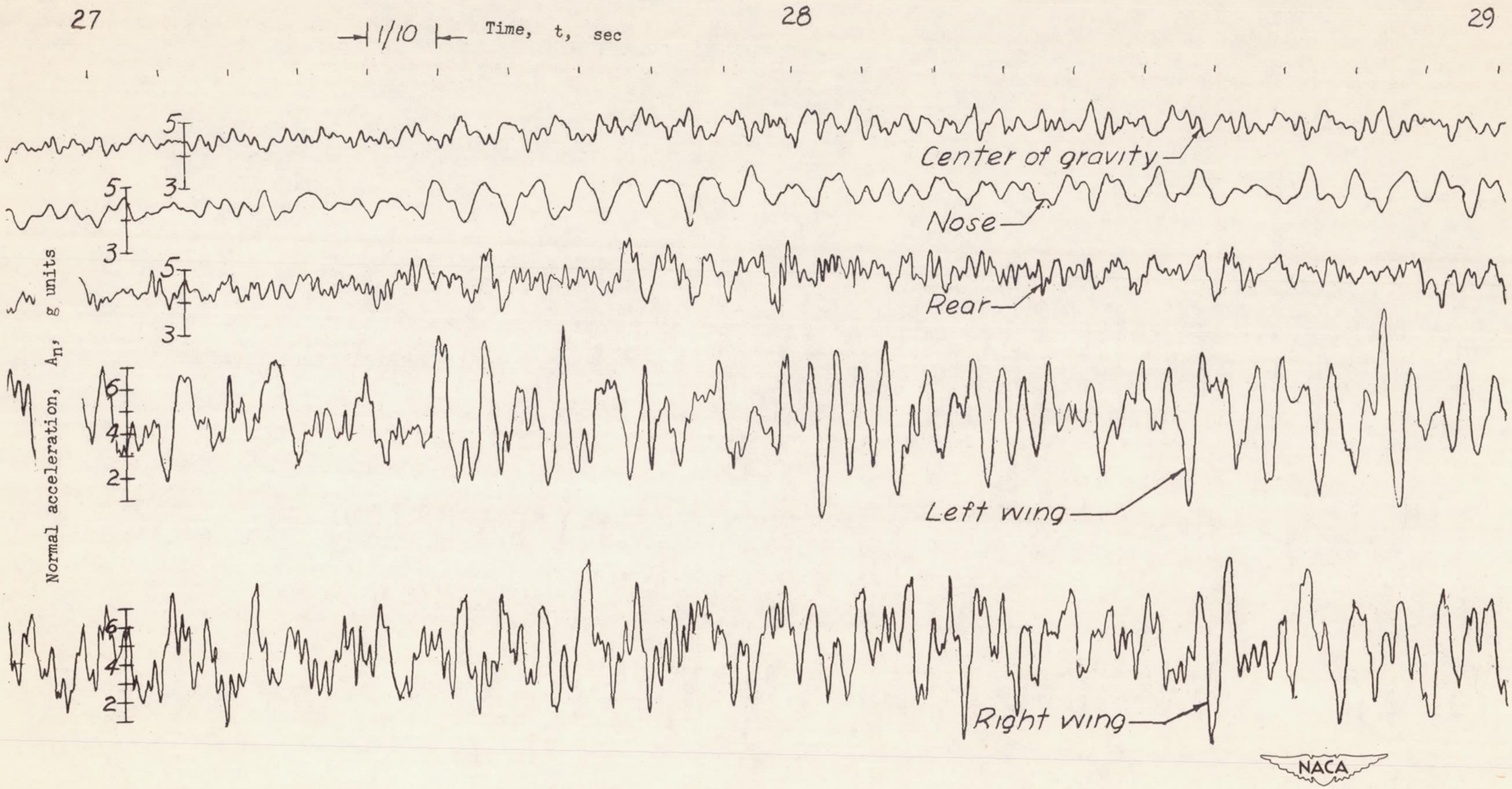

(b) High-speed buffeting case.

Figure 5.- Concluded.

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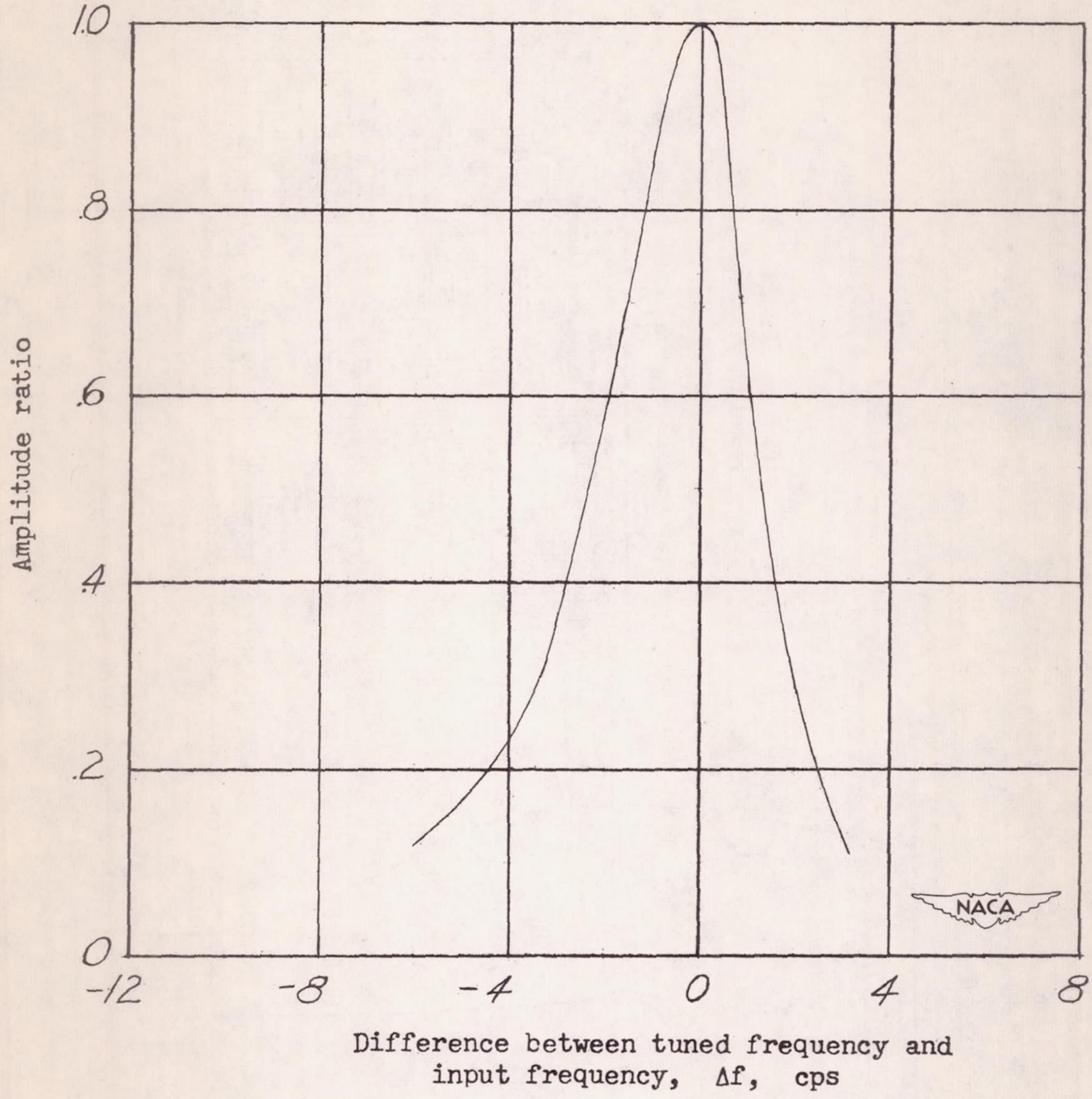

Figure 6.- Variation with filter tuning of the ratio of the response at the tuned frequency to response at the input frequency.

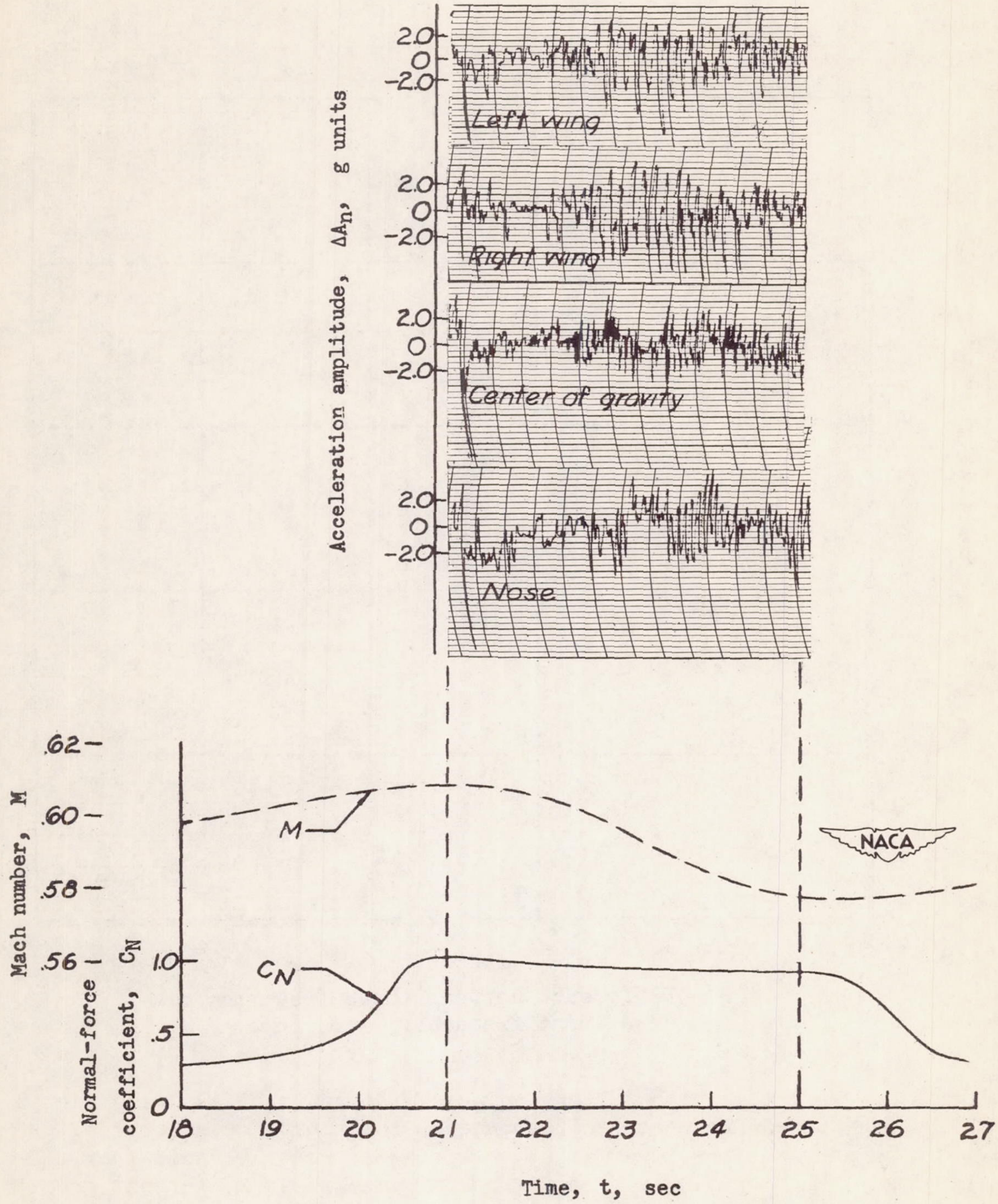

Figure 7.- Time histories showing the unfiltered records of the accelerations at the left and right wing tips, center of gravity, and nose, and the accompanying variations of lift coefficient and Mach number during the stall buffeting case.

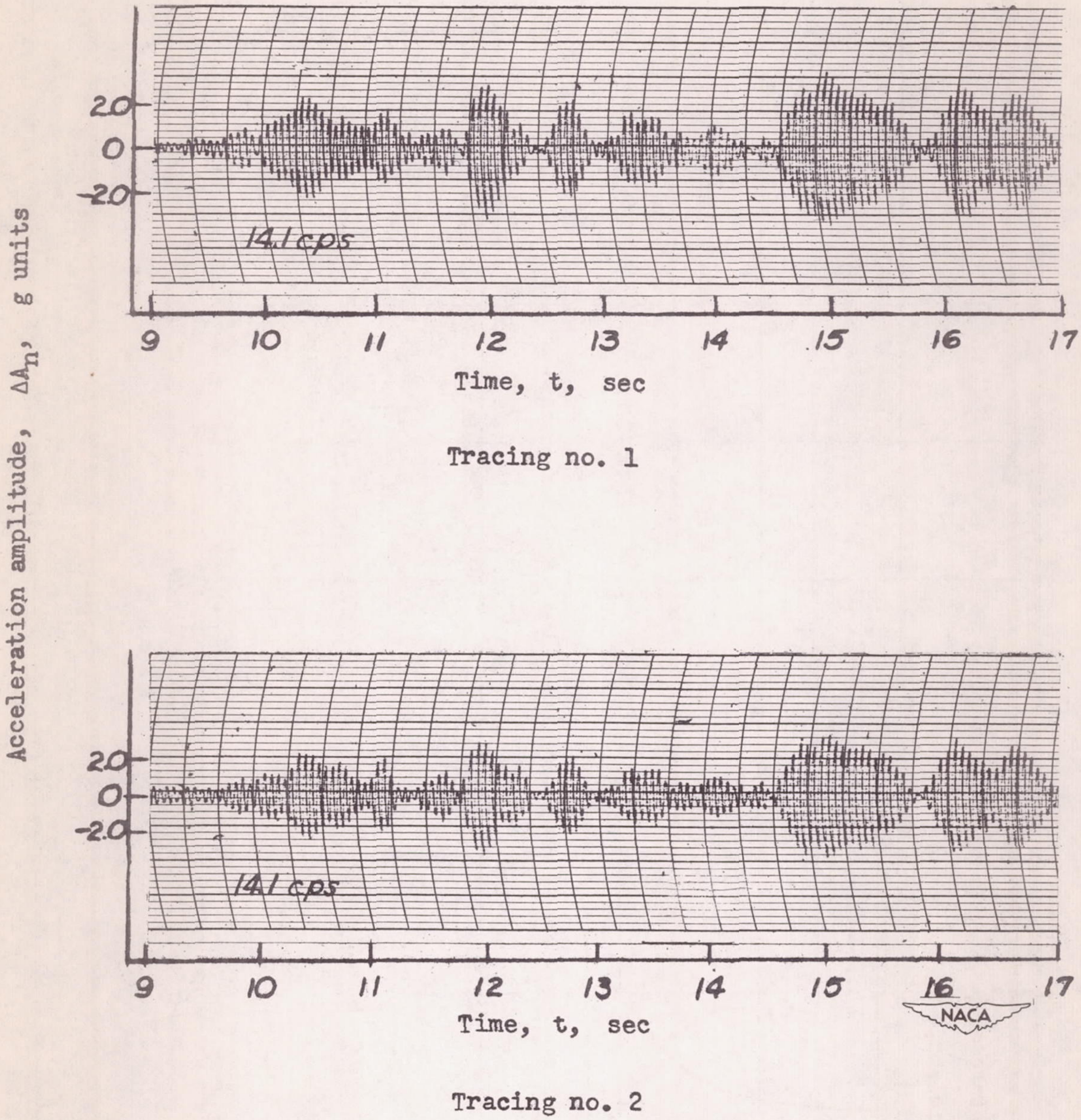

Figure 8.- Comparison of the filtered output at 14.1 cps recorded from separate tracings of a flight acceleration record. Note that the normal-acceleration scale of tracing number 1 is 20 percent greater than that of tracing number 2.

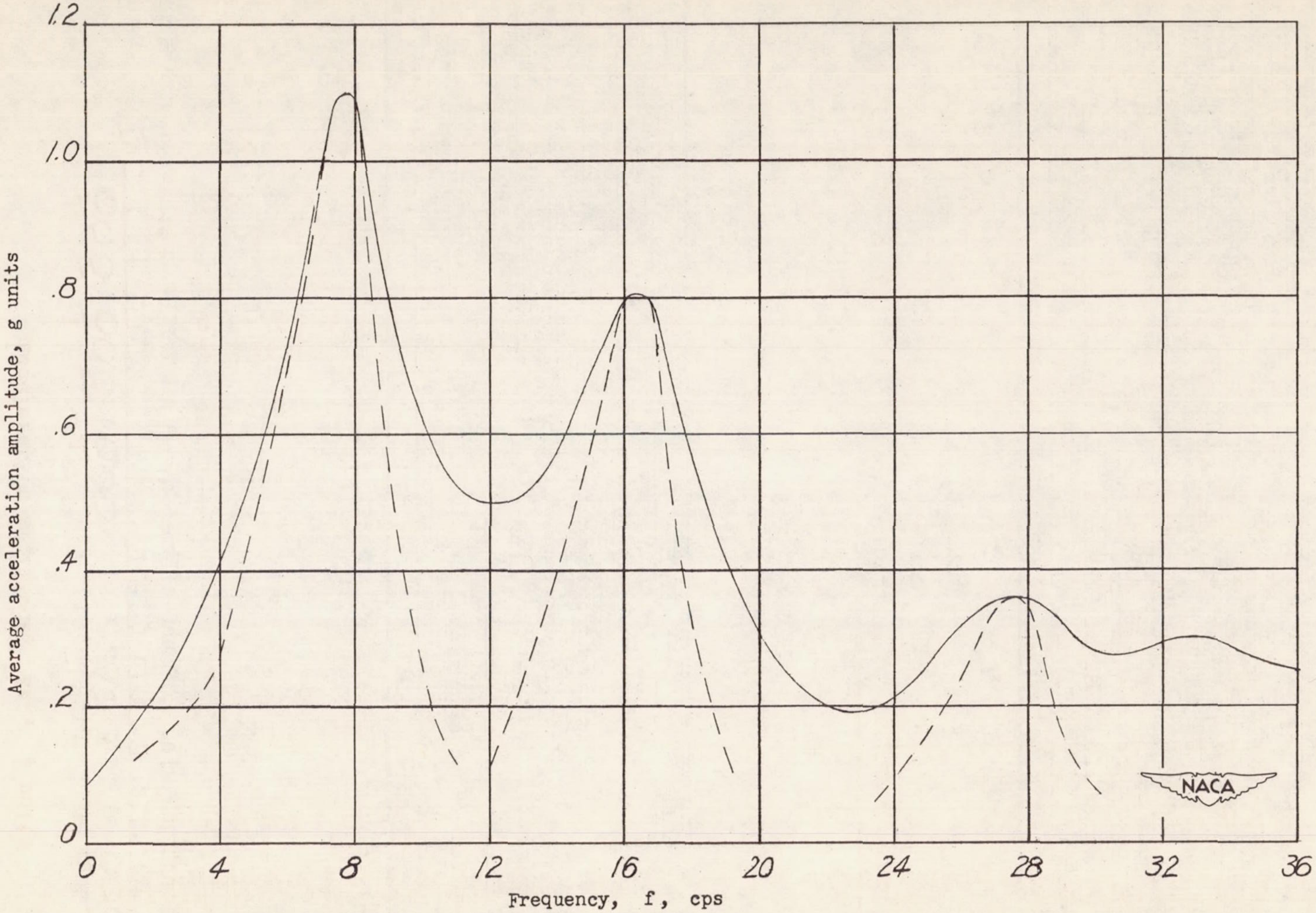

Figure 9.- Average amplitude spectrum of the normal acceleration at the left wing tip during the stall buffeting case. The filter shape (dashed lines) is shown superimposed at the frequencies of maximum response.

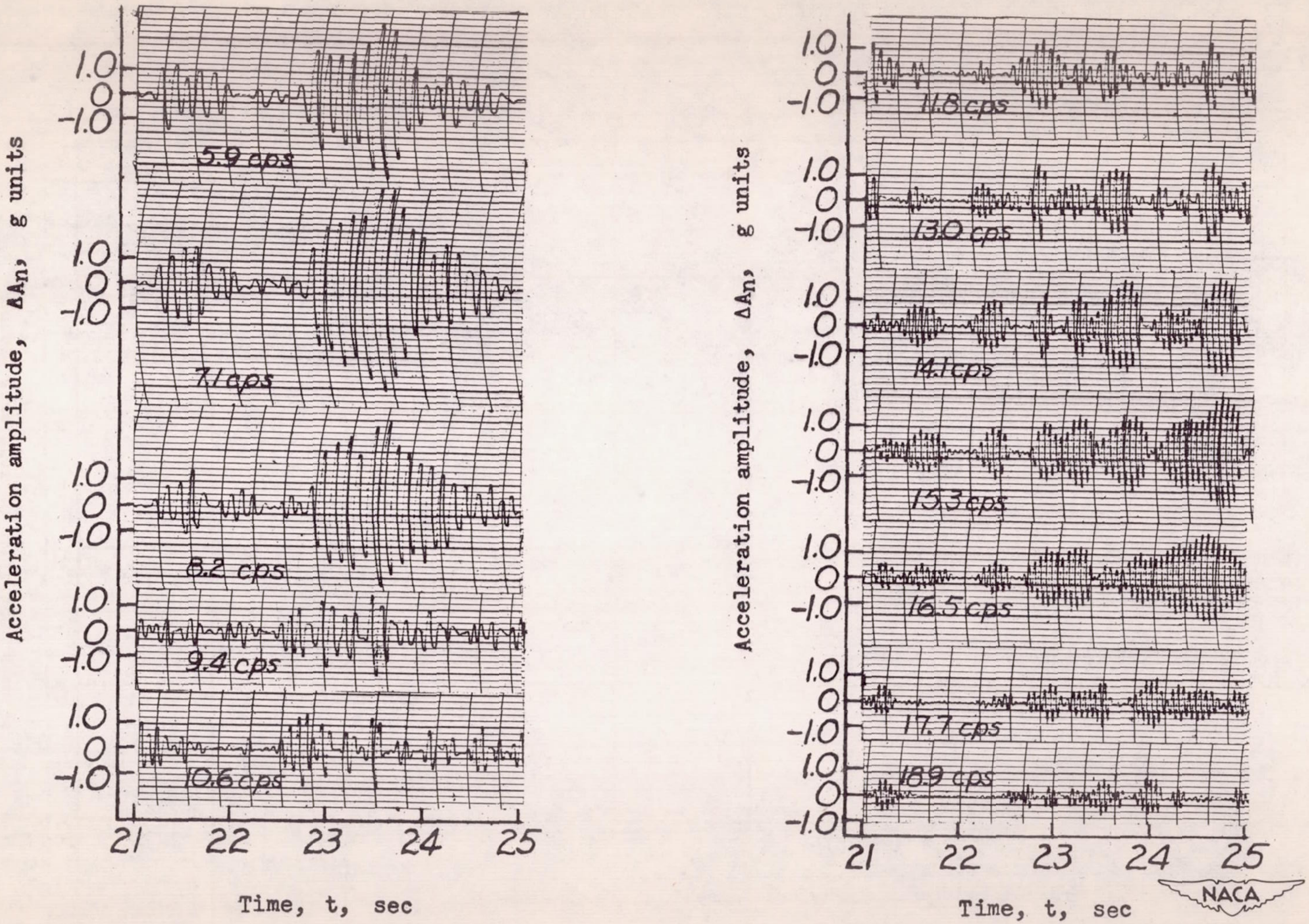

Figure 10.- Time histories of the filtered components of the acceleration at the left wing tip during the stall buffeting case for a range of filter tunings.

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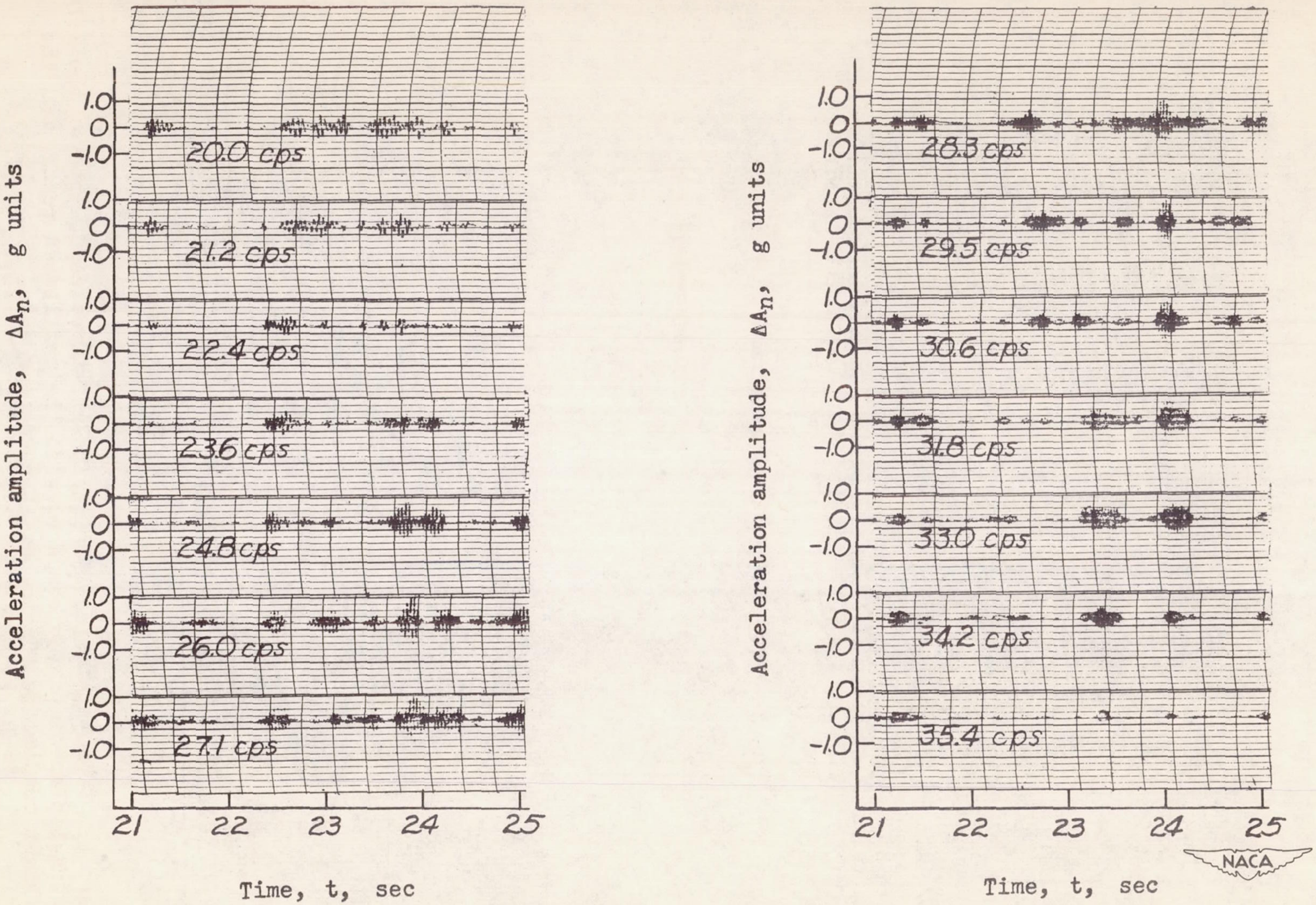


Figure 10.- Concluded.

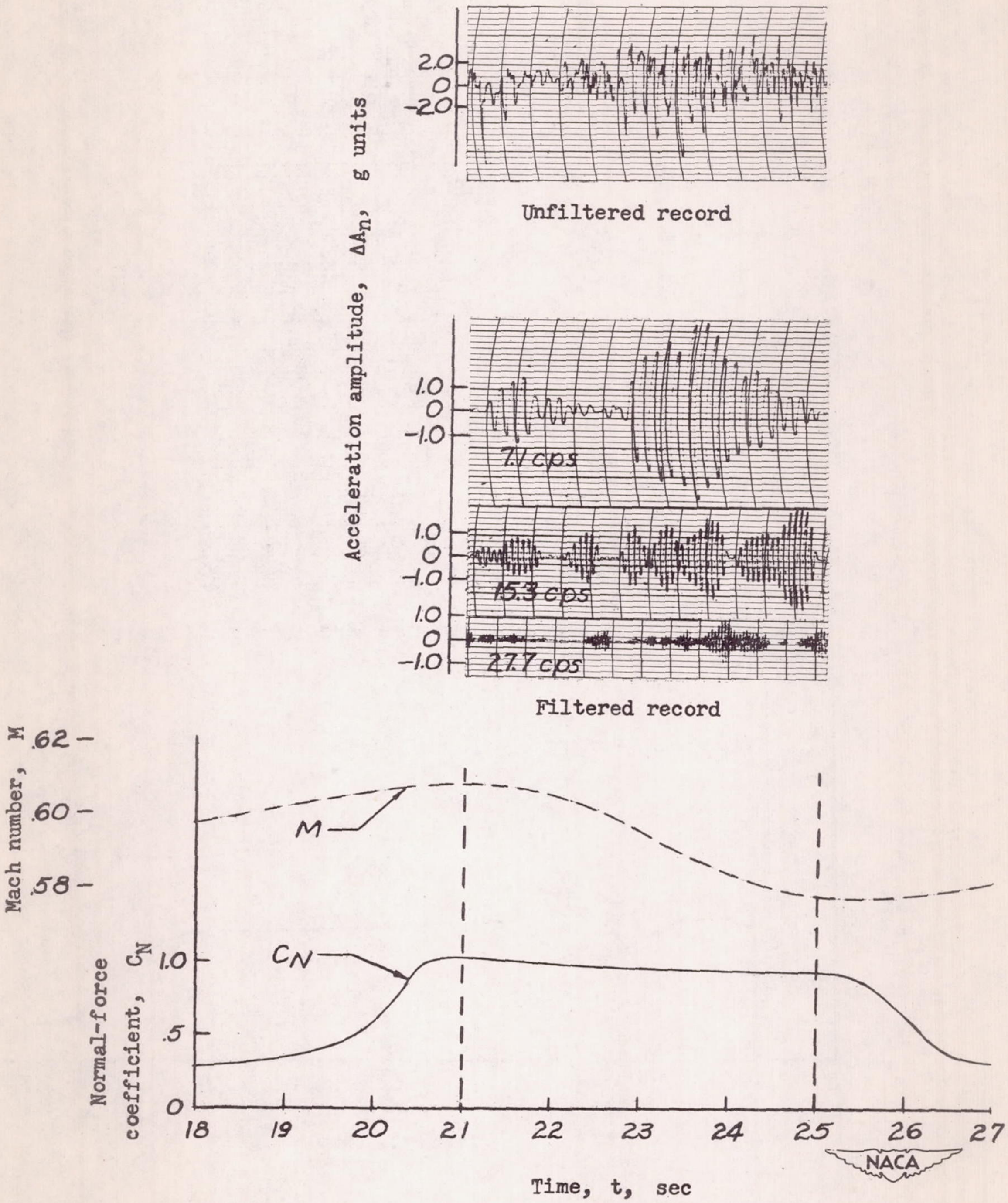


Figure 11.- Time histories of principal filtered components of the left-wing-tip acceleration compared with the unfiltered record and the flight conditions for the stall buffeting case.

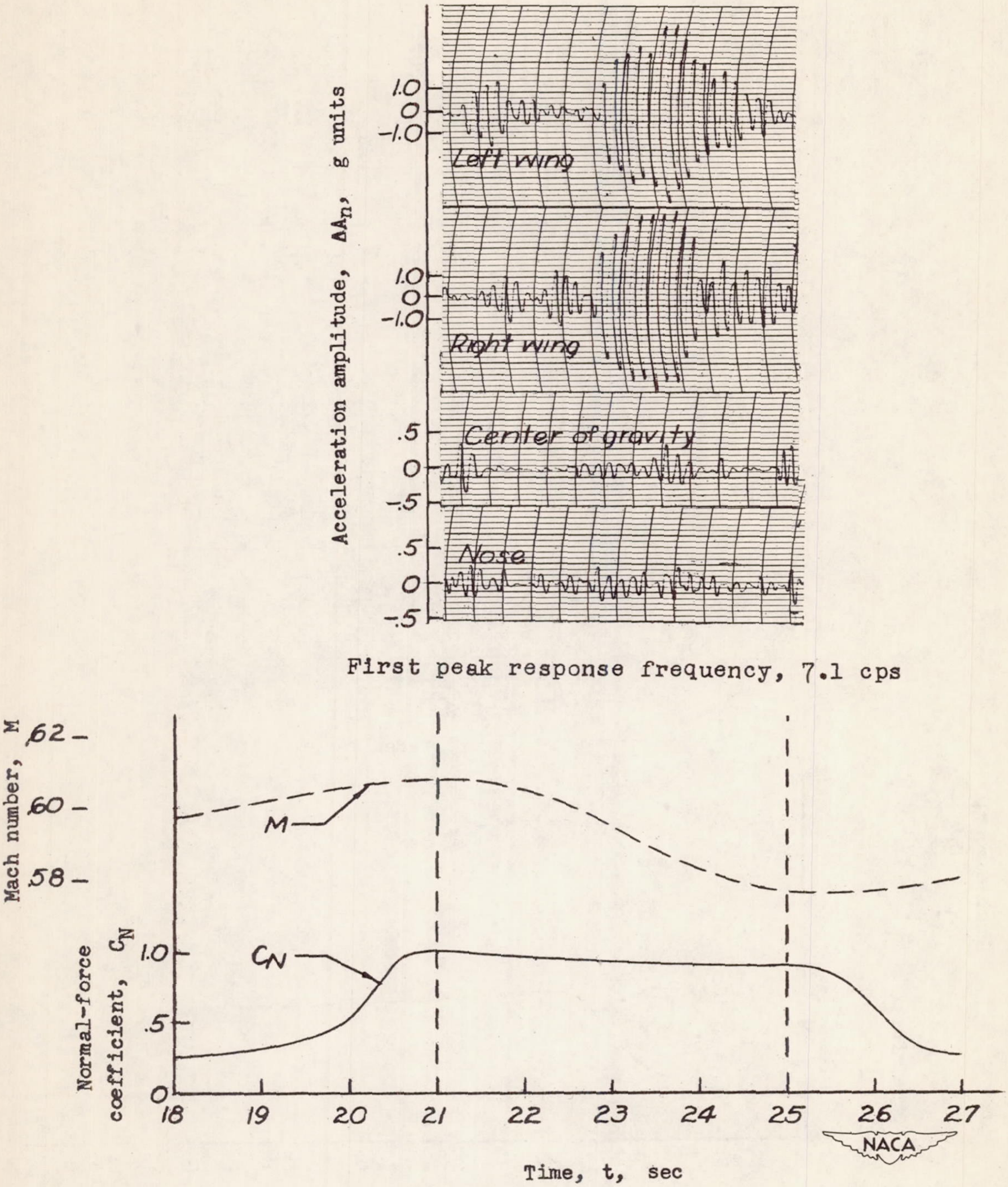
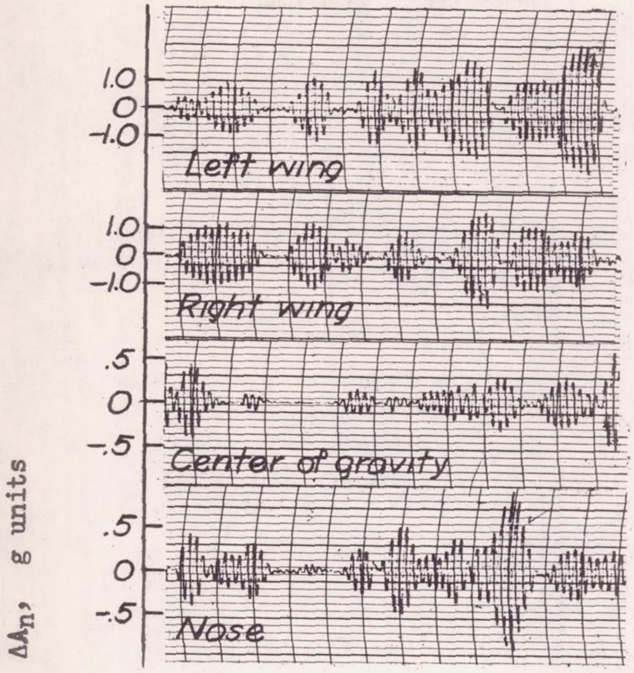
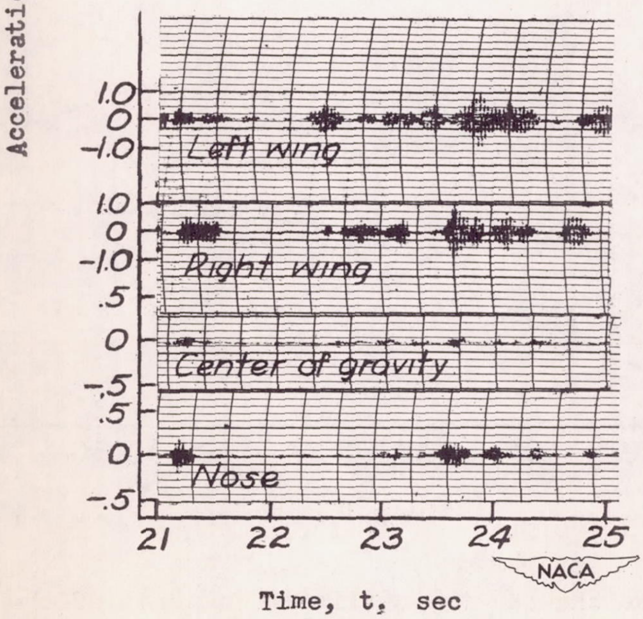


Figure 12.- Time histories of the filtered components of the acceleration at the peak response frequencies for the left and right wing tips, center of gravity, and nose compared with the flight conditions for the stall buffeting case.



Second peak response frequency, 15.3 cps



Third peak response frequency, 27.7 cps

Figure 12.- Concluded.

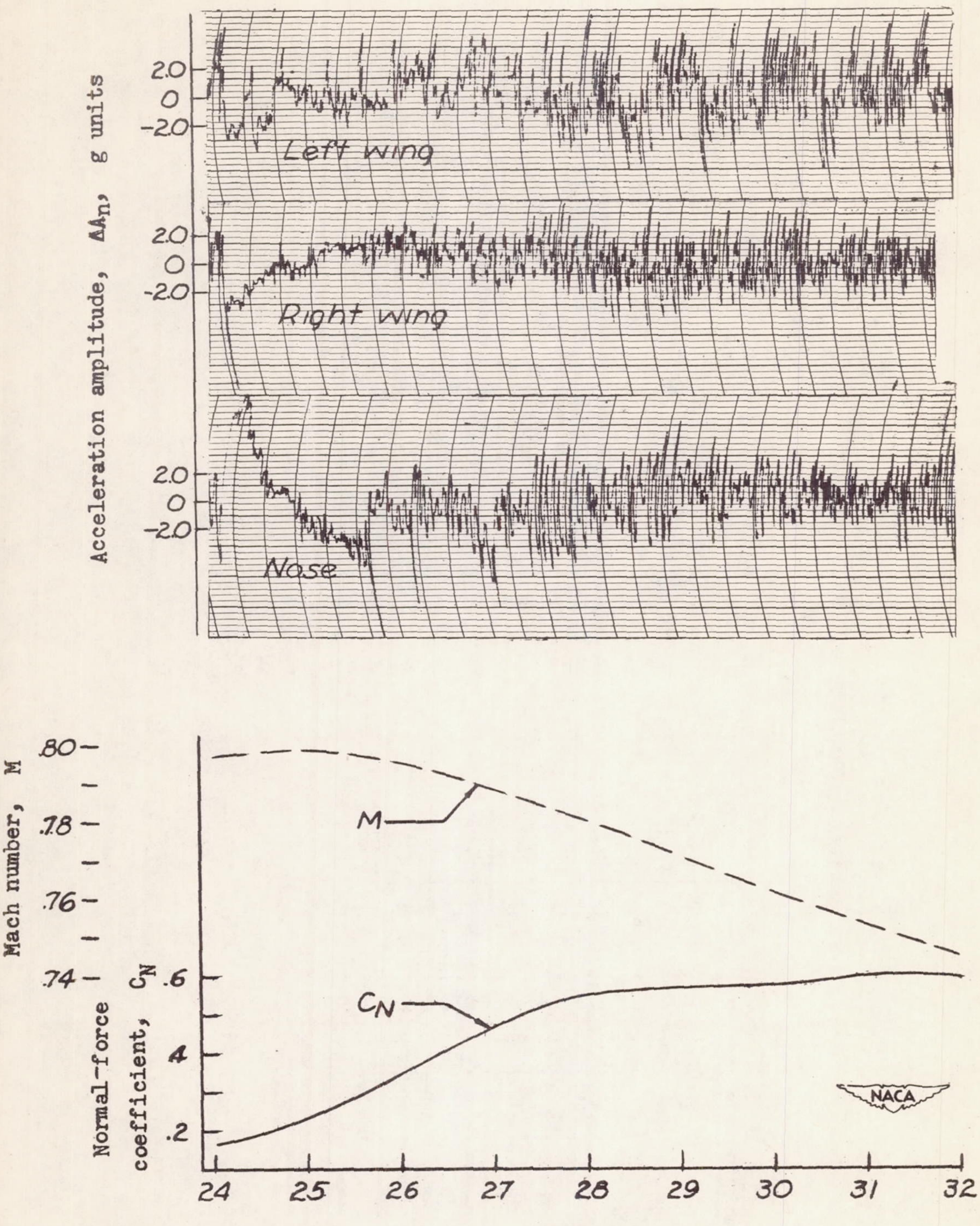


Figure 13.- Time histories showing the unfiltered records of the accelerations at the left and right wing tips and nose and the accompanying variations of normal-force coefficient and Mach number during the high-speed buffeting case.

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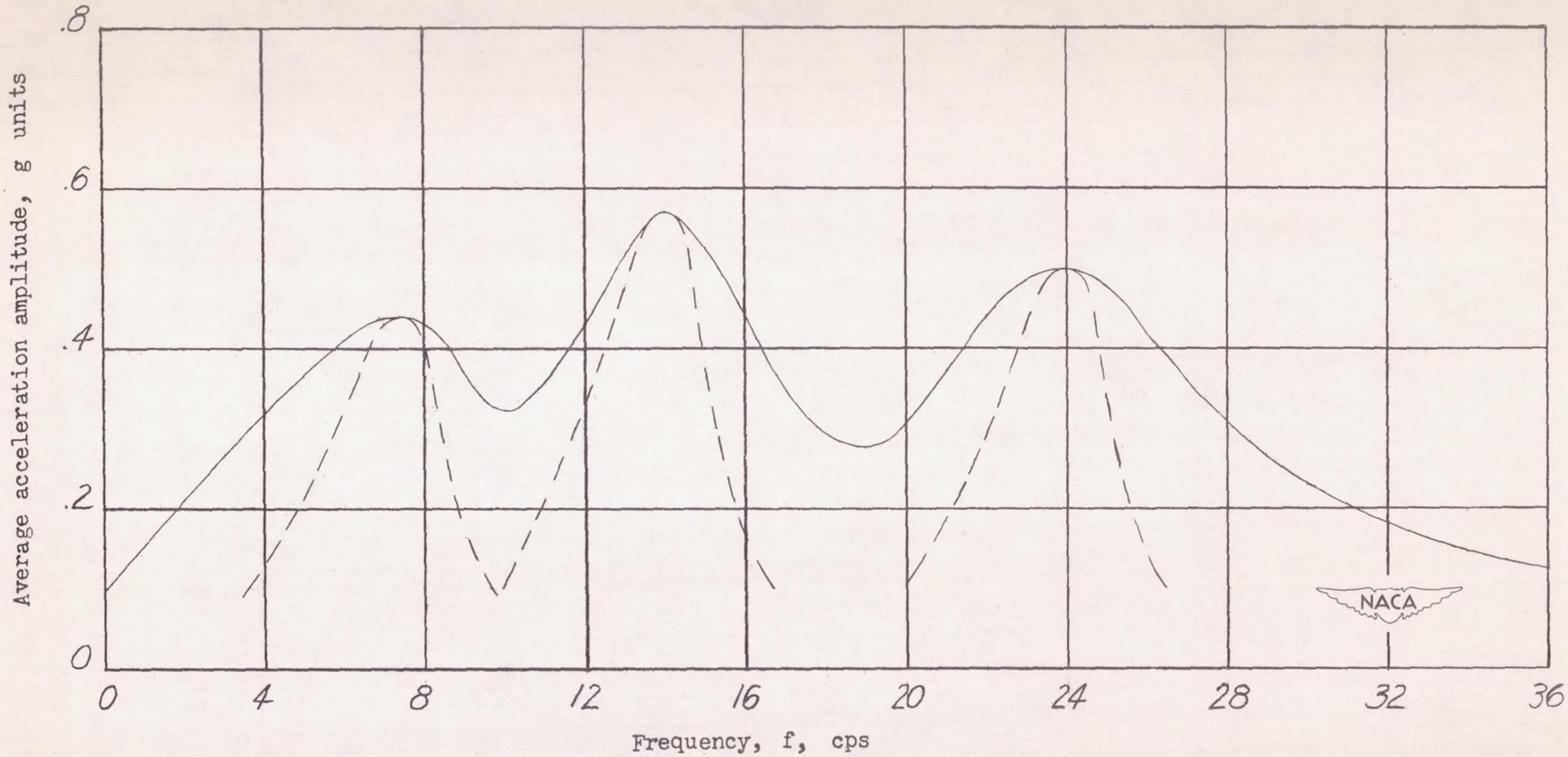

Figure 14.- Average amplitude spectrum of the normal acceleration at the left wing tip during the high-speed buffeting case. The filter shape (dashed lines) is shown superimposed at the frequencies of maximum response.

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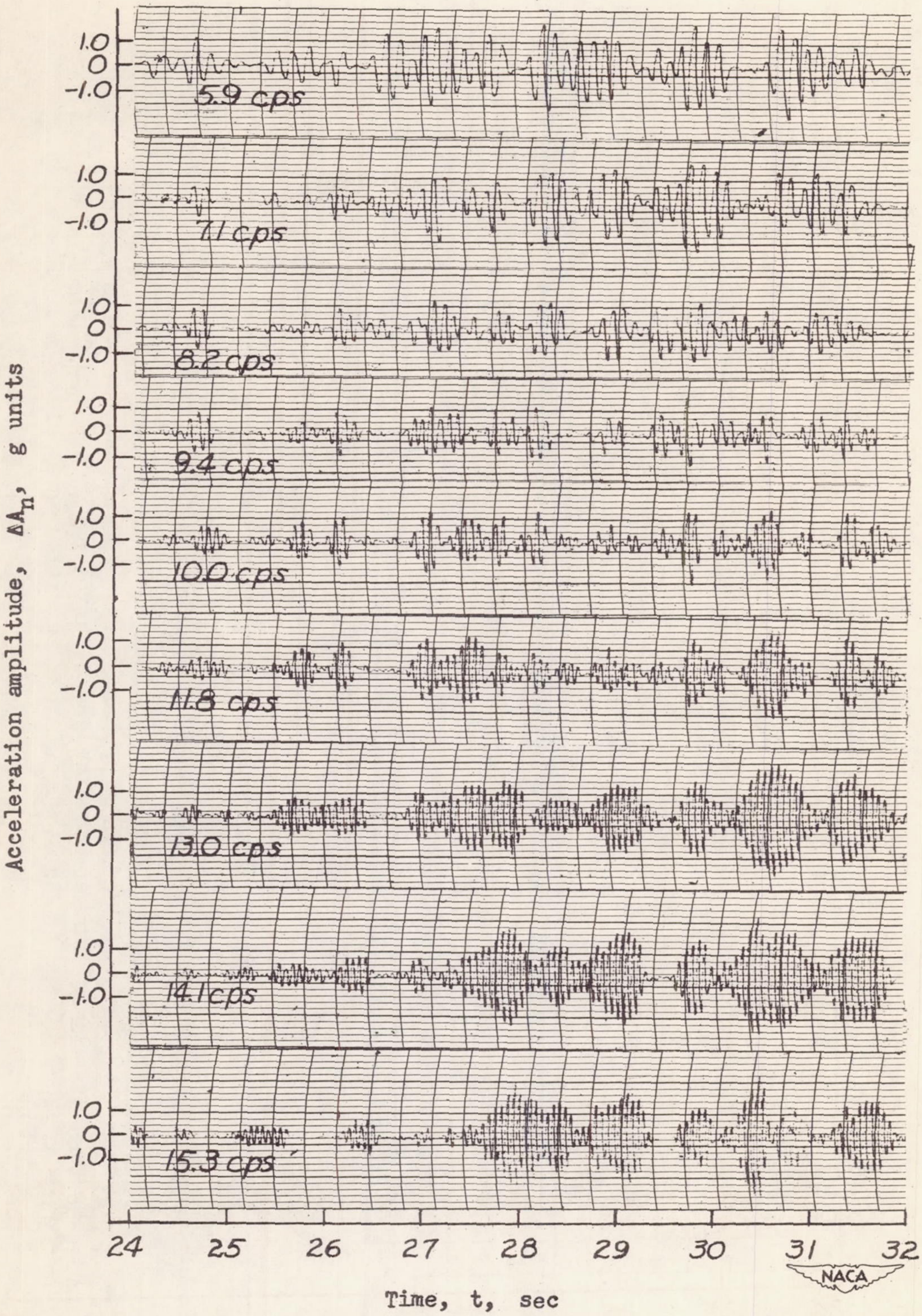


Figure 15.- Time histories of the filtered components of the acceleration at the left wing tip during the high-speed buffeting case for a range of filter tunings.

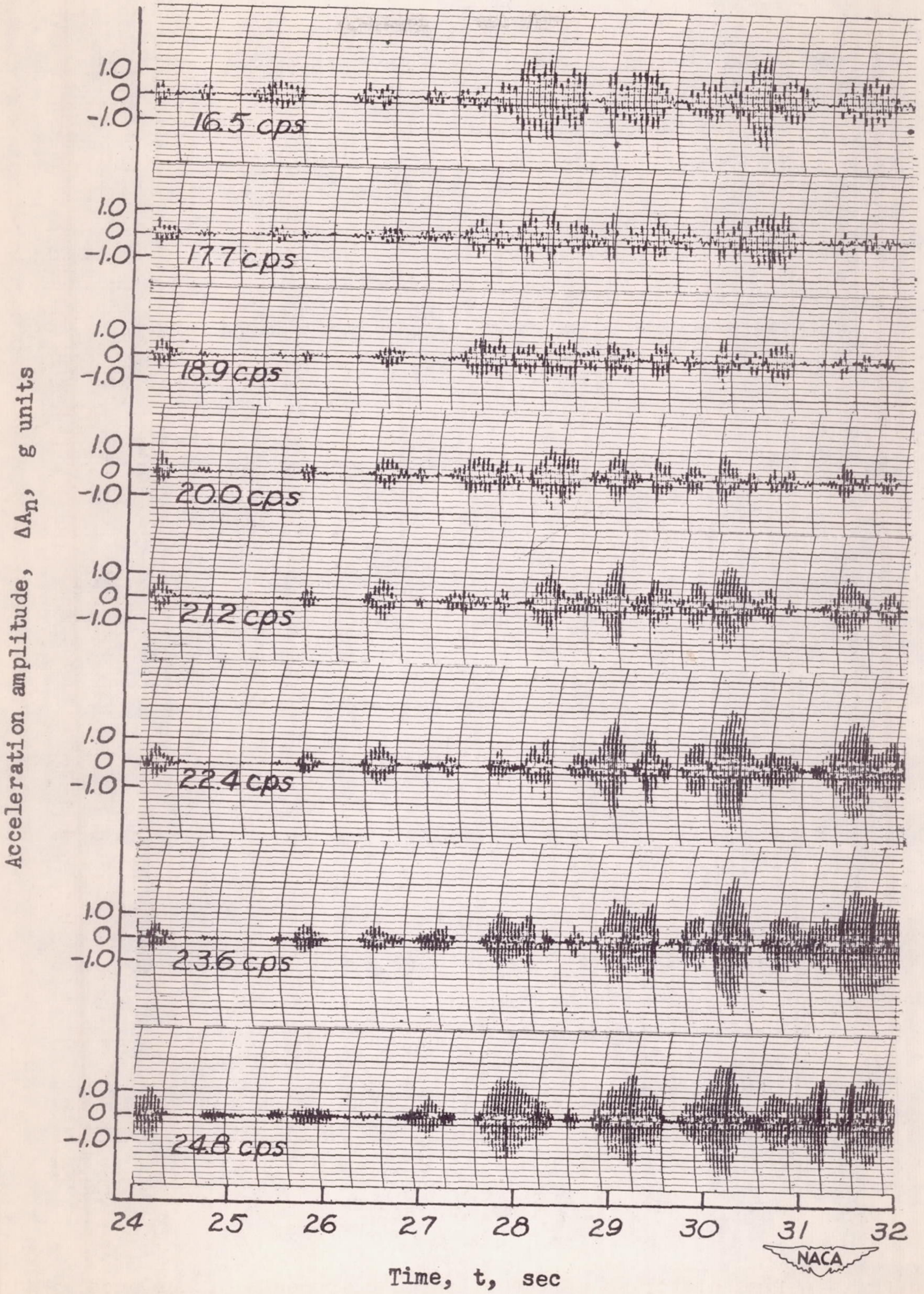


Figure 15.- Continued.

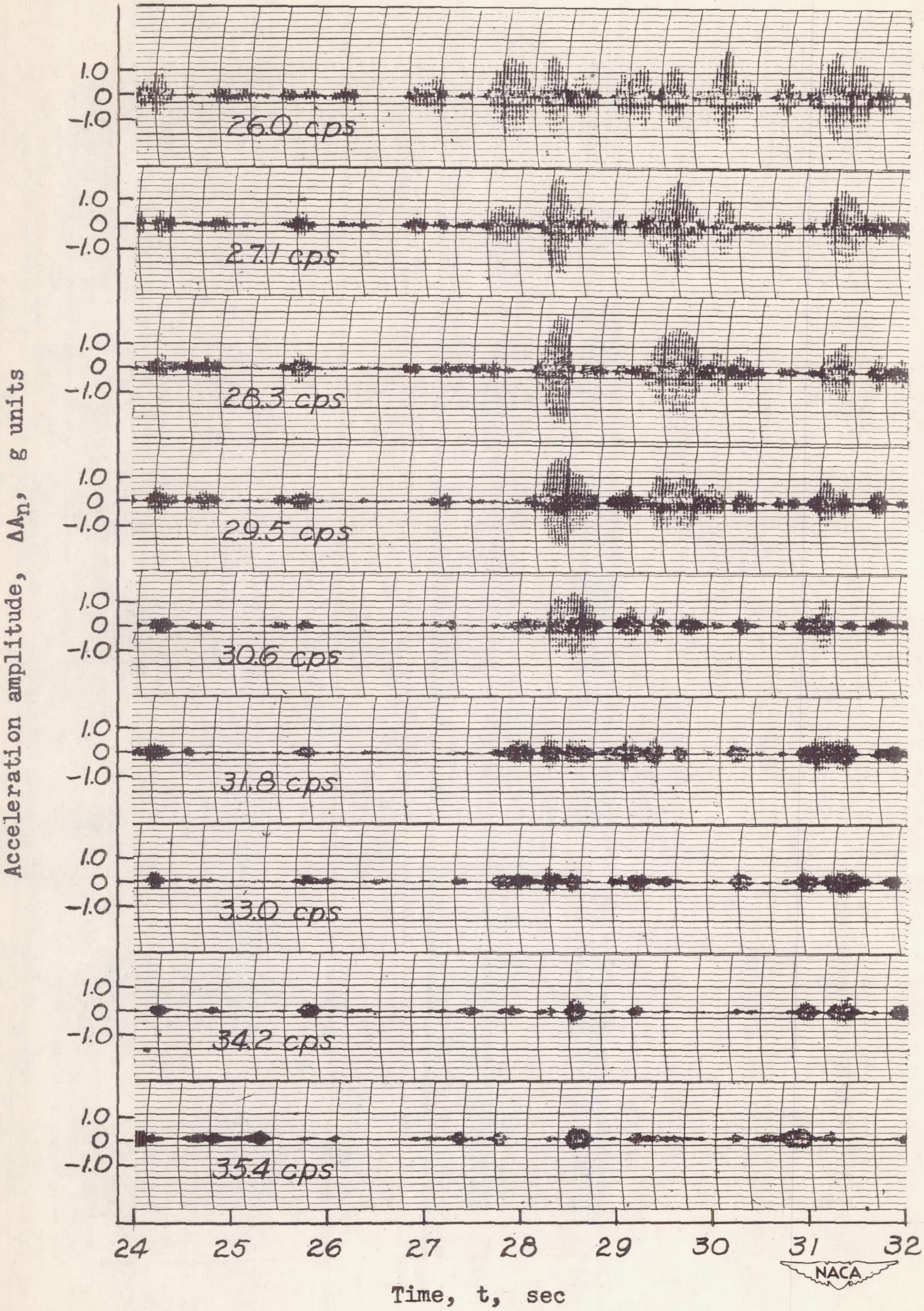


Figure 15.- Concluded.

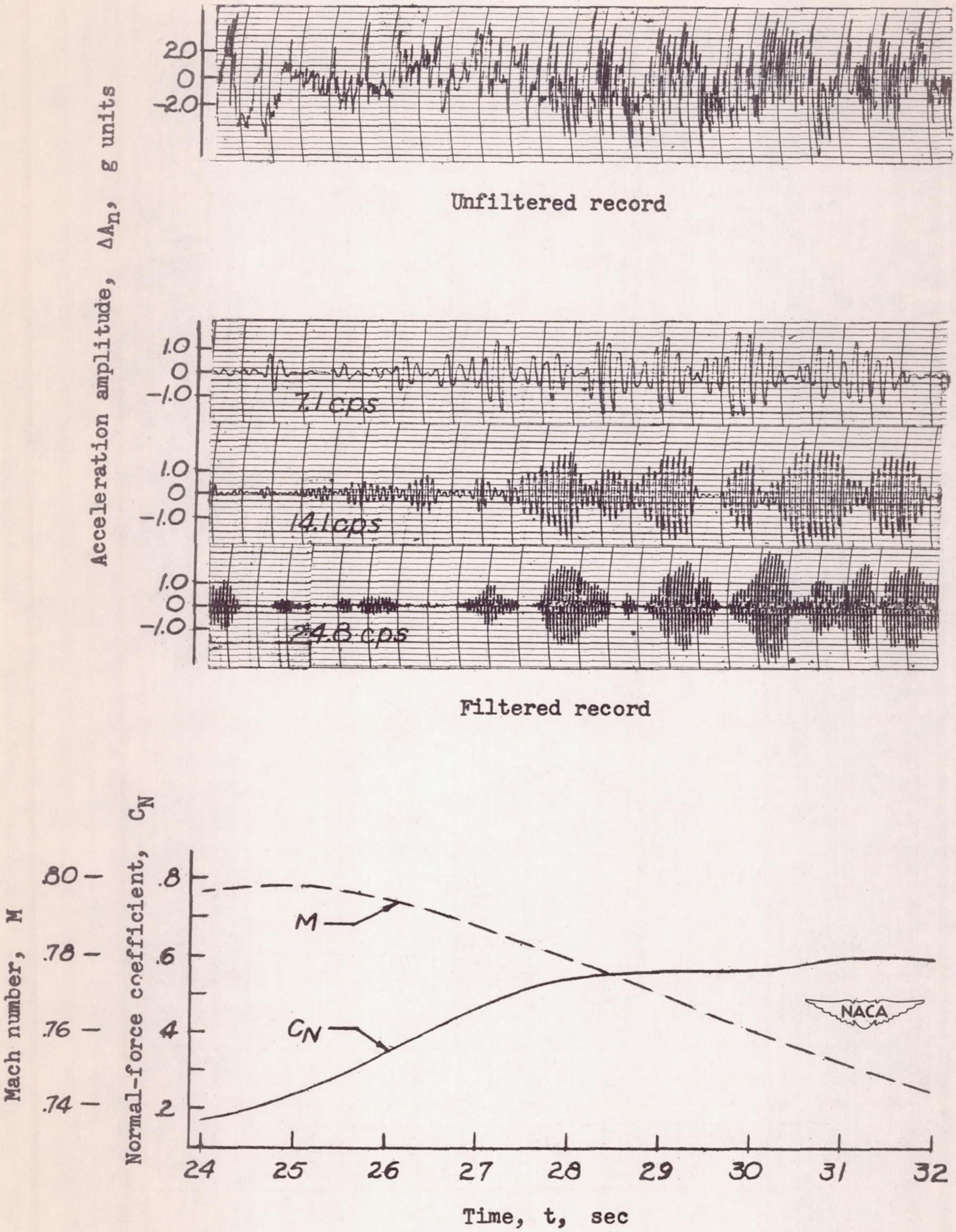


Figure 16.- Time histories of principal filtered components of the left-wing-tip acceleration compared with the unfiltered record and the flight conditions for the high-speed buffeting case.

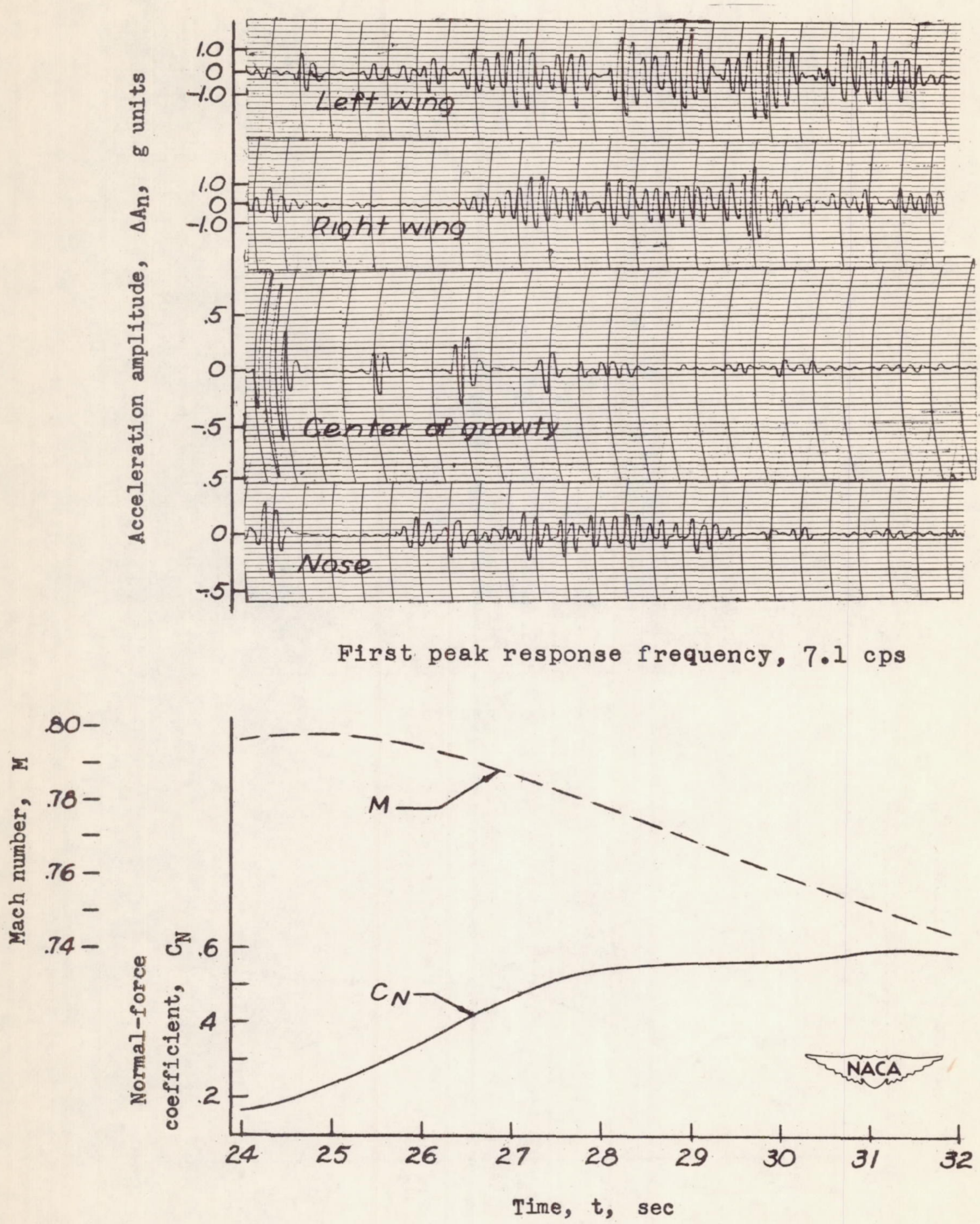
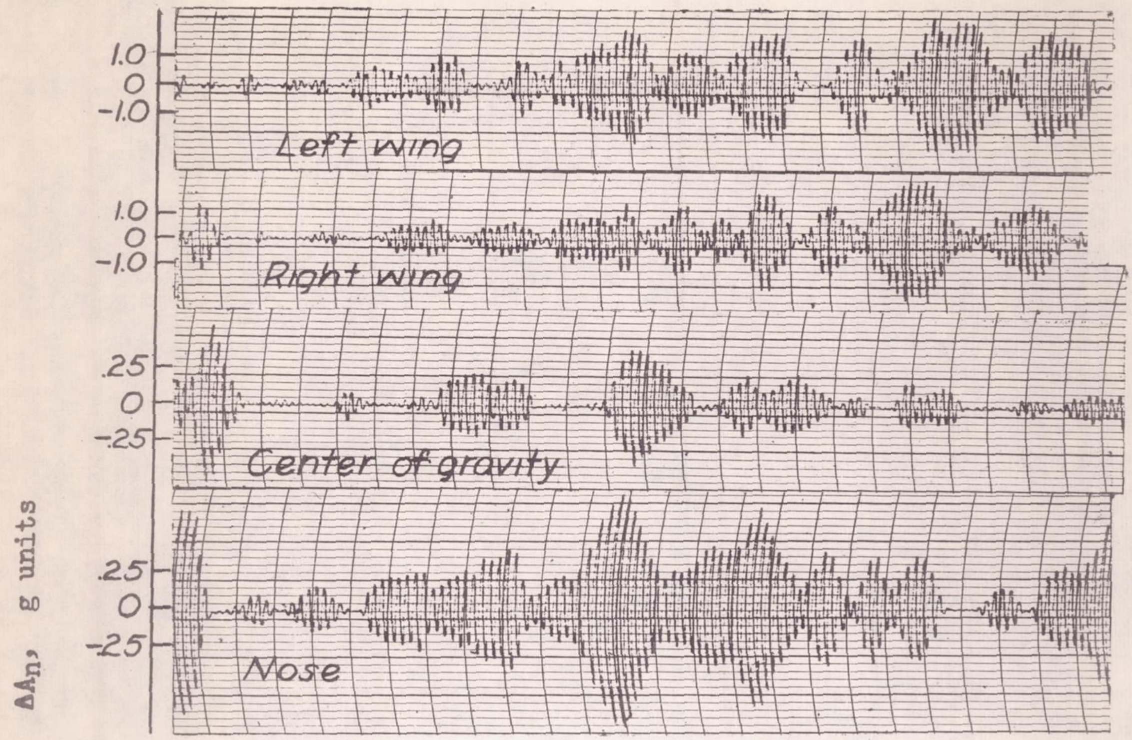
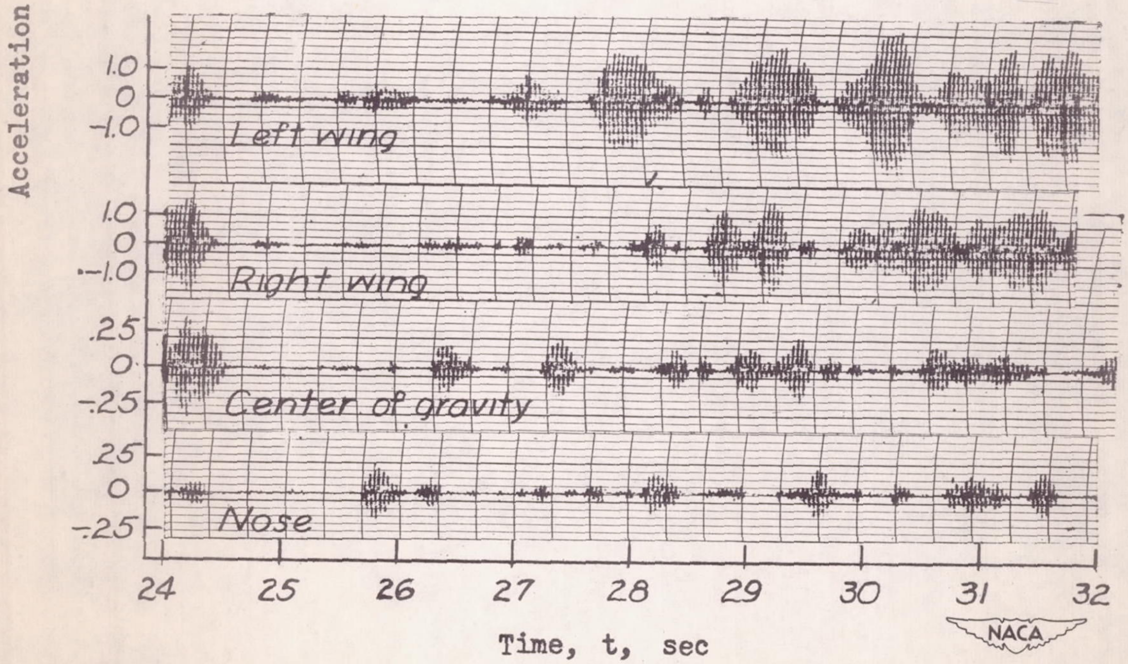


Figure 17.- Time histories of the filtered components of the acceleration at the peak response frequencies for the left and right wing tips, center of gravity, and nose compared with the flight conditions for the high-speed buffeting case.



Second peak response frequency, 14.1 cps



Third peak response frequency, 24.8 cps

Figure 17.- Concluded.