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R81-914838

An Analysis of the Inlet Plane Aerodynamics of an Oscillating Subsonic Cascade: An Evaluation Of Experimental Data

Sponsored by the Office of Naval Research under Contract: N00014-79-C-0772

REPORTED BY A. O. St. Hilaire

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DATE Feb. 1981

NO. OF PAGES ______ COPY NO. ______

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER: UTRC R81-914838	2. GOVT ACCESSION NO.: AD-A096077
3. RECIPIENT'S CATALOG NUMBER:	
4. TITLE (and Subtitle): An Analysis of the Inlet Plane Aerodynamics of an Oscillating Subsonic Cascade: An Evaluation of Experimental Data	5. TYPE OF REPORT & PERIOD COVERED: Final rept. 1 Sep [redacted] 79 – 28 Feb [redacted] 81
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): Arthur O. St. Hilaire	8. CONTRACT OR GRANT NUMBER(s): N00014-79-C-0772
9. PERFORMING ORGANIZATION NAME AND ADDRESS: United Technologies Research Center, Silver Lane, East Hartford, CT 06108	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Office of Naval Research, Arlington, Virginia 22217	12. REPORT DATE: 27 Feb 81
	13. NUMBER OF PAGES: 50
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): 12 54	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Subsonic Cascade, Flutter, Unsteady Flow Theory, Gap-to-Chord Ratio, Interblade Phase Angle, Pitching Oscillations, Freestream Disturbance Measurements, Cascade Load Measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An analysis has been performed on unsteady pressure data measured in the leading edge region of a subsonic cascade oscillating in pitch. The objectives of the investigation were (1) to determine the sensitivity of the freestream velocity disturbance at the inlet plane to variations in interblade phase angle, (2) to compare the behavior of the freestream velocity disturbance as a function of interblade phase angle with that of

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both the inlet area oscillation and the measured moment response of the cascade, and (3) to determine the influence of the gap-to-chord ratio on the blade loading near the leading edge.

In this study, it was found that the behavior of the unsteady freestream flow entering an oscillating subsonic cascade is strongly influenced by the interblade phase angle. A more important finding was that the primary trends in the freestream disturbance match those of both the inlet area oscillation and the moment response of the cascade. Because of this correlation, a hypothesis is presented that describes how the interaction between the inlet area oscillation and the freestream flow might be relevant to the behavior of the cascade moment response and thus to the stability of the cascade motion. Analytical predictions based on this hypothesis are in qualitative agreement with the measured trends.

The effect of gap-to-chord ratio on the unsteady blade loading was studied and found to be substantial in two ways: (1) it alters the degree of influence of leading edge dynamic stall on the chordwise load distribution, and (2) it alters the degree of influence of the interblade phase angle on the amplitude of the load response.

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INTRODUCTION

Subsonic positive incidence turbomachinery flutter has been an ongoing problem since the earliest days of the jet age and continues to impede progress toward maximizing the engine thrust to weight ratio. Before this problem can be minimized by design, there must be an increased understanding of the underlying aeroelastic interaction. Evidence of such understanding would be indicated by the ability of analytical models to predict the existence and cause of flutter instability. The classical approach to analyzing subsonic positive incidence flutter has not yet produced practical predictions and it appears that a more comprehensive account of the primary aerodynamic events will be required in future theoretical models.

Although substantial progress has been achieved in the development of unsteady subsonic cascade solutions, they have been confined to flat plate blades at zero mean incidence to a uniform stream (Refs. 1-3). Current solutions for this configuration do not reveal instabilities under practical operating conditions, and thus fail to meet the needs of turbomachinery designers in predicting or understanding the occurrence of subsonic flutter. Extensions of this classical model have been and are continuing to be attempted by several investigators. These include the effects of compressibility, and blade shape, (e.g., Refs. 4 and 5). At the time of this writing, these modifications to the basic model continue to fail in predicting the onset of unstable motions in the range of practical interest. Therefore, as investigators proceed to more sophisticated solutions, it would appear that a parallel effort should be made to obtain new insight into the mechanism of subsonic flutter by analyzing available experimental evidence.

The present study is a continuation of the effort initiated in Ref. 6 to analyze unsteady pressure data from a linear cascade of oscillating airfoils. The objective of this ongoing analysis is to provide new information about the behavior of turbomachinery aerodynamic disturbances and to eventually assist in the development of improved theoretical models. In past experimental studies, cascade pitching motion instability was determined by computing the unsteady moment from chordwise distributions of pressure time histories and then using the result to compute the work per cycle done by the cascade on the flow. Although this technique is effective in reporting experimentally determined stability criteria, it is usually done with only slight attention focused on the details of the unsteady flow response. This situation was changed in Ref. 6 by directing the data analysis to the details of the aerodynamic events in the leading edge region of the cascade. In particular, the study emphasized the sensitivity of the leading edge region response to variations in interblade phase angle and pitching frequency. This was done at three mean incidence angles.

For the range of parameters tested, the main findings of Ref. 6 were that the unsteady blade loading is concentrated in the forward ten percent region of the blade suction surface and is primarily sensitive to the interblade phase angle. (These results were obtained at a freestream speed of 61 m/sec past NACA 65 series airfoils installed with a gap-to-chord ratio of 0.75 and a stagger angle of 30 deg.) In addition, it was found that the interblade phase angle, σ, is the dominant parameter affecting the integrated moment response and thus the stability of the cascade pitching motion. In all but the most extreme cases examined therein both the unsteady moment and the leading edge region pressure responses shifted from lagging (stabilizing) to leading (destabilizing) the blade pitching motion as the interblade phase angle varied from negative (backward traveling wave) to positive (forward traveling wave) values. On a first order basis, this influence was found to be qualitatively independent of the mean incidence angle.

The consistency of this behavior in the experimental data from case to case suggests that the primary influence of the interblade phase angle, σ, on the cascade motion can probably be predicted with a simple analytical model that is independent of the mean incidence angle. On this premise, a rudimentary analysis was formulated in Ref. 6 to describe how σ might influence cascade stability. In lieu of modeling the cascade geometry, this was achieved by predicting the impact of a simple periodic inlet on the upstream flow field and then computing the resulting unsteady pressure disturbance at the inlet as a function of σ. It was successfully shown that this type of coupling can lead to a first order aeroelastic instability. Specifically, it was shown that this interaction excites the inlet motion over a range of positive σ and that the qualitative trend of the prediction with σ matches that of the measured response in the leading edge region of the cascade over the entire range of σ.

The present investigation to analyze the interaction between an oscillatory cascade and the surrounding unsteady flow field extends the effort initiated in Ref. 6. The total program (including the work reported in Ref. 6) involves (1) the analysis of pressure time histories along the blade chord and along the inlet plane of the blade row, (2) the identification of the parameters that are most influential on the data trends and on the stability of the cascade, and (3) the analysis of cascade inlet area variations and their effect on the freestream flow entering the cascade.

The emphasis of the present report is to analyze the unsteady pressure data measured along the inlet plane between two adjacent blades and to correlate the primary trends with those of the integrated moment response of the cascade. Of principal interest are the dependence of these data on the interblade phase angle and their qualitative correlation with the inflow area time history. Also appearing in this report is a brief discussion of the effect of gap-to-chord ratio on the leading edge region chordwise pressure distribution. This report begins with a brief discussion of the data source and the data reduction procedure. This is followed by a qualitative examination of the influence of interblade phase angle, reduced freqeuncy, and mean incidence angle on the inlet plane pressure time histories. A quantitative analysis is then presented in which the primary trends of the freestream disturbance are compared with those of the integrated moment response and of the inlet area oscillation. An attempt is then made to describe the interaction mechanism between an oscillating inlet and the freestream flow. The report then proceeds with a discussion of the impact of gap-to-chord ratio on the chordwise distribution of load on the suction surface of the blade. The report concludes with a series of recommendations in a continued attempt to finally identify the mechanism of subsonic cascade flutter.

DATA SOURCE AND DATA REDUCTION

The data that are analyzed in this study are mostly from a series of ONR/SQUID sponsored experimental programs that were performed in the United Technologies Research Center Oscillating Cascade Wind Tunnel facility. The scope of these experiments was to measure the aerodynamic response of a subsonic cascade of oscillating airfoils under controlled variations in pitching frequency and interblade phase angle for several values of mean incidence angle and gap-to-chord ratio. All data were measured at a freestream speed of 61 m/sec past a cascade consisting of NACA 65 series airfoils of chord, c = 15.2 cm, and span, ℓ = 25.4 cm with a 10 deg circular arc camber and thickness-to-chord ratio of .06. Figure 1 shows a part of the cascade and the sidewall locations where miniature pressure transducers were mounted to measure the unsteady freestream disturbance at the inlet. This instrumentation setup was biased toward the suction surface side of the leading edge where most of the unsteadiness is concentrated. The specific pressure transducer locations were at the leading edge, 1/16 gap, 1/8 gap, 1/4 gap, and midgap. The test facility, the center blade instrumentation package, and the test procedure are fully described in Refs. 7 and 8.

The investigation reported herein involves two independent sets of data. The first set is associated with the analysis of freestream disturbances along the inlet plane. These were obtained with a constant gap-to-chord ratio of 0.75 at two mean incidence angles (α_M = 6 deg and 10 deg). The second set of data is associated with the analysis of the effects of gap-to-chord ratio on the leading edge region chordwise load distribution. These were all obtained at α_M = 8 deg. Although inlet plane disturbance measurements were included in the latter set of data, their analysis will not be reported until a later time. The test points for the freestream disturbance study and the gap-to-chord variation study are summarized in Tables 1 and 2, respectively.

During the experimental program, the cascade was externally driven in pure sinusoidal pitch at a fixed amplitude of 2 deg. This provided a natural simplification in the analysis of cascade stability; that is, for sinusoidal motions, the energy transfer per cycle between the cascade and the aerodynamic response is entirely determined by the first harmonic component of the unsteady load. Since the main purpose of this study has been to examine the primary influence of the various cascade parameters on the behavior (stability) of the cascade motion, the quantitative analysis of the blade leading edge and inlet plane pressure time histories has been limited to the first harmonic components. This approach to the data analysis also assures the usefulness of the inlet plane data for qualitative study even though the measurements were obtained within the tunnel wall boundary layer.

INLET PLANE DISTURBANCE TIME HISTORIES

Description of Data

Unsteady freestream disturbance time histories were derived from sidewall pressure measurements at two mean incidence angles, (α_M = 6 deg and 10 deg) corresponding to moderately low and high loading conditions, respectively. Each configuration was tested at three pitching frequencies for several values of interblade phase angle within the range of -60 deg to +60 deg. In this report, the discussion of the response time histories is centered on a small selection of cases and is limited to identifying the principal features and trends that were found to be typical of all the data obtained during the experimental program. (See Table 1 for the complete test matrix.)

The freestream disturbance time histories in the ensuing figures were cycle-averaged over 5 cycles and are plotted in dimensionless form as a fraction of the mean freestream velocity, $\tilde{v}/V$, with the positive sign signifying a fractional increase in the freestream velocity. (It is noted that $\tilde{v}/V$ is equal to p/2q where p is the small disturbance pressure corresponding to $\tilde{v}$, and q is the dynamic pressure, $\frac{1}{2}\rho V^2$.) Typical time histories from the two mean incidence angle configurations are shown in Figs. 2 and 3 for three interblade phase angle values (-45 deg, 0 deg, and +45 deg) and a reduced frequency of $k_c = \pi fc/V \cong 0.13$ (f = 17 cps; V = 61 m/sec). The data shown in these two figures were taken at the 1/16, 1/8, 1/4, and 1/2 gap locations along the leading edge locus between two adjacent blades. As shown in Fig. 1, these locations are distances from the suction surface of the instrumented blade.

The time histories in Figs. 2 and 3 generally show that the freestream flow along the inlet plane accelerates and decelerates into the blade passage during the upstroke and downstroke portions of the blade motion, respectively. However, in viewing these responses, it should be kept in mind that the distances between the data acquisition locations and the blade leading edge continuously change as the cascade undergoes sinusoidal pitching motions. This possibly causes the response amplitudes to be somewhat exaggerated thus precluding an assessment of the actual magnitude of the freestream disturbance relative to a constant blade position. Therefore, the results presented in this report are based mainly on comparative analysis. This analysis includes examining the sensitivity of the freestream response to variations in interblade phase angle as well as correlating the freestream response trend with that of both the integrated moment response and the motion of the inflow area.

Impact of Interblade Phase Angle

Figure 2 shows that the influence of interblade phase angle is strong at moderately low incidence (α_M = 6 deg) pitching motions. Most noticeable is the intensified level of the freestream disturbance relative to the zero interblade phase angle case. As an example, the 1/8 gap disturbance level is increased on the order of 120 percent at σ = +45 deg relative to that at σ = 0 deg. This effect of σ on the freestream response can even be seen at the midgap where the response level at σ = 0 deg is minimal. A less obvious but equally important effect of σ is its influence on the phasing of the disturbance with respect to the blade motion. From Fig. 2 this potential effect on stability is most crucial at σ = +45 deg because of the slight lead in the freestream response relative to the blade motion. Details of this observation are quantitatively discussed in the next section.

The high load (α_M = 10 deg) results in Fig. 3 show similar trends in the effect of σ on the freestream response. However, a direct comparison of Figs. 2 and 3 for the two incidence angles at σ = 0 deg shows that the effect of the high incidence angle greatly diminishes the coherence of the freestream response beyond the 1/16 gap location while, at the same time, slightly diminishing the response at σ = +45 deg. Conversely, the response at σ = -45 deg is enhanced by the increase in mean incidence. An analysis seeking the cause for this increased asymmetry in the inflow response about σ = 0 deg at high load will not be presented in this report. Evidence of this asymmetry is also noted in the next section.

As in the moderately low load case (α_M = 6 deg) the high load data in Fig. 3 show that the freestream inlet plane response at σ = +45 deg slightly leads the motion of the blade and thus possibly helps reduce the stability margin of the cascade. This behavior in the aerodynamic response at σ = +45 deg for both the α_M = 6 deg and 10 deg loadings is correlated with the main finding in Ref. 6 which is that the motion of the cascade is unstable at positive σ over the range of mean incidence angles tested.

A more direct view of the influence of σ on the inlet plane response is shown in Figs. 4 and 5 at the 1/8 and 1/4 gap locations of the two mean incidence configurations. In each case, the minimum response occurs at σ = 0 deg with the level of activity increasing as σ moves away from zero. The effect of σ on the phasing of the inflow disturbance can also be seen, especially at α_M = 6 deg, as the responses shift from lagging (at $\sigma < 0$ deg) to leading (at $\sigma > 0$ deg) the blade motion.

INLET PLANE RESPONSE AND CASCADE STABILITY

Introductory Remarks

The inlet plane freestream disturbance is now quantitatively analyzed in terms of its relationship to cascade stability and the inlet area motion. As in the analysis of the relationship between the leading edge response and cascade stability (see Ref. 6), the analysis herein is focused on the first harmonic components of the individual inlet plane responses with special emphasis on plots of the first harmonic amplitudes and phase leads as functions of the interblade phase angle. These plots are used to identify the primary trends in the freestream disturbance and to study their correlation with the main trends in the stability of the cascade motion (cf. Ref. 6). The freestream disturbance results are also qualitatively compared with the behavior of the inlet area motion as a function of interblade phase angle. This is done in an attempt to determine the influence of inlet area motions on the freestream flow and, in turn, on the stability of the cascade. Although the comparisons in this section are encouraging, a much more rigorous theoretical analysis is needed before it can be concluded whether the inlet area motion interaction with the freestream contributes significantly to the stability or instability of the cascade motion. The possibility that this interaction might be relevant to subsonic cascade stability was first proposed in Ref. 6 with the aid of a simple model analysis to illustrate the concept. A review of the basic theory is presented in the next section.

The principal findings of this section are: (1) the inlet plane freestream disturbance is generally correlated with the integrated moment response of the cascade, and (2) the amplitude of the freestream disturbance at moderate loading is proportional to that of the inlet area oscillation over the range of interblade phase angles tested. These results indicate that the inlet area motions may be crucial to the formulation of subsonic cascade analyses that are capable of predicting flutter under practical operating conditions.

Amplitude Trends

Figures 6 and 7 are plots of the first harmonic amplitudes of the inlet plane freestream disturbance at moderate ($\alpha_M = 6$ deg) and high ($\alpha_M = 10$ deg) load conditions, respectively. Each figure contains data from the 1/16 gap, 1/8 gap, and 1/4 gap stations plotted as functions of the interblade phase angle, σ. The data in Fig. 6 show that the minimum disturbance level occurs within an approximate interblade phase angle range of $\pm$ 10 deg about $\sigma = 0$ deg. Thereafter, the disturbance level increases with $|\sigma|$, but with an asymmetry favoring larger increases at negative values of σ. It is also noted that the data are slightly more sensitive to the frequency at negative σ. There is no current explanation for this behavior.

From Fig. 7, the trend in the high load data at α_M = 10 deg is qualitatively similar to the results at α_M = 6 deg, but with an increased asymmetry about $\sigma = 0$ and an increased sensitivity to frequency variations at negative interblade phase angles. Relative to the response at σ = 0 deg, the data in Fig. 7 show that the effect of positive σ at high load is approximately the same as in the lower load (α_M = 6 deg) situation while the effect of negative σ is enhanced, especially at $k_c = 0.13$. It would appear from the results of Figs. 6 and 7 that the degree of asymmetry in the data distribution with σ is somehow dependent on the magnitude of the leading edge activity associated with a given value of mean incidence angle. The nature of this interrelationship is not understood.

During this writing, new inlet plane disturbance data were obtained at α_M = 2 deg (Ref. 9), with the same pitching amplitude as the data of this report. These new data were generated over the entire range of $\sigma(-\pi \leq \sigma \leq \pi)$ and measured in 45 deg intervals. Although there are only three points common with the current analysis (σ = -45, 0, and 45 deg) a plot of the 1/8 gap first harmonic response amplitude at $k_c = 0.12$ shows that the effect of σ at low load is almost purely symmetric about $\sigma = 0$ (cf. Fig. 8). This distribution in the data reinforces the trend observed in Figs. 6 and 7 in which the degree of asymmetry of the data about $\sigma = 0$ appeared dependent on the magnitude of the mean incidence angle.

An attempt is now made to correlate the behavior of these data with the amplitude of the oscillatory inlet area as a function of σ. The primary feature in the trends of Figs. 6, 7, and 8 is the increased level of the inlet plane disturbance as the absolute value of σ increases from zero. This behavior in the disturbance level distribution is what might be expected if the disturbance was primarily dependent on the oscillatory inlet area. In particular, as the magnitude of the interblade phase angle varies over the entire range of possible values (from 0 to 180 deg), the amplitude of the inlet area oscillation varies from approximately zero (blades moving in phase) to a maximum value proportional to twice that of the blade pitching motion (blades moving 180 deg out of phase with each other). It is shown in the following simple analysis that this trend in the area oscillation amplitude closely matches that of the first harmonic component of the measured freestream disturbance at α_M = 2 deg in Fig. 8.

A simple expression for the inlet area time history corresponding to the blade pitching motion is now derived. This is achieved with the simple inlet configuration shown in Fig. 9 in which the inlet boundaries represent adjacent blading. The use of such a geometry in this instance is justified since it expedites the derivation without sacrifice to the main feature of the problem.

As shown in Fig. 9, the object boundary (representing the suction surface of the instrumented blade) is given a sinusoidal motion, $\delta h = \bar{h} \sin \omega t$, while the opposite boundary leads the first by σ. By specifying that the positive displacement of the object boundary is in the direction of positive lift, then $\sigma > 0$ simulates the condition of a forward traveling wave. From Fig. 9, the change in inlet area, δA, corresponding to the motion of the inlet boundaries becomes

$$\delta A = \bar{h}\,[\sin(\omega t + \sigma) - \sin \omega t] \qquad (1)$$

where $\bar{h}$ simulates the deflection of the leading edge, $c\bar{\alpha}/2$ (c = chord, $\bar{\alpha}$ = pitching amplitude). Equation (1) thus represents a first order estimate of the change in inlet area corresponding to the cascade pitching motion.

Equation (1) reduces to

$$\left.\begin{aligned} \delta A &= \bar{h}\sqrt{2-2\cos\sigma}\,\sin(\omega t + \theta) \\ \text{where} \quad \theta &= \tan^{-1}\left(\frac{\sin\sigma}{\cos\sigma - 1}\right) \end{aligned}\right\} \qquad (2)$$

is the phase lead of δA relative to δh. It is noted that $\pi \leq \theta \leq 3\pi/2$ when $-\pi \leq \sigma \leq 0$ and that $\pi/2 < \theta \leq \pi$ when $0 < \sigma \leq \pi$. (Phase angle trends are discussed later in this section.)

For convenience, the steady state inlet area per unit span is set equal to the cascade gap length, τ, and is used to normalize the inlet area oscillation amplitude: $(\bar{h}/\tau)\sqrt{2-2\cos\sigma}$. Normalized plots of Eq. (2) are shown in Fig. 10 for several values of σ to illustrate the sensitivity of the inlet area motion to the interblade phase angle. Figure 11 shows plots of the inlet area oscillation amplitude and phase lead over the interblade phase angle range of $-60 \text{ deg} \leq \sigma \leq +60$ deg.

The inlet area amplitude variation with σ (shown at the top of Fig. 11) is now fitted to the velocity disturbance data of Fig. 8 over the range: $-\pi \leq \sigma \leq \pi$. This heuristic comparison is carried out under the assumption that if the magnitude of the freestream velocity disturbance is related to the magnitude of the inlet area motion, then its distribution with σ would closely match that of the inlet area motion. The result of the comparison is shown in Fig. 12 in which the two point theoretical curve fit is given by

$$\tilde{V}/V = 0.04 + 0.07\sqrt{2-2\cos\sigma} \; .$$

The closeness of the fit over the entire range of σ indicates that inlet area oscillations have some controlling influence on the magnitude of the freestream disturbance at the inlet plane. This is a potentially important finding, especially at high absolute σ where the area change becomes large and the resulting influence may no longer be negligible in the formulation of theoretical models.

A similar fit is shown in Fig. 13 in which the data (cf. Ref. 9) are the first harmonic amplitudes obtained on the blade suction surface near the leading edge for the same case as in Fig. 12. This latter comparison is consistent with Fig. 12 and supports the hypothesis of Ref. 6 that inlet area oscillations may have a strong influence on the leading edge load (and thus on the stability of the cascade) at moderately high values of σ. It should be noted that, in addition to the effect of inlet area oscillations, the influence of σ on the aerodynamic response also comes from surface generated disturbances which are already accounted for in conventional analyses. A comparison of the magnitudes of their contributions needs to be made to properly assess the overall impact of σ. This will be done at a future time.

Phase Lead Trends

Figures 14 and 15 show the trend of the first harmonic disturbance phase lead as a function of σ at three inlet plane locations, (1/16 gap, 1/8 gap, and 1/4 gap stations) for α_M = 6 deg and 10 deg, respectively. Each figure also contains the corresponding phase lead trend of the integrated moment response (taken from Ref. 6) shown at the lower right hand corner to show the correlation between the inlet plane response and cascade stability. In these figures, a positive value of phase lead indicates that the response leads the blade motion and thus could act to excite the cascade. The converse is true for negative phase lead.

For the range of frequencies tested at moderate loads (cf. Fig. 14), the behavior of the freestream disturbance phase lead closely matches that of the integrated moment response. In particular, the freestream disturbance was found to lead the blade motion when $\sigma \gtrsim 10$ deg thus indicating a potential capacity to destabilize the blade motion. This trend also agrees with the behavior of the leading edge region suction surface response which is discussed in detail in Ref. 6.

As in the first harmonic disturbance amplitude data of Fig. 6, the trends in Fig. 14 are generally insensitive to the frequency except at negative σ where an increase in frequency increases the phase lag (and thus perhaps the stabilizing influence) of the freestream disturbance. This increased lag in the response with frequency is due to the inertia of the fluid. However, there is no explanation for the diminution of the effect of frequency as σ becomes positive and the disturbance leads the motion. Figure 14 also shows an increase in the scatter of the inlet plane data with the distance from the blade surface. This behavior is consistent with the reduced amplitude and accompanying gradual deterioration of the response with distance from the leading edge of the blade (cf. Fig. 2).

In the case of high loading (α_M = 10 deg), scatter appears to dominate the results of Fig. 15. However, even under this fairly irregular condition, the inlet plane data are reasonably well correlated with each other and with the integrated moment phase lead when $|\sigma| \gtrsim 20$ deg. The main difference between these data and those of Fig. 14 is that they were obtained in a region of high incidence pitching motion in which the flow pattern is sufficiently different to cause a change in the character of the primary disturbance source. As in Fig. 14, the effect of the frequency is most prominent at negative σ; however, unlike the results of Fig. 14, the freestream disturbance does not have a stabilizing influence at $k_c = 0.07$ over negative σ and is only marginally so at $k_c = 0.13$. Conversely, the overall trend in the phase lead dependence on σ at $k_c = 0.19$ matches that of the moderate load results shown in Fig. 14. In spite of these differences, the trend of the data with frequency (in the negative σ range) is the same as in the moderate load result; that is, an increase in k_c tends to have a stabilizing influence on the response.

As in the discussion of the amplitude behavior with σ earlier in this section, it is useful to compare the current experimental trend of phase lead with the trend of new data collected at α_M = 2 deg. The phase lead trend with σ shown in Fig. 16 corresponds to the amplitude trend in Fig. 8. Although there are only three points in common between the results of Fig. 16 and those of Figs. 14 and 15 (σ = -45 deg, 0 deg, and 45 deg), the primary trend is the same; that is, the freestream disturbance lags the blade motion at $\sigma \lesssim 0$ deg and leads when $\sigma \gtrsim 0$ deg. A specific comparison between the results of Fig. 14 (α_M = 6 deg) and Fig. 16 also shows that the crossover of the data from lagging to leading occurs at a value near σ = 0 deg and that the magnitude of the phase lag at $\sigma \lesssim 0$ deg exceeds the magnitude of the phase lead at $\sigma \gtrsim 0$ deg. This behavior in the data suggests that the measured disturbance possibly comprises two parts: (1) a term which is dissipative over the entire range of σ, although perhaps not independent of σ, and (2) a disturbance term which is very nearly symmetric about σ = 0 deg and tending to destabilize the motion when $\sigma \gtrsim$ deg. This hypothesis in the makeup of the disturbance is appealing because the latter term provides the framework for bringing into the discussion the influence of the inlet area motion on the behavior of the freestream disturbance phase angle. An attempt to relate the inlet area phase angle to the inlet plane disturbance phase angle is presented next.

Earlier in this section a heuristic comparison was made between the experimental trend in the disturbance amplitude and the predicted trend in the amplitude of the inlet area change as functions of σ. This type of comparison can be made at small amplitudes because linear analysis shows that the amplitude of a disturbance is proportional to the amplitude of the disturbance source. The degree of success from such a comparison is very important in establishing the potential relevance of the hypothesized disturbance source to the experimental data. However, a similar heuristic comparison between the measured disturbance phase lead and the computed inlet area phase lead cannot be made directly without accounting for the complex aeroelastic interaction between the inlet area motion and the surrounding flow field. Nevertheless, even in the absence of a theoretical aeroelastic model it is still possible to make some sort of useful comparison to identify gross similarities in the primary behavior. Figure 17 compares the behavior of the inlet area phase lead given by Eq. (2) with the measured trends at the 1/8 gap station and on the blade suction surface at $\chi = 0.012$. (For convenience, the curve given by Eq. (2) was inverted to highlight the main features relative to the measured data.) The strong similarity in the three trends reinforces the potential importance of inlet area motions on the aerodynamic disturbance and perhaps on stability. Particularly striking is the phase shift in the three results as σ goes from negative to positive values and their linear dependence on σ on either side of the phase shift.

Discussion

At the beginning of this report it was stated that the inlet plane data were obtained to study the influence of σ on the freestream flow at the inlet and to compare the resulting trends with those of the integrated moment response from Ref. 6. Although the comparisons were successfully achieved (Figs. 6 to 9), there was no attempt to determine their cause and effect relationship. This is the next logical step in the data analysis and will be the subject of a future study.

Another important objective of the current study was to compare the primary (first harmonic) features of the inlet plane response with the behavior of the inlet area motion during flutter and thus determine if the evidence of correlation is compelling enough to include inlet area oscillations in future investigations of subsonic cascade flutter that involve nonzero interblade phase angles. The ultimate objective of this line of study is to identify and understand the controlling mechanism of subsonic cascade flutter. This is a crucial prerequisite to developing a rational approach to improving the stability boundary by design.

The strong correlations obtained in this study between the aerodynamic response and the behavior of the inlet area motion is encouraging. The combined results of Ref. 6 and of the work herein shows that σ is the dominant parameter affecting subsonic cascade stability and that an important mechanism by which σ influences the cascade response may be via the interaction between the inlet area motion and the inflow.

A description of the interaction mechanism and a brief review of the theoretical analysis of Ref. 6 is presented in the next section.

REVIEW OF INLET INTERACTION MECHANISM

For the range of parameters tested, it was shown in Ref. 6 that the interblade phase angle is the dominant parameter affecting cascade stability. In the present study, correlations were presented (cf. Figs. 12, 13, and 17) that indicate this influence may be partly attributable to the interaction between the inflow and the inlet area motion. Although the relevance of this interaction to the actual subsonic cascade flutter problem is yet to be conclusively shown, the current qualitative evidence is compelling. An ability to accurately identify the main source of aeroelastic excitation for the subsonic cascade would be a significant result. This is true because it would describe how flow energy is transferred to the cascade motion and which parameters can be varied to help minimize the problem. A qualitative description of this coupling mechanism is presented next using a simple oscillating inlet to illustrate the principal concept.

In the classical analytic treatment of airfoil flutter (e.g., Refs. 10 and 11), velocity field disturbances are attributed to the displacement of fluid by the oscillating airfoil surface. A small disturbance analysis is used to derive these surface-generated disturbances which are then linearly superimposed onto the basic steady flow. The altered flow potential is then substituted into the unsteady Bernoulli equation to predict the induced unsteady loading. In this method, the boundary conditions simulating the motion of the airfoil are applied at the position of the boundaries for the basic steady flow. Therefore, it is tacitly assumed that the streamline pattern of the unsteady flow is the same as that of the steady flow. This is acceptable in aeroelastic analysis as long as the basic steady flow potential is everywhere independent of potentially time-dependent configuration parameters such as angle of incidence or inflow area. In the case when the basic steady flow is dependent on a configuration parameter, the unsteady problem increases in complexity relative to the classical formulation. This is because as the configuration oscillates, the corresponding change in the geometry causes the near field streamline pattern to undergo a periodic adjustment. This disturbance source is different from and is in addition to the more familiar surface-generated disturbance. The contribution of these two disturbance sources to the aeroelastic interaction is schematically illustrated in Fig. 18 for the case of the cascade in oscillatory pitch. Each disturbance source is shown contributing to the total freestream unsteadiness. The bottom loop represents the traditional aeroelastic problem and the top loop represents the corresponding aeroelastic interaction associated with the periodic change in the cascade inlet area. An objective of the present study has been to present correlations supporting this hypothetical description of the total aeroelastic problem. This was achieved in the previous section where it was shown that the trend in the magnitude of the measured inflow perturbation and of the leading edge response matches that of the inlet area motion as σ (interblade phase angle) increases beyond moderately small values ($\simeq$ 10 deg). It is noted from this description that the impact of inlet area motions is negligible for small σ and that the residual unsteady load is due to surface-generated disturbances and wake interaction effects.

The interaction mechanism between a time varying system geometry and the surrounding flow field can be described qualitatively by examining the simple case of a periodically varying flow inlet area separating an upstream and a downstream reservoir. When the inlet area undergoes a periodic change, a quasi-steady application of the Bernoulli equation to account for corresponding changes in the flow at the inlet is approximately valid only if the oscillation frequency is small enough to permit the condition at infinity to periodically adjust to the changing flow area. In reality, however, the condition at infinity is insensitive (on a first order basis) to periodic changes in the inlet area. This resistance to change of the far field occurs because most of the fluid inertia is contained in the flow far from the inlet. Therefore, the adjustment of the flow to inlet area oscillations is confined to the near field region. Physically, this means that some of the constant supply of mass flow from infinity becomes periodically blocked at the inlet. In this situation, as the inlet area increases, the volume flow rate into the inlet also increases, causing the pressure at the inlet to decrease. This is unlike the quasi-steady problem in which the volume flow rate through the inlet remains unchanged and the inlet pressure increases with increasing inlet area.

On the basis of this description, the far field inertial resistance and near field compliance of the flow to a periodically changing geometry causes the freestream mass flow to cyclically accelerate and decelerate into the inlet. This produces an unsteady loading which is in addition to that due to surface-generated disturbances. This additional disturbance will excite a system motion if the imaginary part of the induced freestream impedance is positive and large enough to overcome the intrinsic loss factors of the oscillating system. The ability of this interaction mechanism to produce an actual excitative load was originally shown in Ref. 12 and subsequently applied in Ref. 13. The underlying concept was adapted in Ref. 6 to demonstrate how a simple oscillating inlet might induce an aeroelastic instability.

The analysis in Ref. 6 was carried out in two parts. First, the basic flow problem was solved showing how an oscillating inlet area interacts with the surrounding flow field. Second, an expression was derived for the oscillatory inlet area as a function of σ. The two analyses were combined to yield the freestream disturbance near the inlet plane as a function of σ. The principal assumptions that were made are described in Section 7.2 of Ref. 6. The resulting approximate expression for the aerodynamic damping parameter was found to be proportional to

$$C_A = \frac{1-\cos\sigma - A\sin\sigma}{1-A^2} \qquad (3)$$

where A is a function of the system geometry and frequency. (In this equation, A is an increasing function of frequency.) Plots for two values of A are presented in Fig. 19.

For comparative purposes, Fig. 20 shows plots of the aerodynamic damping coefficients measured at moderate load (mean incidence angle equal to 6 deg) for three values of reduced frequency (cf. Ref. 6). It is immediately seen that the experimental trends are qualitatively matched by the theoretical result, indicating the potential dependence of cascade stability on the σ-dependent inlet area motion of the cascade.

EFFECT OF GAP-TO-CHORD RATIO ON THE CASCADE LOAD RESPONSE

This section of the report is a continuation of the survey that was initiated in Ref. 6 on the sensitivity of the leading edge region aerodynamic response to the various system parameters (k_c, α_M, σ, and τ/c). The impact of k_c, α_M, and σ have already been presented in Ref. 6. A summary of the results obtained on the effect of the gap-to-chord ratio (τ/c) is presented next. This portion of the experimental program was limited to a mean incidence angle of 8 deg and a pitching amplitude of 2 deg. The complete test matrix is shown in Table 2. The specific set of data chosen for discussion in this section was obtained at a reduced frequency of $k_c = 0.13$. These data are representative of the influence of τ/c on the leading edge response for the range of k_c tested. (The effect of k_c on the distribution of load for $\tau/c = 0.75$ was investigated in Ref. 6 and was found to be minor over the range of parameters tested.) The time histories presented herein have been cycle-averaged over 5 cycles and normalized with respect to the steady component of the freestream dynamic pressure. This report focuses on the forwardmost 40 percent of the suction surface with special emphasis on the unsteady responses at $\chi = 0.012$ and $\chi = 0.062$.

One of the principal results of Ref. 6 was finding that for $\tau/c = 0.75$ the behavior of the response at the 1.2 percent chord station ($\chi = .012$) is narrowly confined to the leading edge region. Specifically, the events displayed there are mostly absent from the time histories obtained at the 6.2 percent station and beyond. Such behavior was then thought to be partly attributable to the confinement of the flow within the blade passage downstream of the inlet. The results of Fig. 21 bear this out. This figure shows the time histories of the pressure response over the forward 40 percent chord for three values of τ/c at an interblade phase angle of 0 deg. It is immediately seen that the gap-to-chord ratio has a significant influence on the qualitative behavior of the individual time histories, especially downstream of the 1.2 percent chord station. As the gap-to-chord ratio increases, the flow through the blade passage becomes less confined and the response along the chord becomes progressively influenced by the leading edge dynamic stall (loss of lift during the upstroke). Note, in particular, the change in the character of the response at $\chi = .062$ as τ/c is increased from 0.75 to 1.50. Also note the behavior of the load response beyond $\chi = .062$ as τ/c is increased further to 2.25. The latter set of responses generally resemble those of the isolated airfoil ($\tau/c = \infty$).

Particular features of the load response that are significantly affected by the gap-to-chord ratio are: (1) the magnitude, (2) the harmonic content, and (3) the phase lead. All of these (but especially the latter) impact the stability margin of the cascade motion. The aerodynamic damping coefficients corresponding to these data were computed in an earlier effort (Ref. 7) where it was shown that increases in the gap-to-chord ratio tend to reduce the stability margin of the cascade. This trend in the stability margin with τ/c, however, should not be generalized as applicable to other values of mean incidence angle until actual experimental evidence has been obtained.

Figure 22 highlights the effect of τ/c on the responses at $\chi = 0.012$ and $\chi = 0.062$ for three values of interblade phase angle, σ. This figure shows that the influence of τ/c on the aerodynamic response is also significant at nonzero interblade phase angles. It is noted from these plots that as τ/c increases, the differences in the responses due to σ tend to decrease both at $\chi = 0.012$ and at $\chi = 0.062$. This apparent weakening in the effect of σ with increasing τ/c is not surprising. However, taking another look at the same data arranged to highlight the effect of σ for each value of τ/c (cf. Fig. 23) shows that the influence of σ on the phase lead remains substantial even for $\tau/c = 2.25$. This outcome continues to reinforce the main finding in Ref. 6 that σ is the dominant parameter affecting the stability of a subsonic cascade.

CONCLUSIONS

In the present investigation an analysis was made of unsteady aerodynamic data measured in the leading edge region of a subsonic cascade both along the inlet plane and along the chord of the center blade. The two main areas of study were: (1) the analysis of the inlet plane data to determine the effects of interblade phase angle and reduced frequency on the behavior of the freestream disturbance and (2) the analysis of chordwise data to determine the influence of the gap-to-chord ratio on blade loading.

During part of this study, the various trends between the freestream disturbance, the inlet area oscillation, and the moment response of the cascade were compared. In addition, a hypothesis was presented suggesting that the dependence of cascade stability on interblade phase angle might be partly due to the freestream flow interaction with the inlet area oscillation of the cascade. The potential relevance of this interaction was implied by the strong correlation between measured data and a simple analytical prediction of the inlet area oscillation as a function of the interblade phase angle.

The following are the main findings of the data analysis in the approximate order of their appearance in the report:

1. For the range of σ (interblade phase angle), and α_M (mean incidence angle) tested, the minimum level of the freestream disturbance occurs near $\sigma = 0$ deg with the level intensifying as $|\sigma|$ increases.

2. The phasing of the freestream disturbance generally shifts from lagging to leading the motion of the adjacent blade as σ varies from negative values (backward traveling wave) to positive values (forward traveling wave).

3. The variation in the first harmonic amplitude of the freestream response with σ is not symmetric about $\sigma = 0$; however, the asymmetry in the disturbance level decreases with decreasing mean incidence angle.

4. At small incidence ($\alpha_M = 2$ deg), both the freestream disturbance and the leading edge region suction surface responses are strongly correlated with the trend in the amplitude of the inlet area oscillation as a function of σ.

5. The main features in the derived variation of the inlet area oscillation phase angle with σ closely match those of the measured freestream and blade load responses. These comprise the phase shift near $\sigma = 0$, and the linear dependence of the phase angle on α on either side of the phase shift.

6. The qualitative behavior of the blade load response is strongly influenced by the gap-to-chord ratio. In particular, as the gap-to-chord ratio increases, the chordwise load distribution becomes progressively influenced by the leading edge dynamic stall.

7. Although an increase in the gap-to-chord ratio from 0.75 to 2.25 significantly reduces the influence of σ on the amplitude of the leading edge region blade load, the influence of σ on the phasing of the blade load remains substantial. This reinforces the finding in Ref. 6 that σ is the dominant parameter affecting the behavior of the cascade motion.

RECOMMENDATIONS

In the work reported herein, a mutual relationship between the inlet area oscillation, the moment response of the cascade, and the freestream unsteadiness at the inlet was shown to exist. The main implication of the results is that the stability of the cascade might be influenced by the interaction between the inlet area oscillation and the freestream flow. However, additional work needs to be done before it is possible to conclude whether this cascade/aerodynamic interaction mechanism is actually relevant to subsonic cascade flutter.

The following are lines of investigation that should be followed:

1. Analyze existing low incidence (α_M = 2 deg) data to determine the cause and effect relationship between the freestream disturbance and the unsteady blade load.

2. Develop a more rigorous aerodynamic analysis of the single inlet configuration (Fig. 9) to predict the order of magnitude of the freestream disturbance near the inlet. A comparison of this result with cascade measurements would be used to further assess the relevance of the inlet area/freestream disturbance interaction to cascade aerodynamic analysis. (It is noted that the current analytical result is of qualitative value only.)

3. Compare the magnitude of the prediction of Item 2 with that of classical subsonic cascade theories.

4. Analyze the gapwise distribution of freestream disturbance between adjacent blades from available experimental data. This would be done to assist in the performance of Item 1.

5. Further extend the analysis of Item 2 to a more representative geometry, by including stagger and multiple passages.

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$\sigma \backslash k_c$	0.07	0.13	0.19
-60	X	X	X
-45	X	X	
-30	X	X	X
-20	X	X	X
-10	X(*)	X(*)	X(*)
- 5		X(*)	X(*)
0	X	X	X
5	X(*)	X(*)	
10	X(*)	X(*)	X(*)
20	X	X	X
30	X	X	X
45	X	X	X
60	X	X	X

*Data not obtained at α_M = 10 deg

Table 1. Reduced Frequency - Interblade Phase Angle Matrix of Test Points for Inlet Plane Disturbance Analysis (α_M = 6 deg, 10 deg).

k_c \ τ/c	0.75	1.50	2.25	∞
.05	X			
.07	X	X(*)	X	X
.09	X			X
.13	X	X(*)	X	X
.14	X			X
.16	X	X(*)	X	X

*Data also obtained at σ = -20 deg and +20 deg

Table 2. Gap-to-Chord Ratio - Reduced Frequency Matrix of Test Points for Gap-to-Chord Ratio Effects Analysis (α_M = 8 deg; σ = -45 deg, 0 deg, 45 deg)

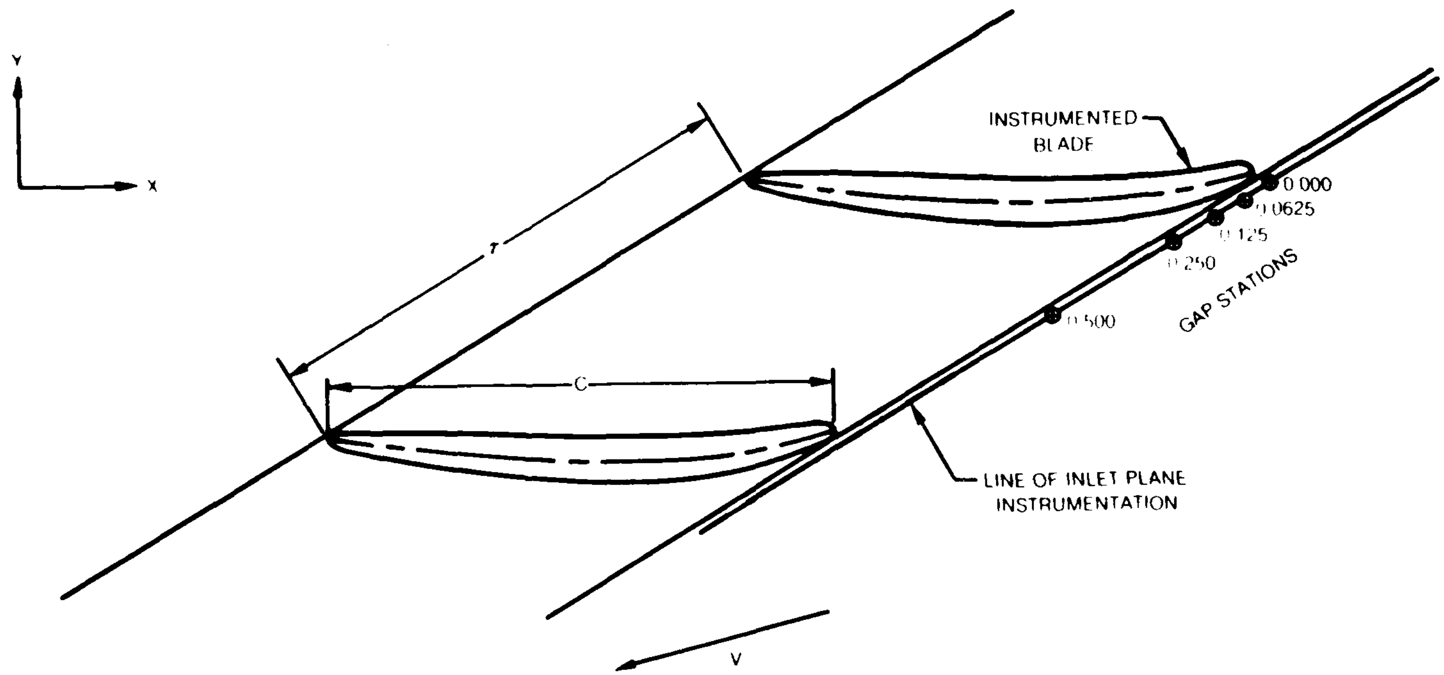

Fig. 1 Schematic of Inlet Plane Pressure Instrumentation of SQUID Sponsored Program

80-4-10-6

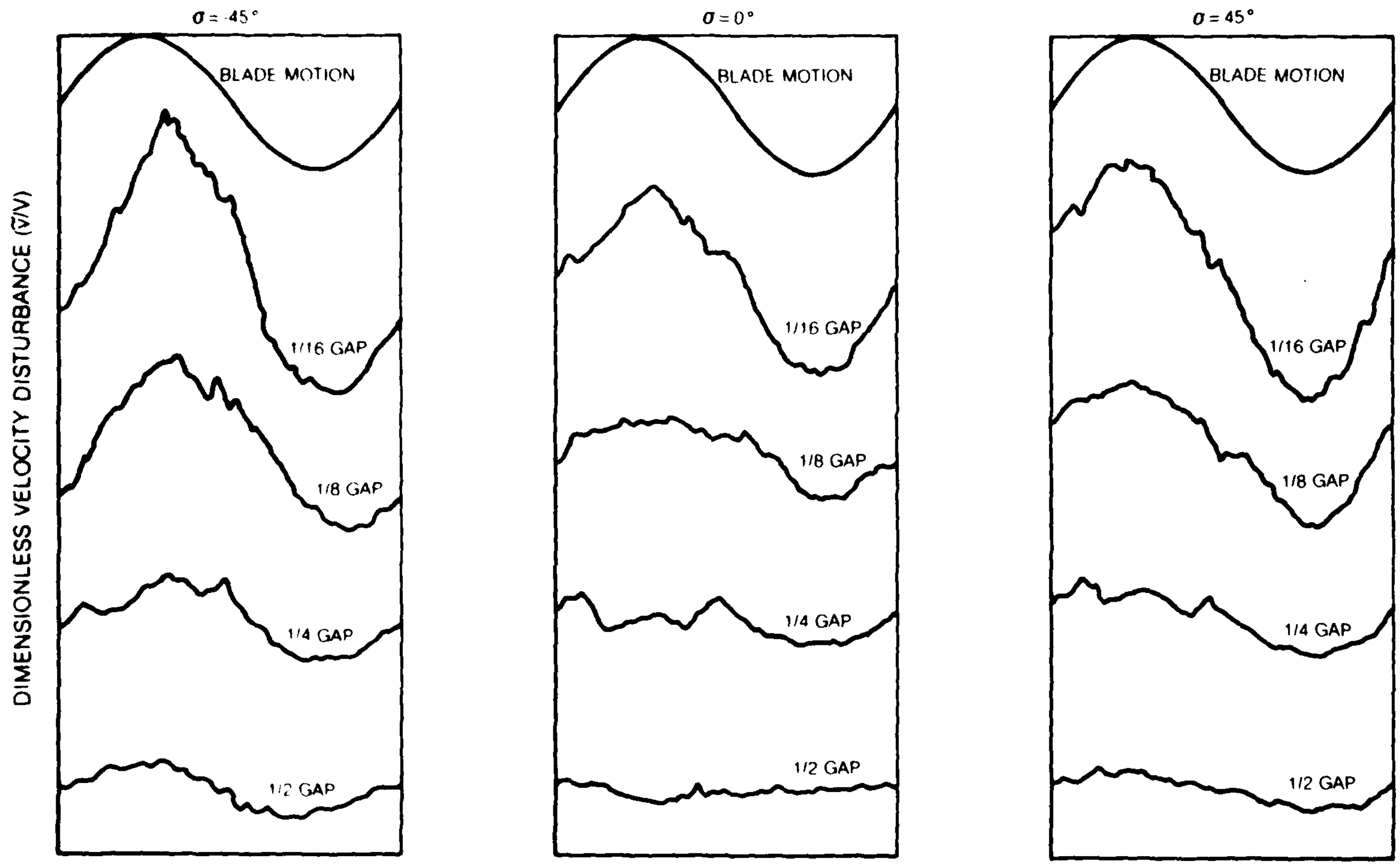

Fig. 2 Inlet Plane Disturbance Time Histories ($\alpha_M = 6$ deg; $k_c = 0.13$)

80-12-11-2

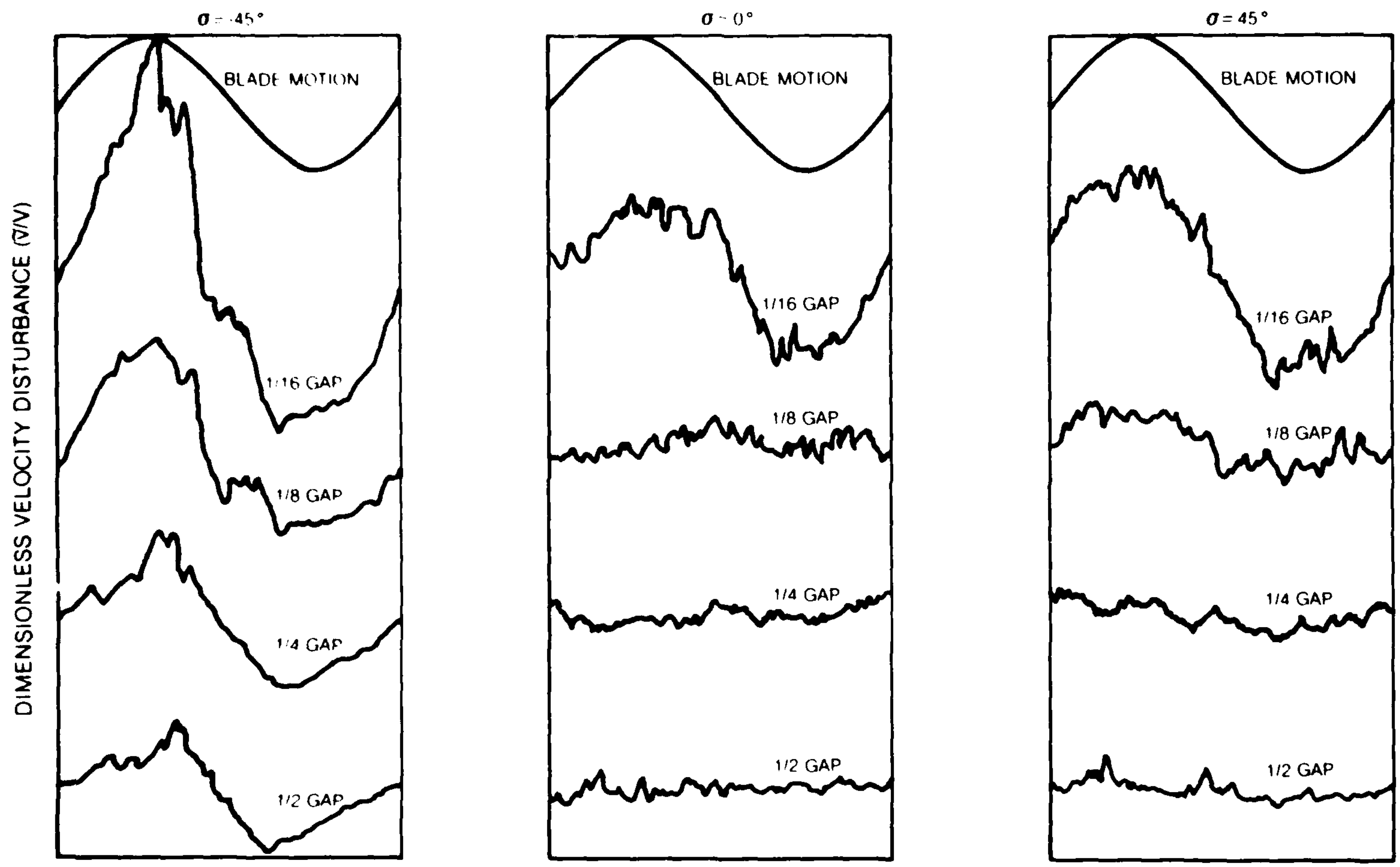

Fig. 3 Inlet Plane Disturbance Time Histories ($\alpha_M = 10$ deg; $k_c = 0.13$)

80-12-11-3

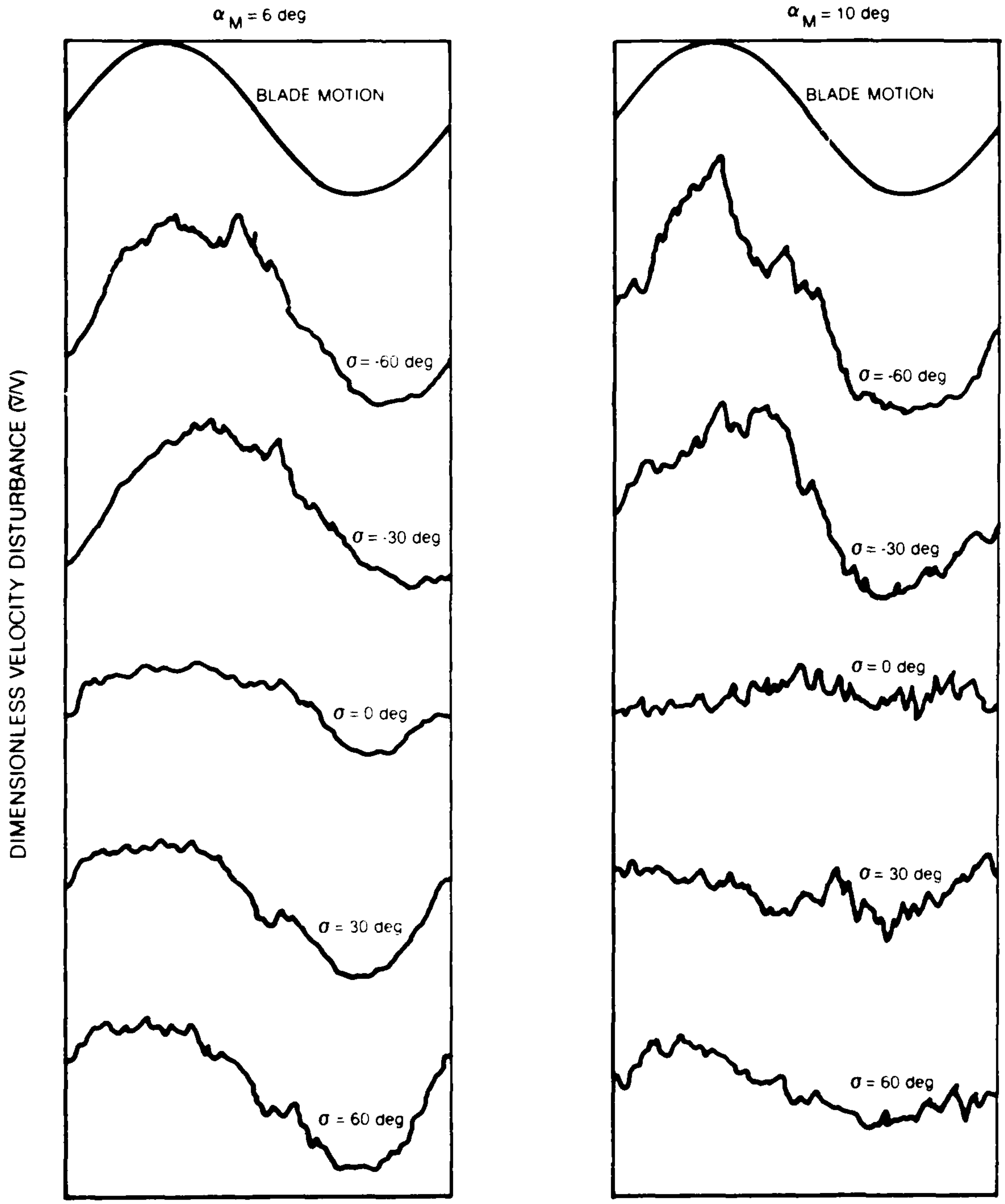

Fig. 4 Effect of Interblade Phase Angle on the 1/8 Gap Response Time History (k_c = 0.13)

80-12-11-4

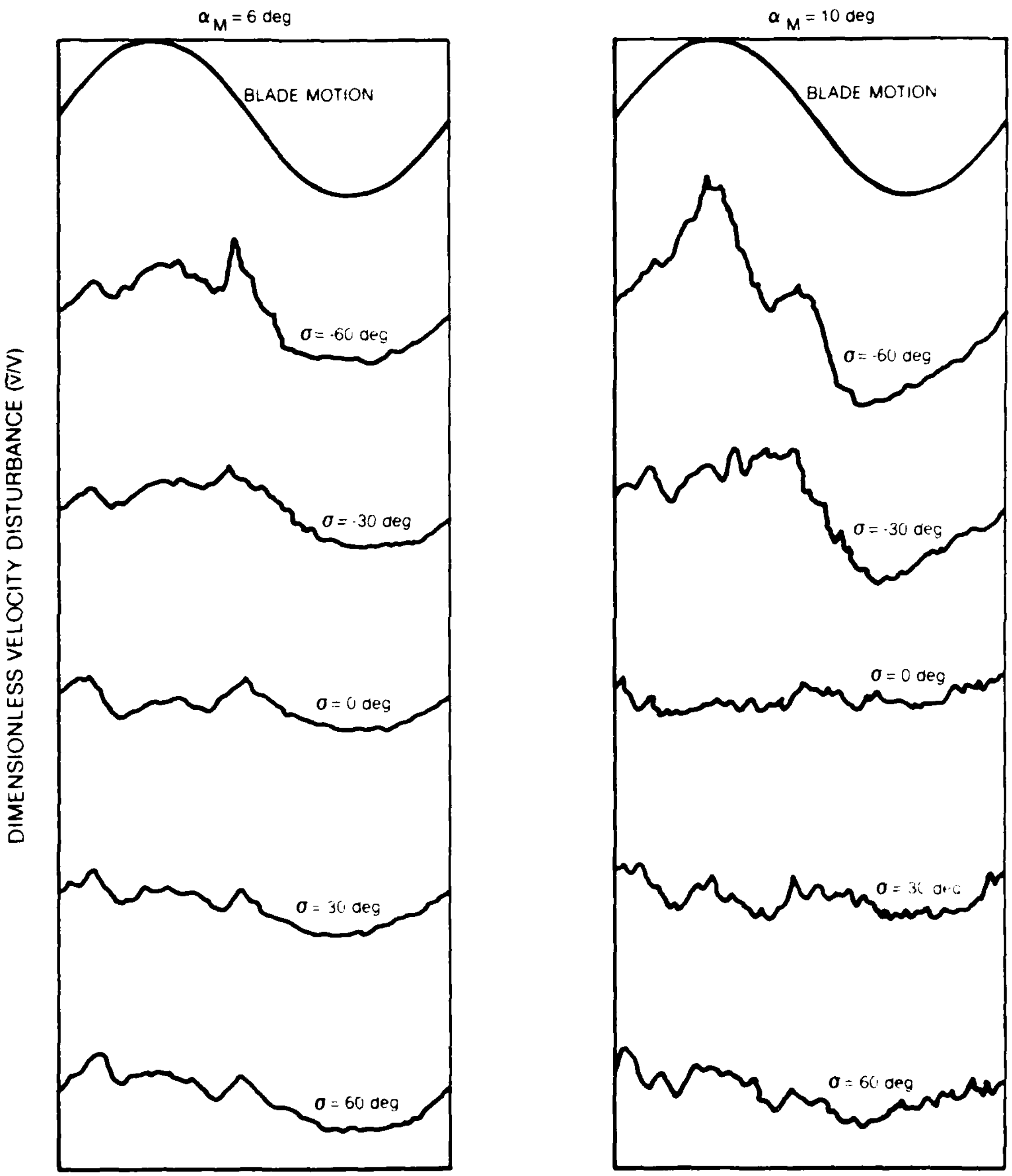

Fig. 5 Effect of Interblade Phase Angle on the 1/4 Gap Response Time History (k_c = 0.13)

80-12-11-5

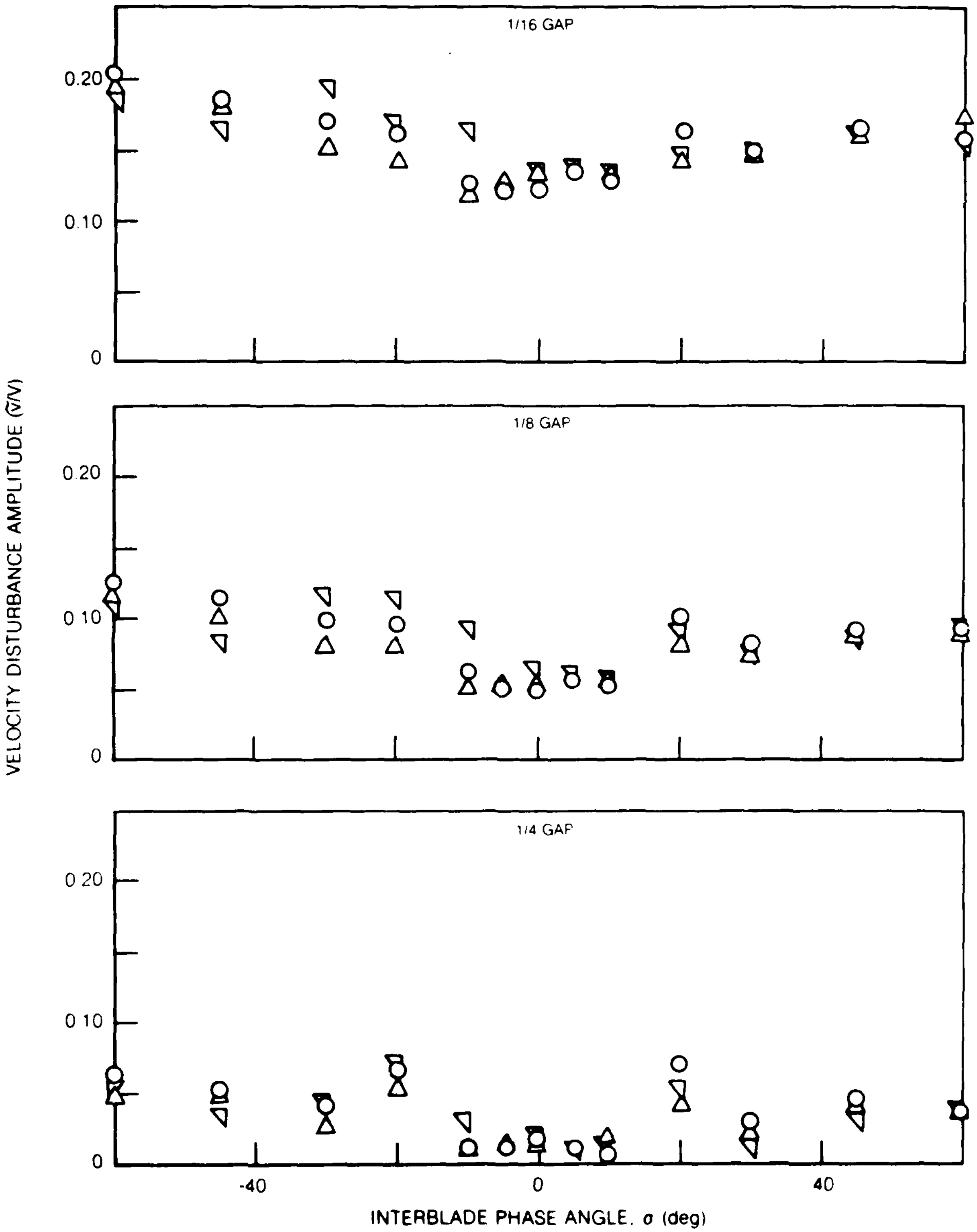

Fig. 6 First Harmonic Amplitude of Inlet Plane Disturbance as a Function of Interblade Phase Angle (α_M = 6 deg). k_c: ▽, 0.07; ○, 0.13; △, 0.19

80-12-11-6

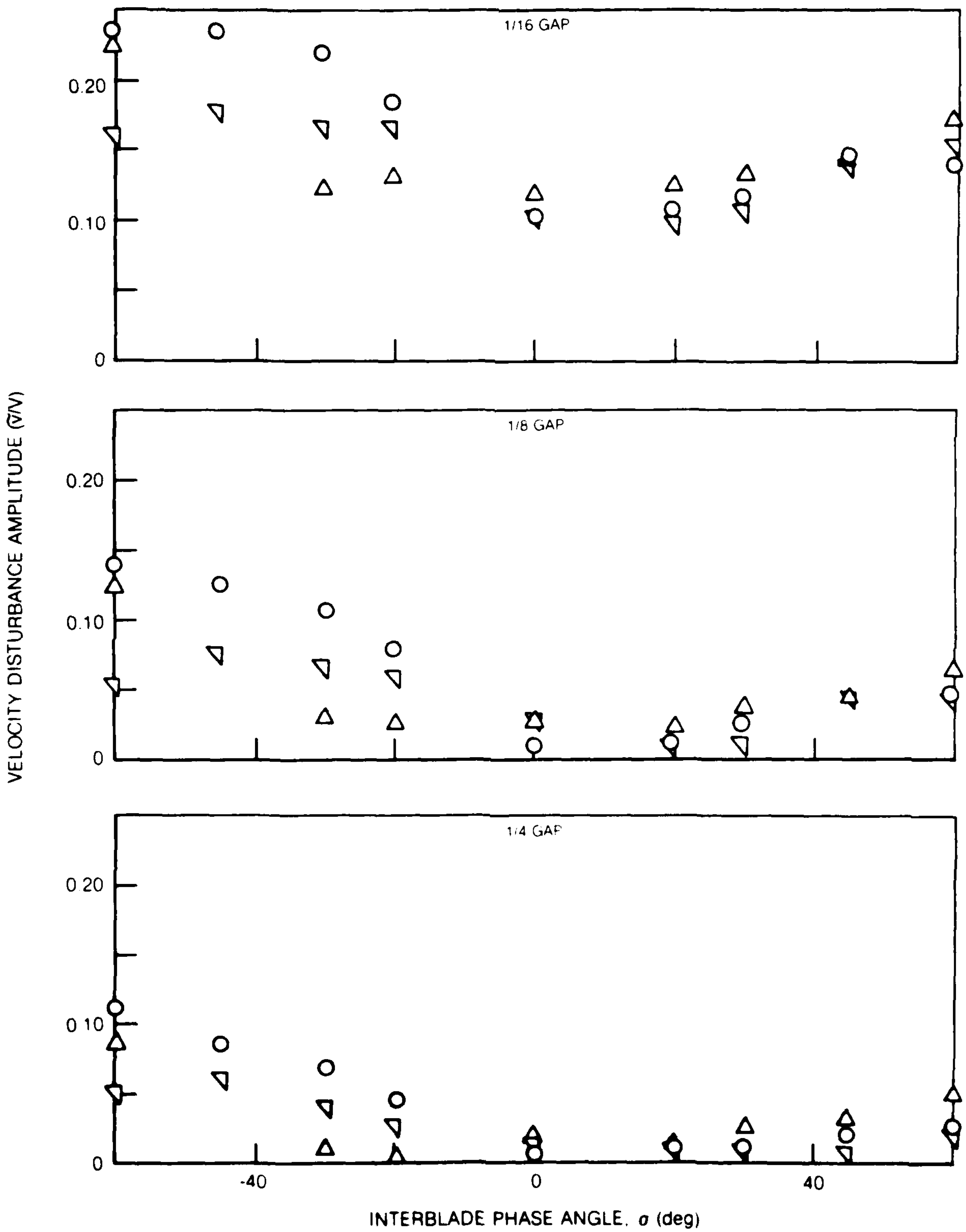

Fig. 7 First Harmonic Amplitude of Inlet Plane Disturbance as a Function of Interblade Phase Angle (α_M = 10 deg). k_c: ▽, 0.07; ○, 0.13; △, 0.19

80-12-11-7

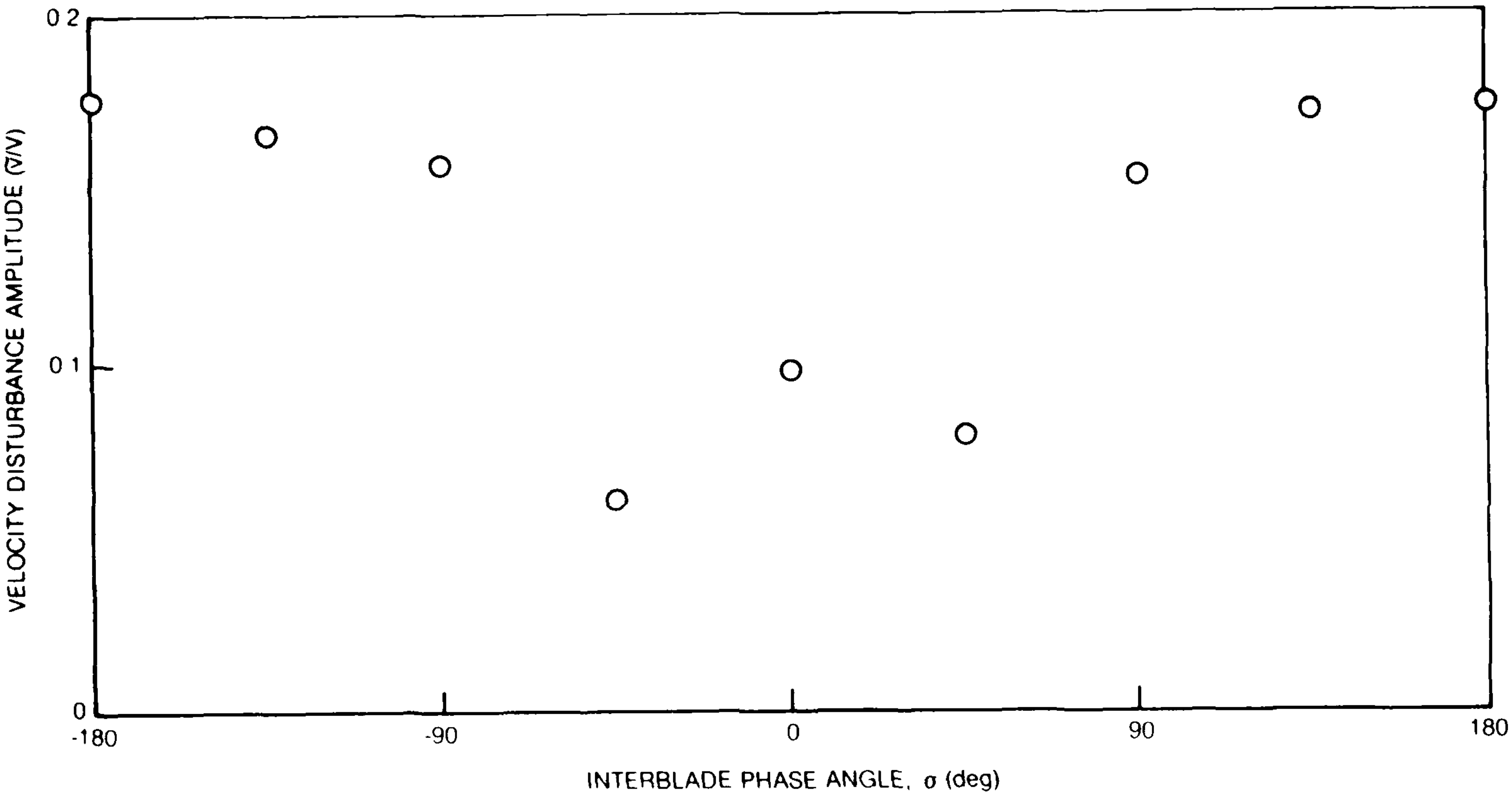

Fig. 8 First Harmonic Amplitude of Inlet Plane Disturbance at the 1/8 Gap Station as a Function of Interblade Phase Angle (See Ref. 9 for Data Source). $k_c = 0.12$; $\alpha_M = 2$ deg; $\bar{\alpha} = 2$ deg; $\tau/c = 0.75$

80–12–11–18

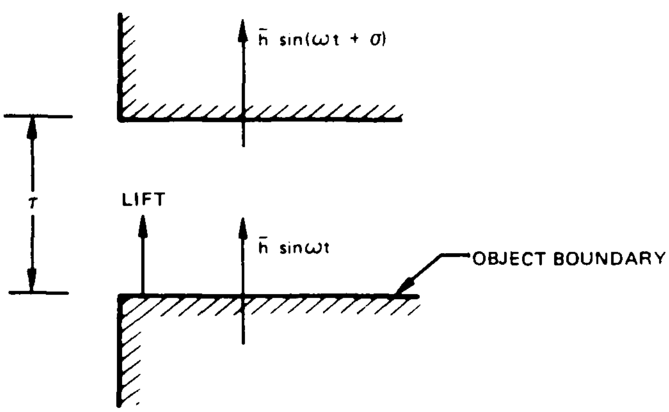

Fig. 9 Schematic of Influence of Interblade Phase, σ, Angle on Inlet Area, τ

79-03-47-3

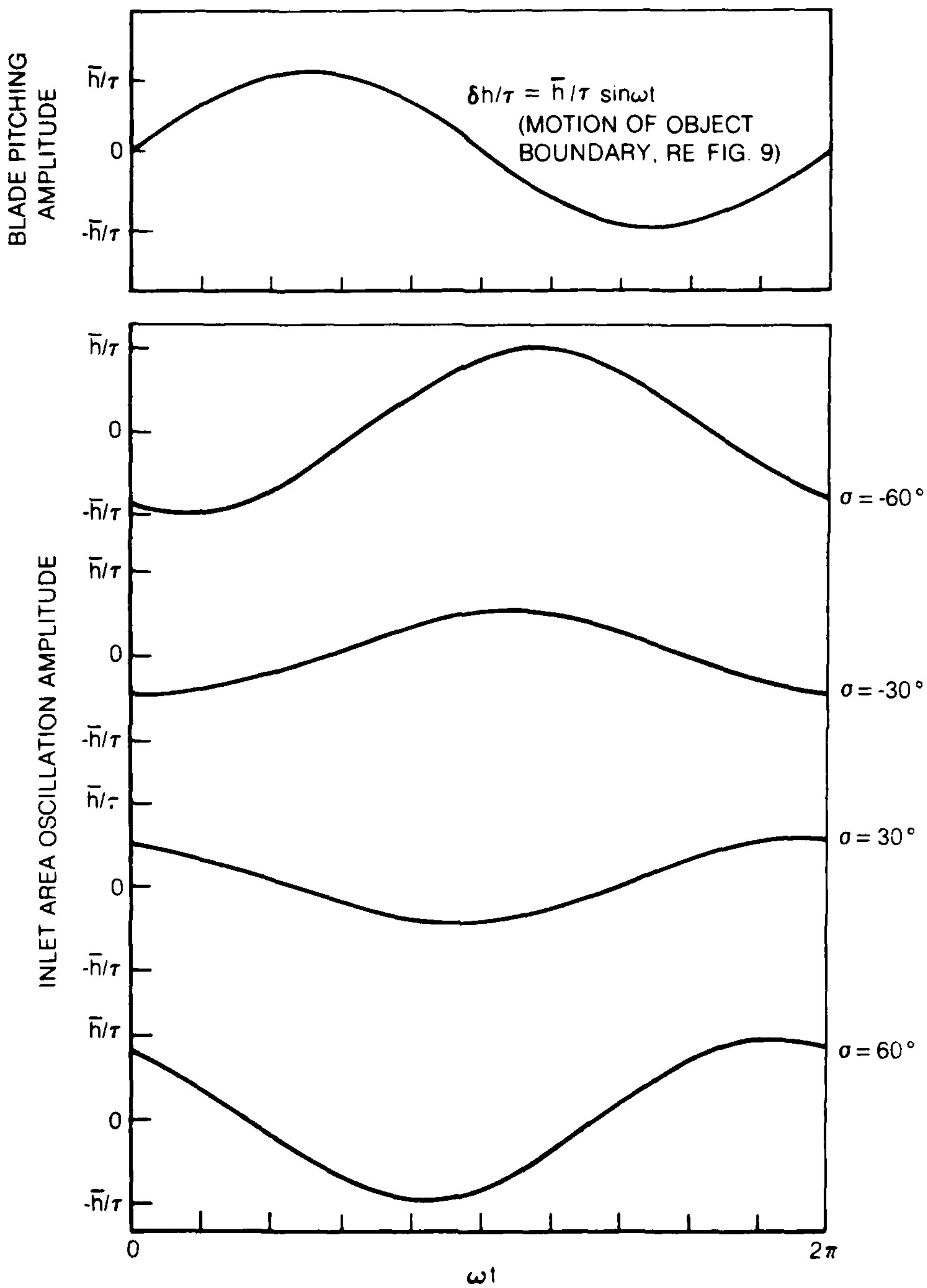

Fig. 10 Influence of Interblade Phase Angle on Inlet Area Motion

80-12-11-9

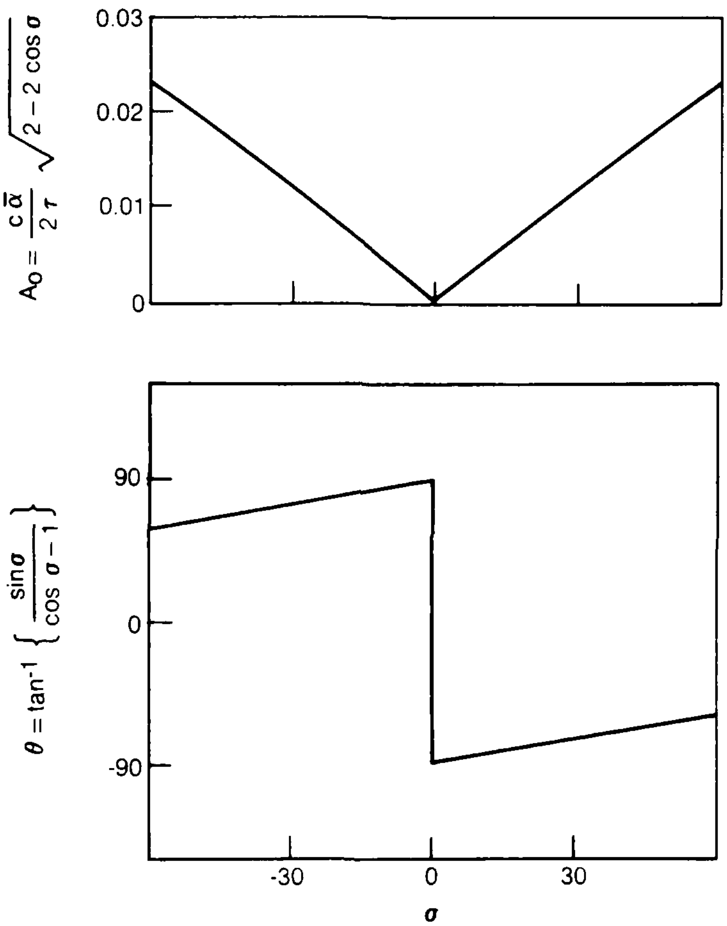

Fig. 11 Inlet Area Amplitude and Phase Angle Variation with Interblade Phase Angle (Eq. 2)

80-12-11-10

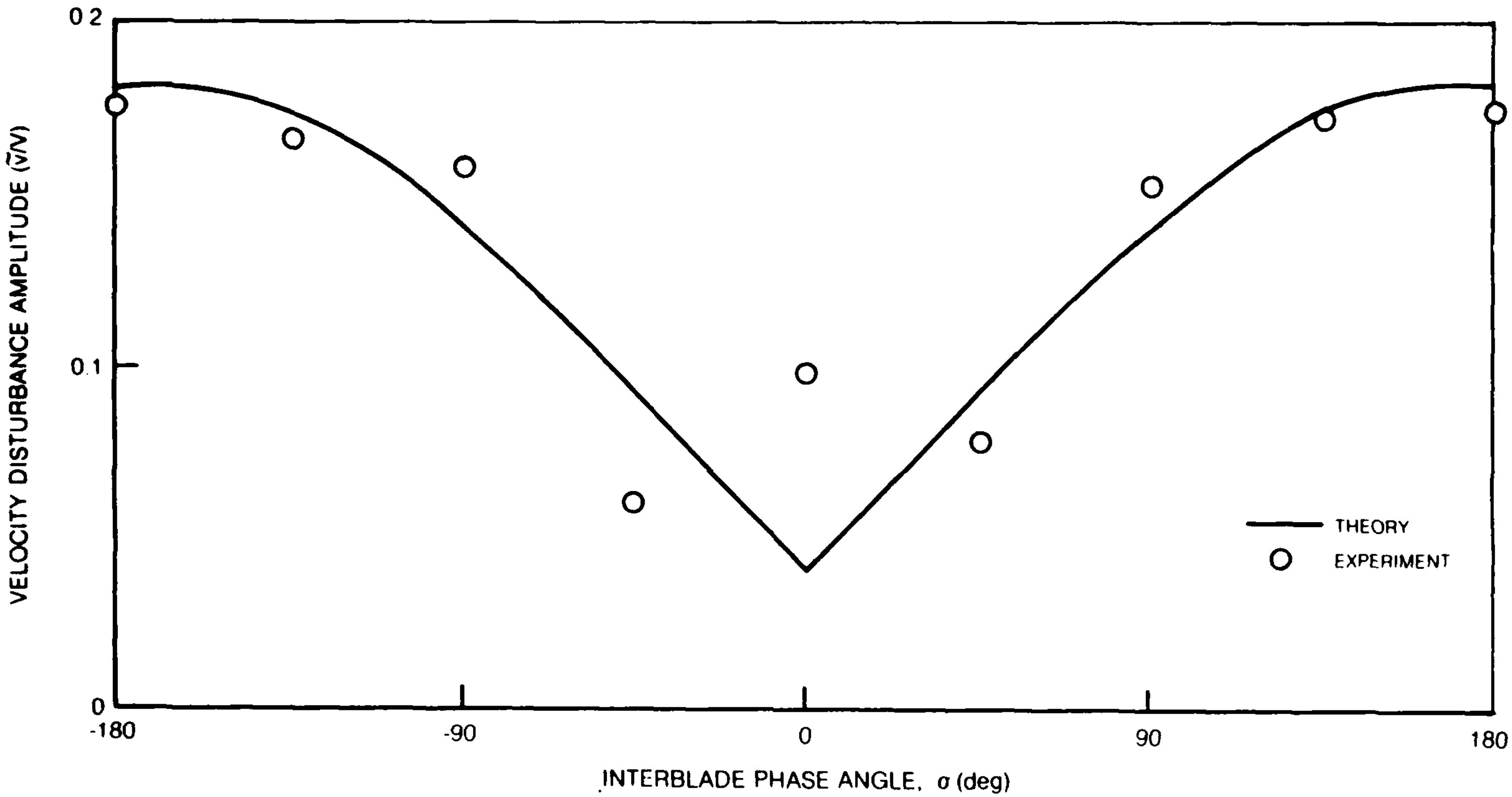

Fig. 12 Qualitative Comparison Between Inlet Plane Response Amplitude (1/8 Gap Station) and Inlet Area Oscillation Amplitude as Functions of Interblade Phase Angle (See Ref. 9 for Data Source). $k_c = 0.12$; $\alpha_M = 2$ deg; $\bar{\alpha} = 2$ deg; $\tau/c = 0.75$

80-12-11-19

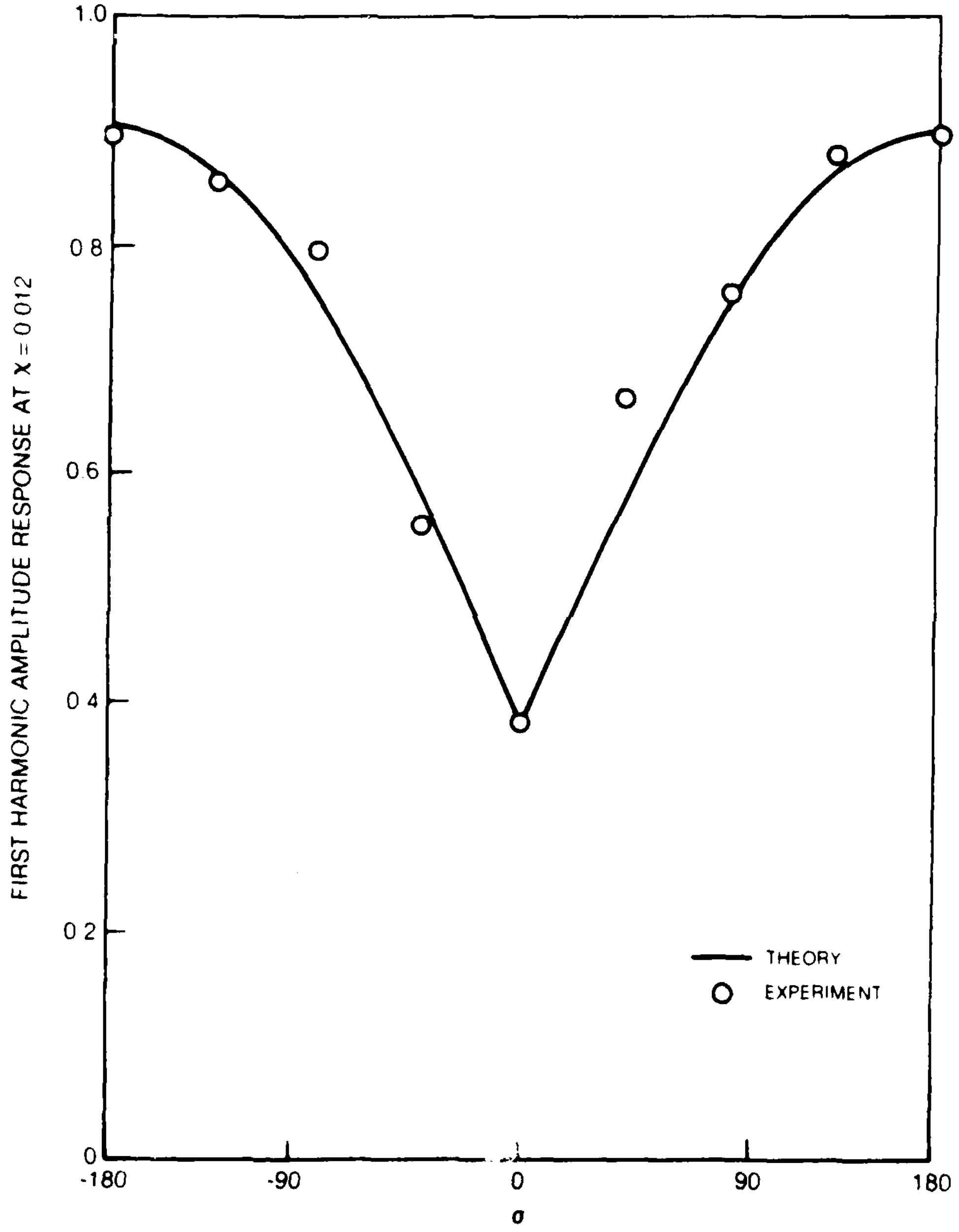

Fig. 13 Qualitative Comparison Between Leading Edge Suction Surface Response Amplitude ($X = 0.012$) and Inlet Area Oscillation Amplitude as Functions of Interblade Phase Angle. (See Ref. 9 for Data Source).
$k_c = 0.12$; $\alpha_M = 2$ deg; $\bar{\alpha} = 2$ deg; $\tau/c = 0.75$

80-12-11-11

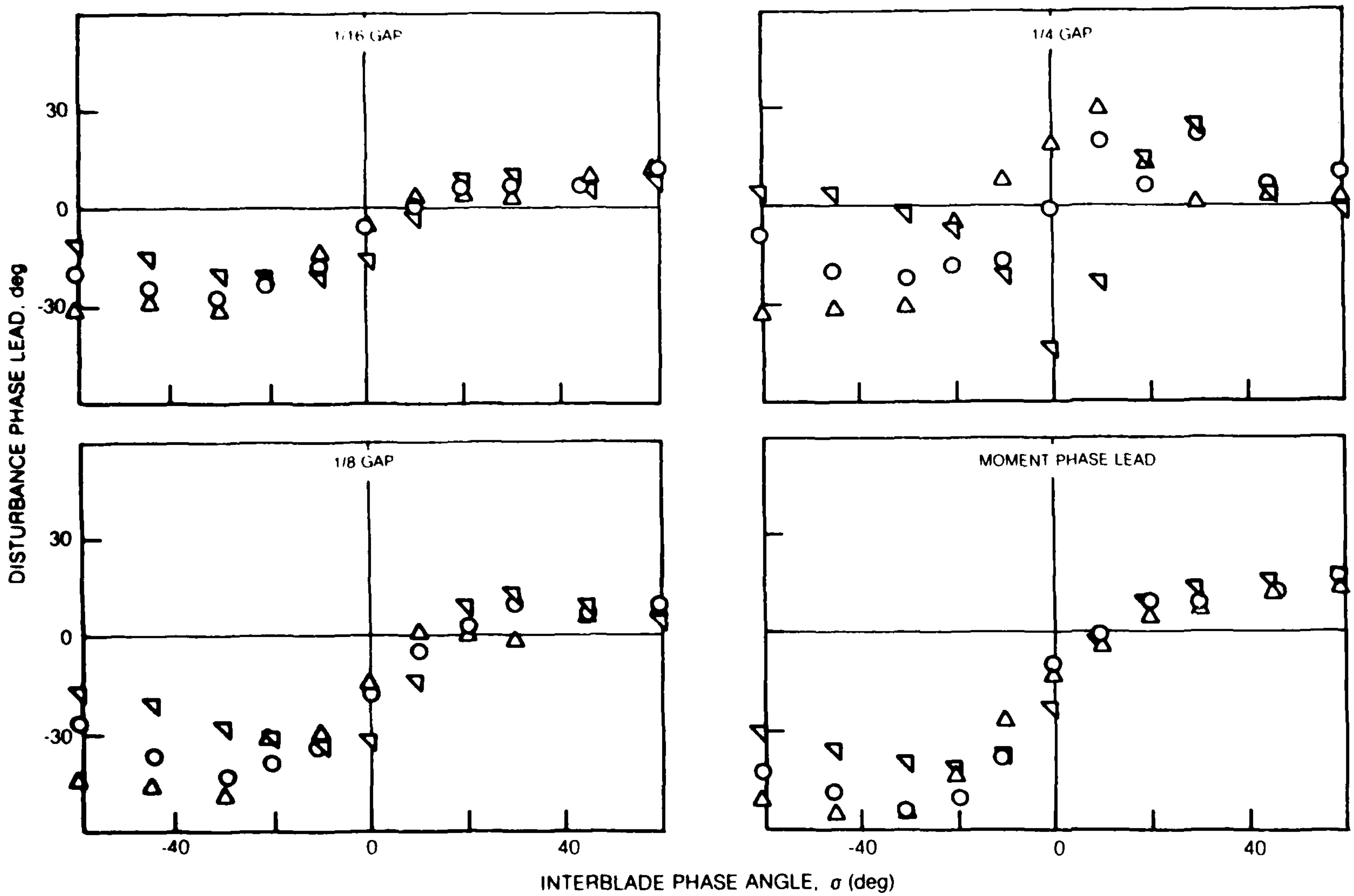

Fig. 14 First Harmonic Phase Lead of Inlet Plane Disturbance as a Function of Interblade Phase Angle ($\alpha_M = 6$ deg). k_c: ▽, 0.07; ○, 0.13; △, 0.19

80-12-11-8

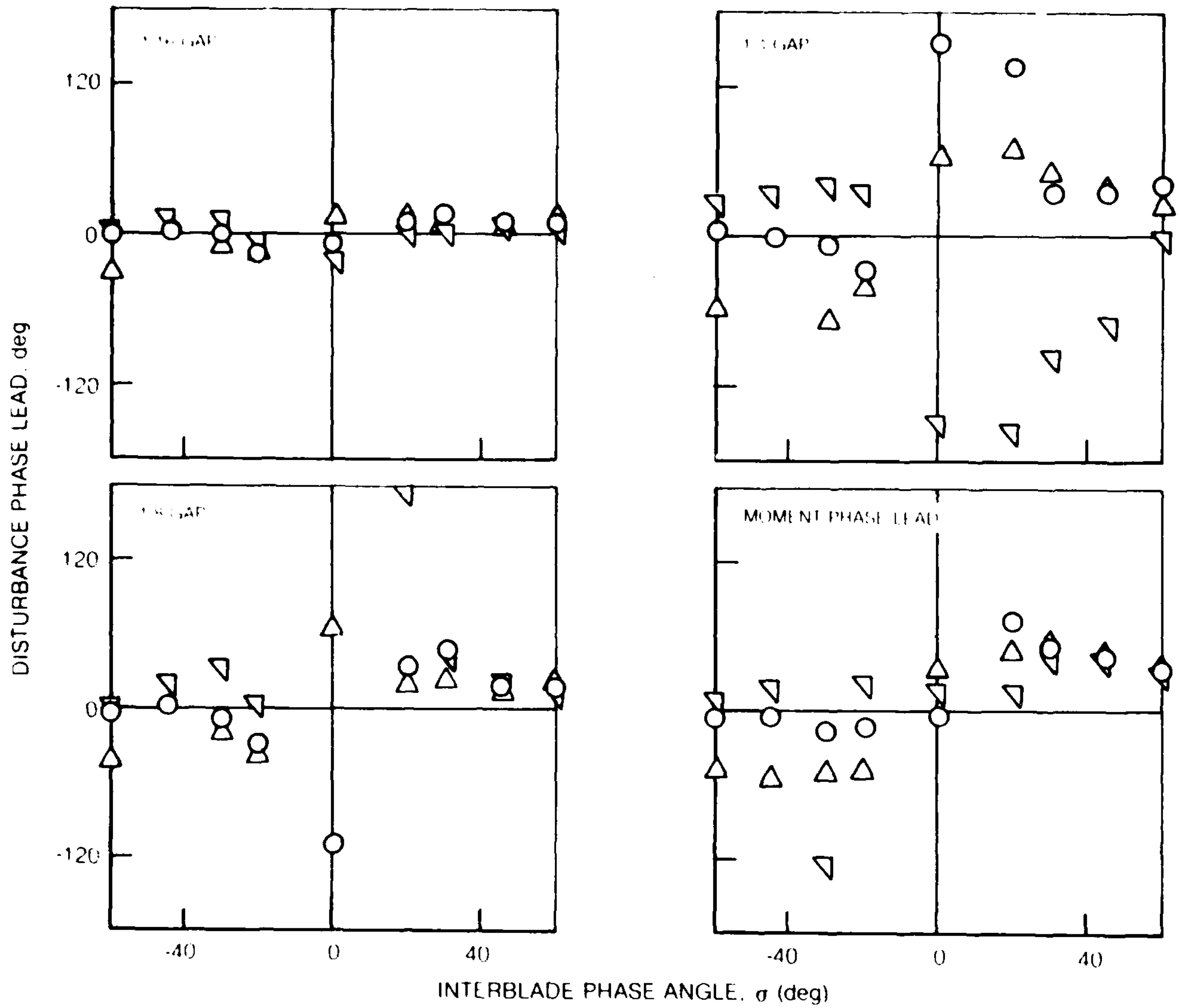

Fig. 15 First Harmonic Phase Lead of Inlet Plane Disturbance as a Function of Interblade Phase Angle ($\alpha_M = 10$ deg). k_c: ▽, 0.07; ○, 0.13; △, 0.19

80-12-11-1

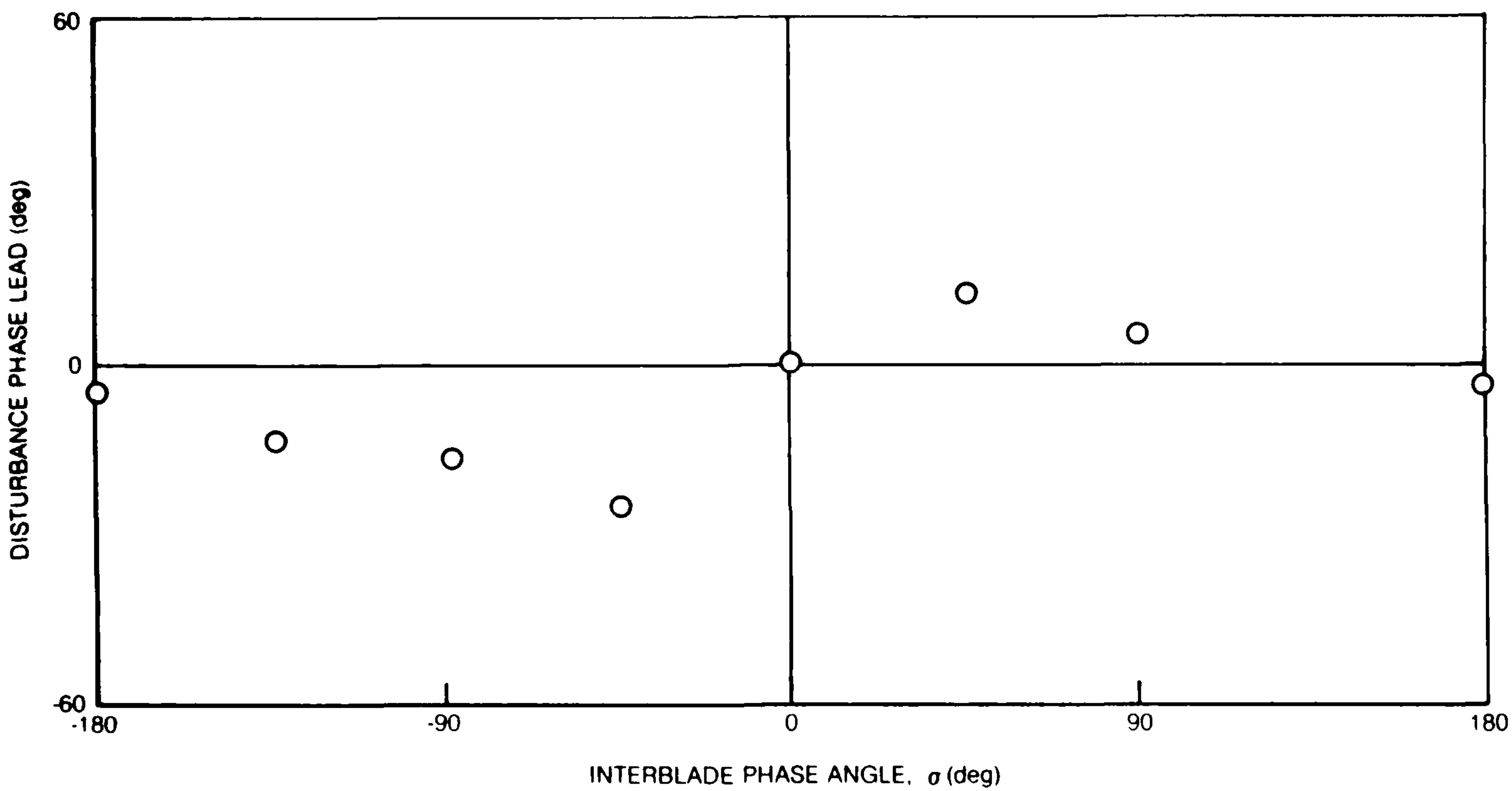

Fig. 16 First Harmonic Phase Lead of Inlet Plane Disturbance at the 1/8 Gap Station as a Function of Interblade Phase Angle (See Ref. 9 for Data Source).
$k_c = 0.12$; $\alpha_M = 2$ deg; $\bar{\alpha} = 2$ deg; $\tau/c = 0.75$

80-12-11-17

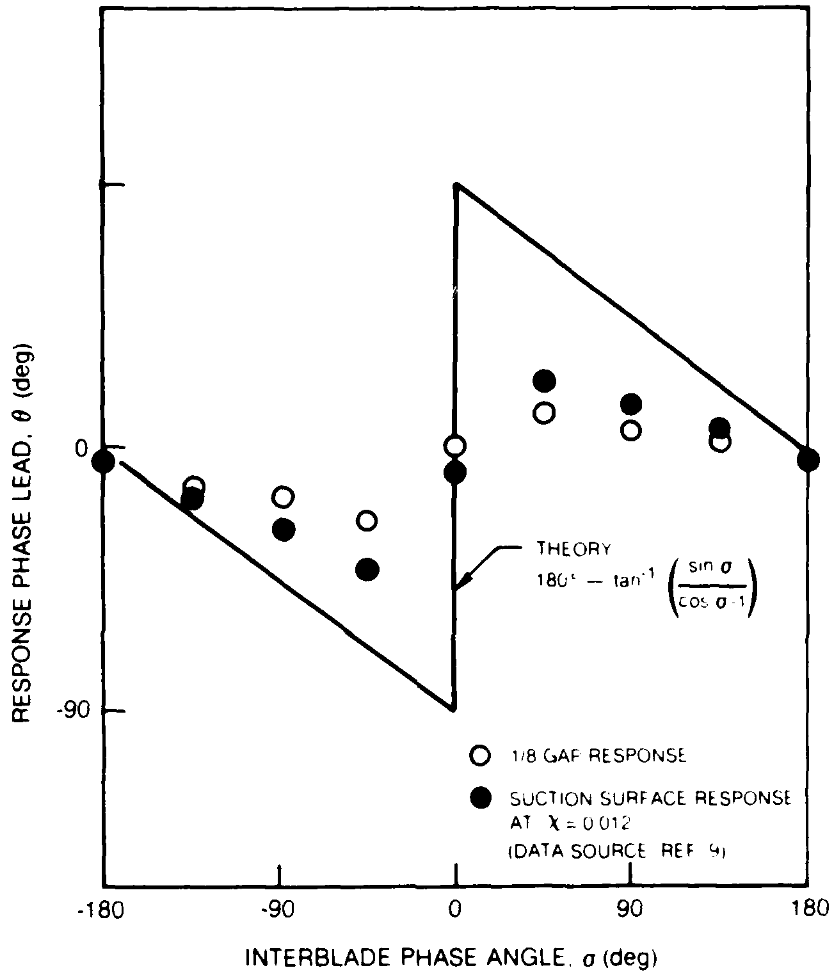

Fig. 17 Comparison of Trend in Inlet Area Phase Lead with First Harmonic Components of Inlet Plane Disturbance (1/8 Gap Station) and Suction Surface Response ($\chi = 0.012$). $k_c = 0.12$; $\alpha_M = 2$ deg; $\bar{\alpha} = 2$ deg; $\tau/c = 0.75$

80-12-11-16

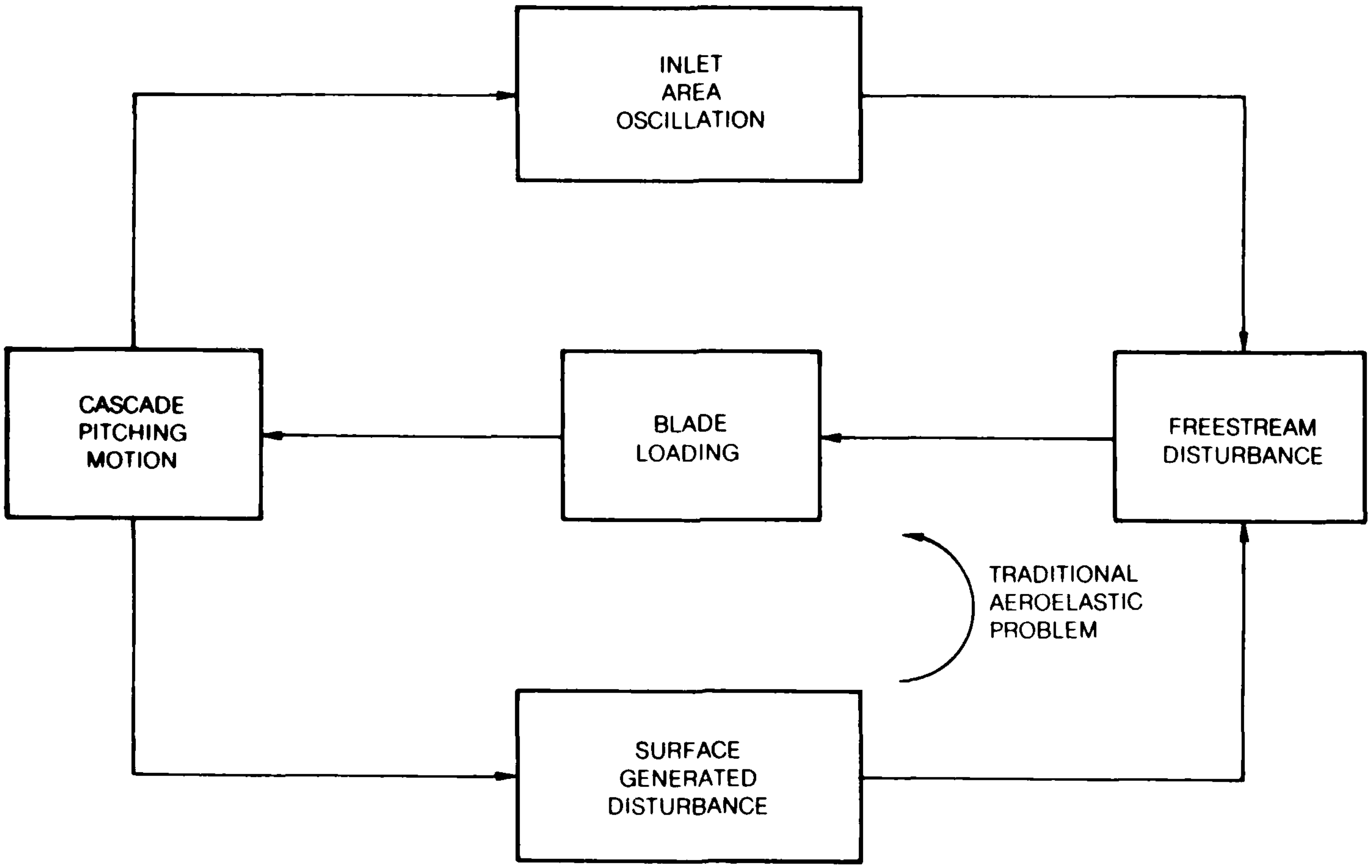

Fig. 18 Schematic of Aeroelastic Coupling Mechanism

80–12–11–12

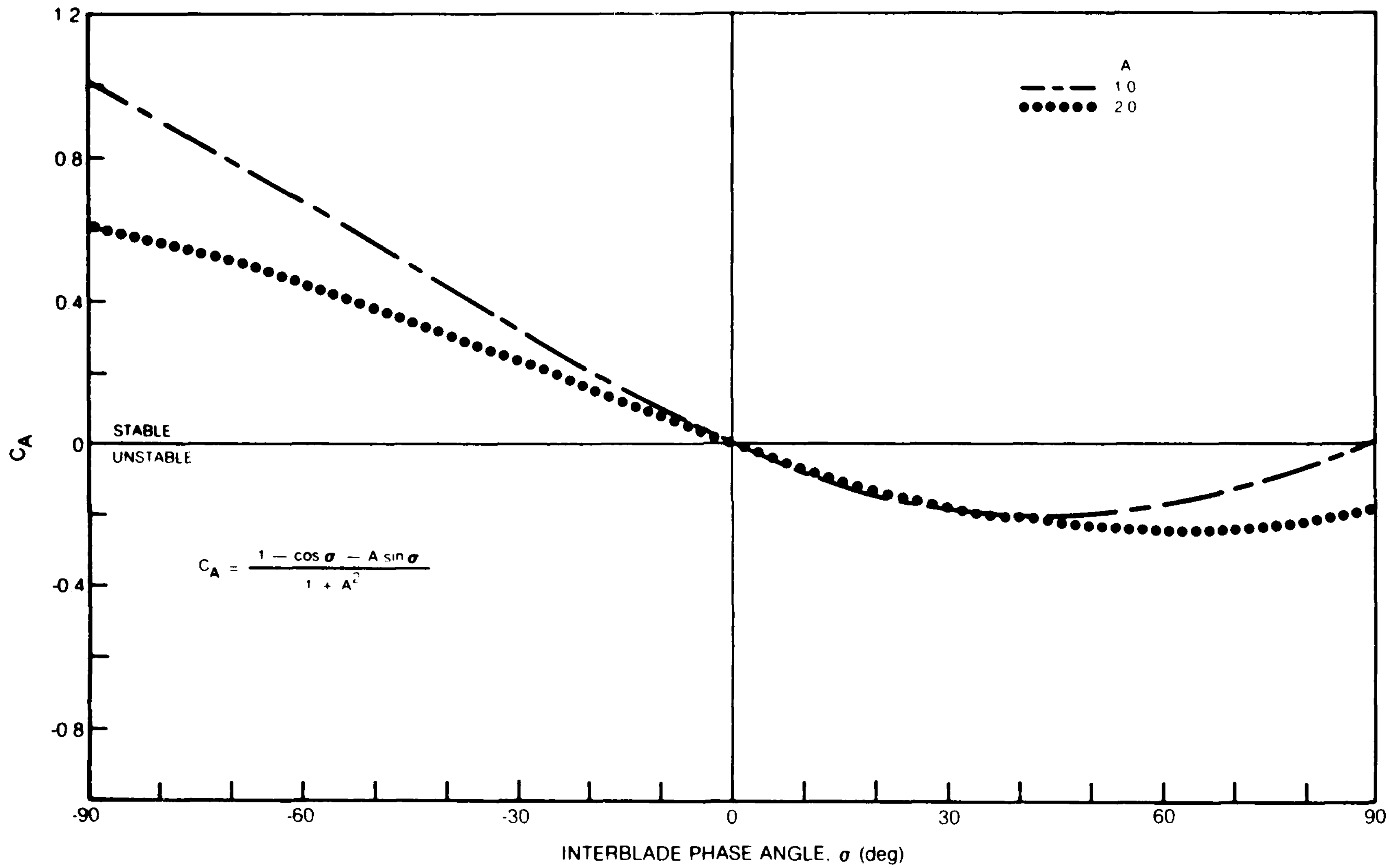

Fig. 19 The Effect of A on the Induced Loading Parameter, C_A

80-4-10-5

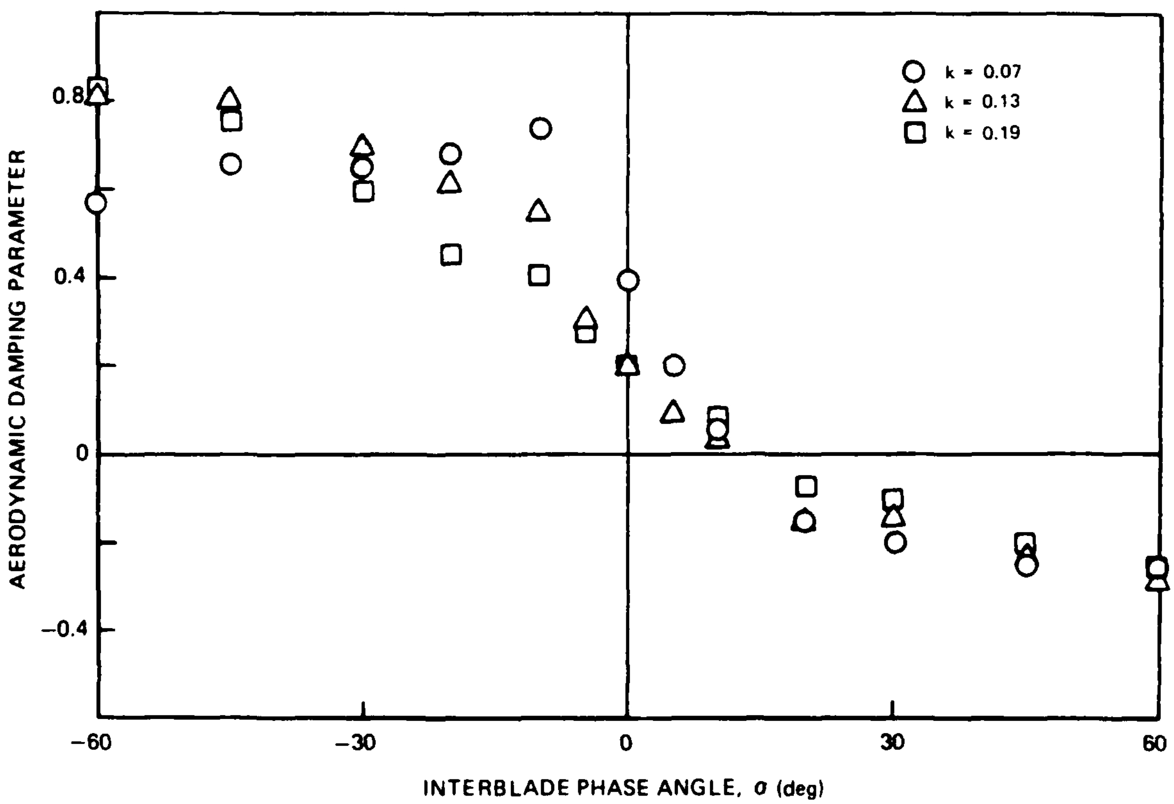

Fig. 20 Variation of Aerodynamic Damping Parameter with Interblade Phase Angle at α_M = 6 deg.

79–04–189–13

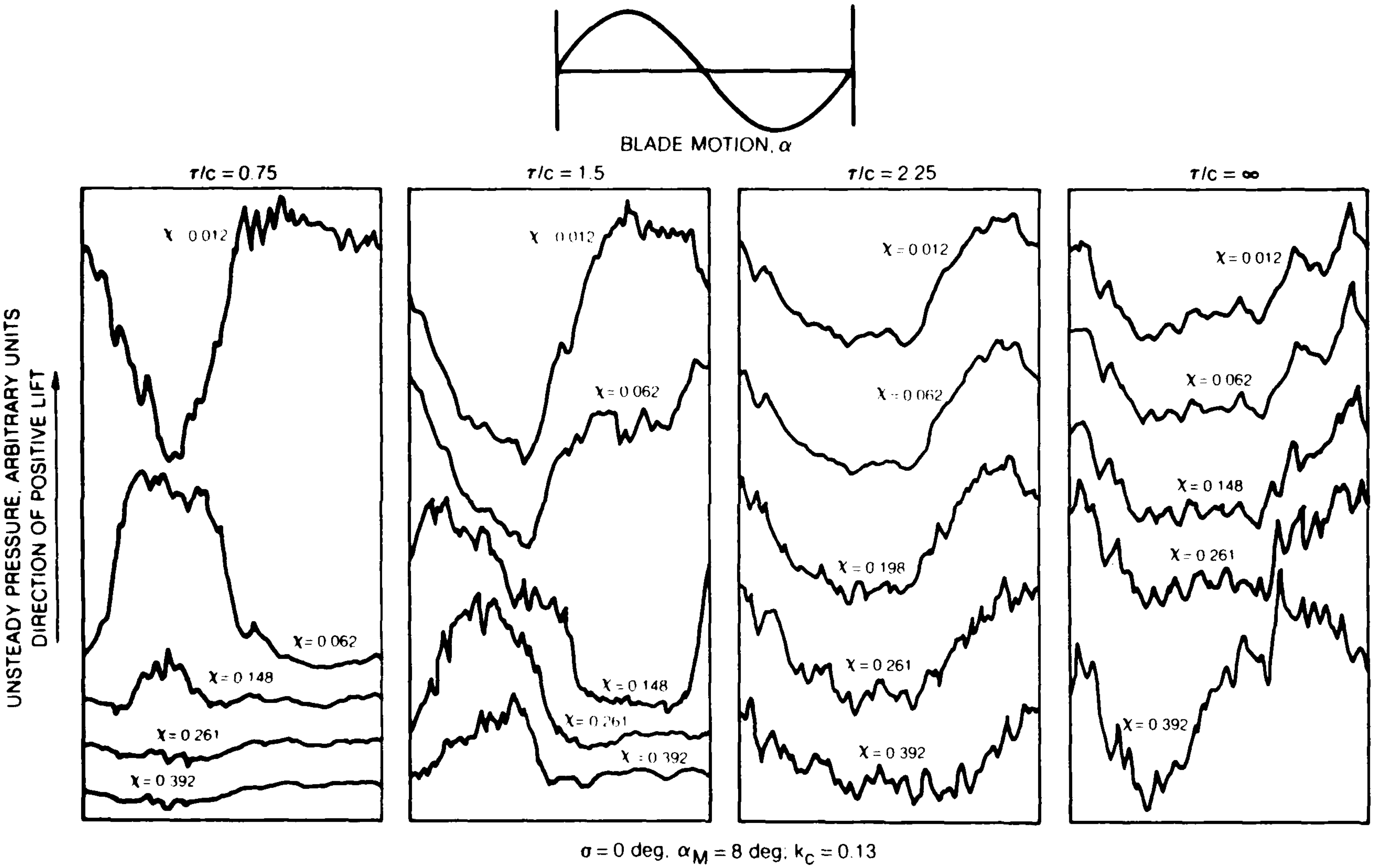

Fig. 21 Effect of Gap-to-Chord Ratio on Suction Surface Pressure Responses Over Forward 40 Percent Chord

80-12-11-13

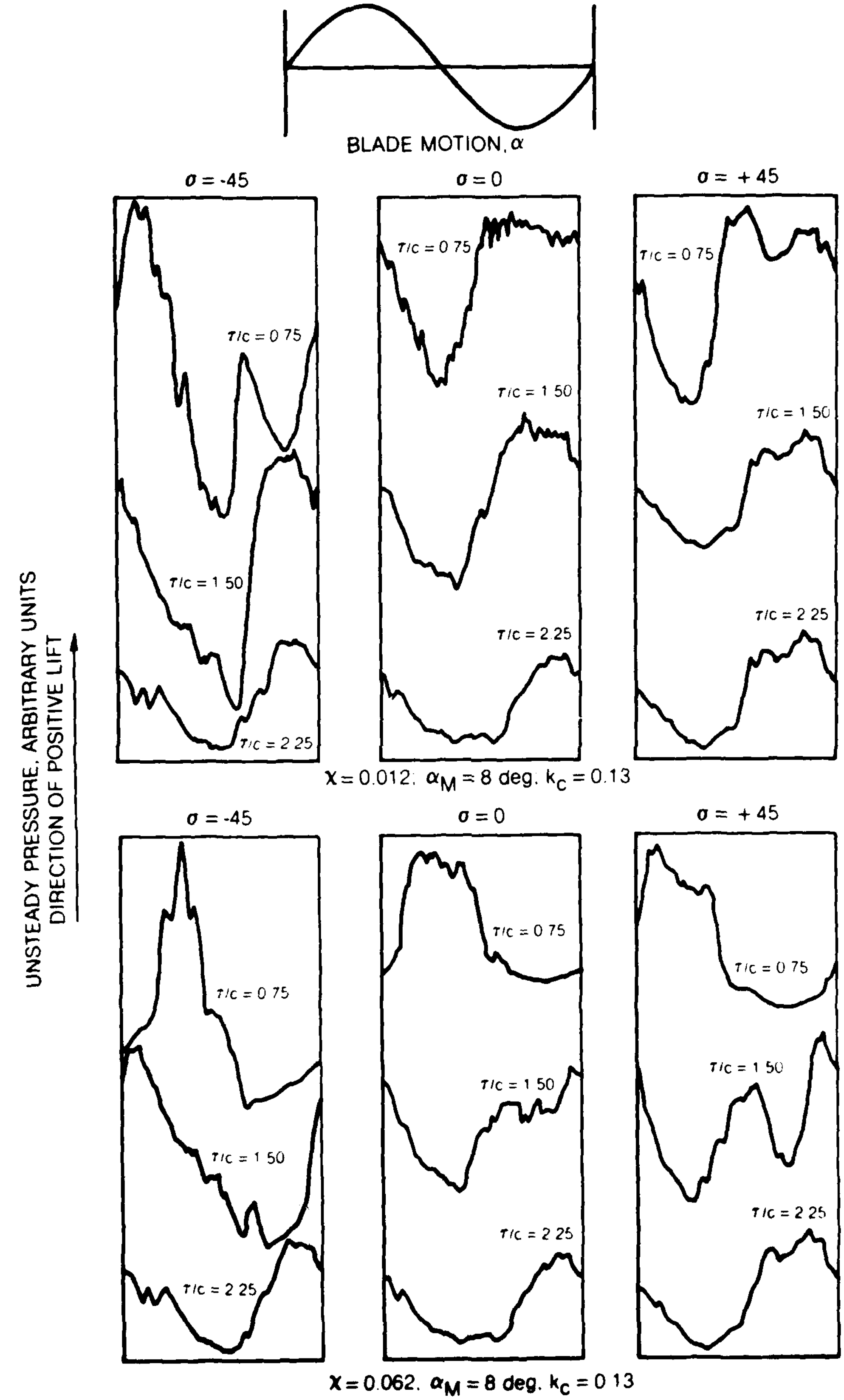

Fig. 22 Effect of Gap-to-Chord Ratio on Pressure Response

80-12-11-14

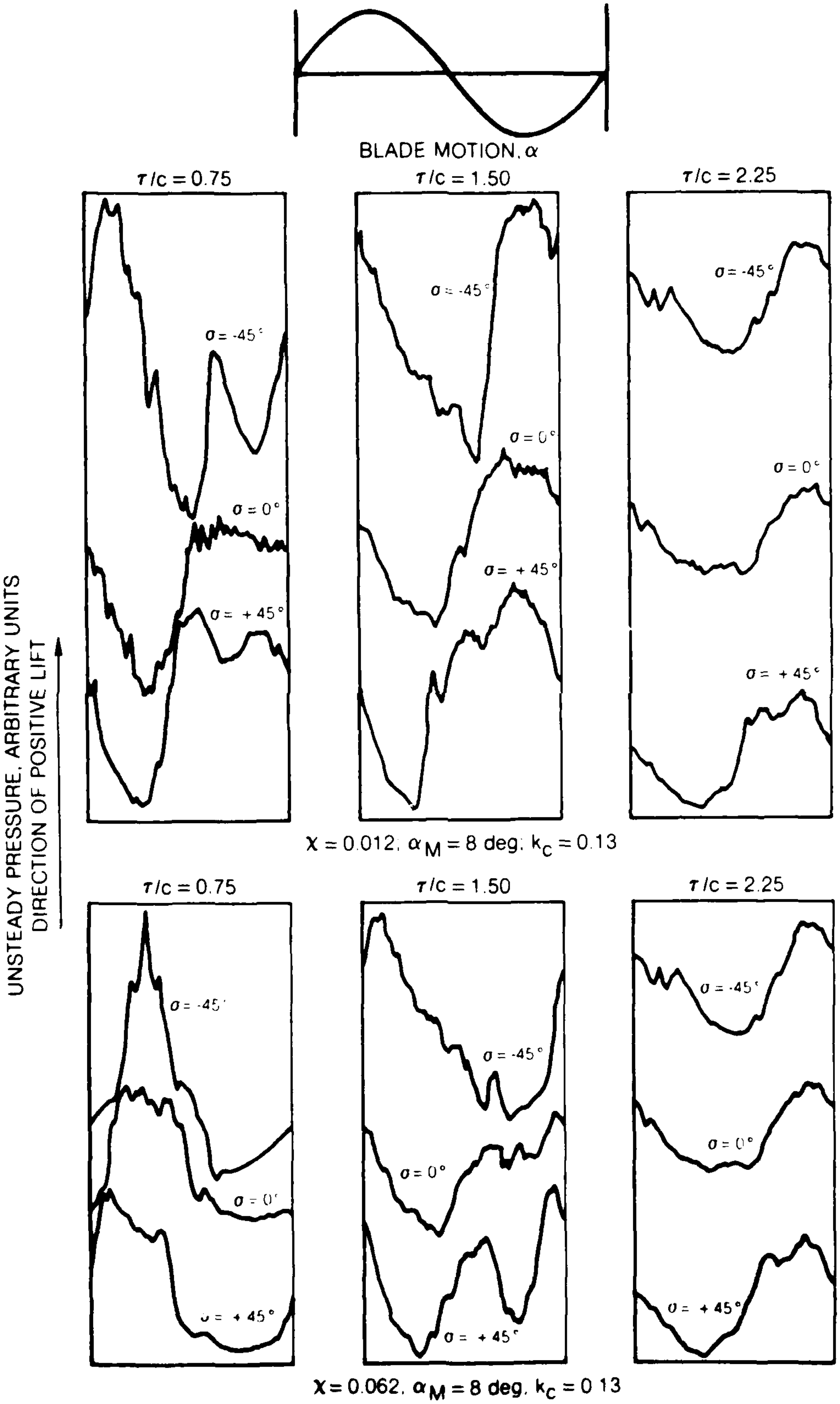

Fig. 23 Effect of Interblade Phase Angle on Pressure Response

80-12-11-16

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