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by

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AN HYPOTHESIS FOR THE PREDICTION OF FLIGHT PENETRATION OF WING BUFFETING FROM DYNAMIC TESTS ON WIND TUNNEL MODELS

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D. G. Mabey

SUMMARY

Buffeting coefficients appropriate to the maximum flight penetration of wing buffeting for both transport and fighter type aircraft are deduced from the comparison of flight observations and measurements of unsteady wing-root strain on stiff wind tunnel models. The buffeting coefficients thus deduced are appropriate for predictions of buffet penetration on future aircraft. These predictions are likely to be particularly useful for comparative tests on project models with alternative wing designs.

The necessary buffeting coefficients are derived rapidly from the unsteady wing-root strain measurements. The tunnel unsteadiness (which must be known) is used as a given level of aerodynamic excitation to calibrate the model response at the wing fundamental frequency; a detailed knowledge of the structural characteristics of the model is thus not required.

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* Replaces RAE Technical Report 70189 - ARC 32684.

CONTENTS

1 INTRODUCTION

Dynamic tests on a stiff wind tunnel model can give useful predictions for buffet onset boundaries on aircraft[1] if scale effects on the boundary layer development are small, and if the tunnel unsteadiness does not exceed the criteria specified in Ref.2. In addition to buffet onset boundaries, maximum flight penetration boundaries for transport and strike aircraft are also of current interest. These penetration boundaries should be related in some way with the severity of buffeting loads. The severity of buffeting loads in flight[3,4,5] can also be predicted from dynamic tests on stiff models* if the scale effects on the excitation spectra are small and if the buffet excitation spectra are uncorrelated with the tunnel unsteadiness.

For this classic method[3,4,5] of predicting buffet severity the mass, stiffness and damping on both the model and the aircraft must be fully specified but this information may not be available for the aircraft during early project stages. In the new method described here, also based on measurements of wing-root strain on models, the mass, stiffness and damping need not be specified for either the model or the aircraft. The hypothesis is that the tunnel unsteadiness (which must be known), can be used as a given level of aerodynamic excitation to calibrate the model response at the wing fundamental frequency, and hence to derive buffeting coefficients from the buffeting measurements. These buffeting coefficients are a measure of the generalised force in the wing fundamental mode due to any distribution of pressure fluctuations on the wing. It has been concluded from past experience with 9 aircraft models that levels of buffeting coefficient obtained in this way can be identified appropriate to the maximum flight penetration of buffet for both transport and fighter type aircraft. The buffeting coefficient appropriate to the heavy buffeting limit appears consistent with measurements of normal force fluctuations[6&7].

It is interesting that almost the same buffeting coefficients have been obtained on 2 similar research models at different scale tested at the same Reynolds number but with different structural damping, different wing frequencies and different levels of reference tunnel unsteadiness. This suggests that the basic hypothesis with respect to the use of the tunnel unsteadiness as a scale for the buffet excitation is valid.

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* Ordinary wind tunnel models made with solid wings of steel or light alloy are used for buffeting tests[1,3,4,5]. For these models the high ratio of (model density)/(free stream density) ensures that the structural damping coefficient predominates over the aerodynamic damping coefficient, so that the total damping of the wing fundamental mode is independent of wind velocity and density. This important observation is implicit in equation (1) below.

2 THE RELATION BETWEEN TUNNEL UNSTEADINESS AND THE MODEL RESPONSE

The basic hypothesis is that the response of the model wing to the unsteadiness in the air stream before the onset of significant flow separations on the model can be linearly related to the tunnel unsteadiness (linear systems are generally assumed for response calculations) and that the tunnel unsteadiness does not interfere with the development of the flow separations.

At any angle of incidence above buffet onset the wing responds to both the tunnel unsteadiness and the buffet pressure fluctuations. If we assume that the same linear relationship between the wing response and the tunnel unsteadiness applies between the wing response and the buffet pressures, model response is then a direct measure of the buffet pressures and may be calibrated by the known tunnel unsteadiness. If this hypothesis can be substantiated, curves of unsteady wing-root strain (model response) against angle of incidence can be transformed into curves showing the variation of equivalent excitation or buffeting coefficients on the model. The corresponding excitation below buffet onset is the tunnel unsteadiness function, $\sqrt{nF(n)}$, at the wing fundamental bending frequency f_1.

The tunnel unsteadiness $\sqrt{nF(n)}$ is defined so that the total rms pressure fluctuation coefficient is given by

$$\overline{p^2}/q^2 = \int_{-\infty}^{\infty} nF(n)\, d\,(\log n)$$

where $n = f_1 w/V$

w = tunnel width

V = free stream velocity

and $F(n)$ = contribution to $\overline{p^2}/q^2$ in a frequency band Δf.

The tunnel unsteadiness at the wing fundamental frequency required for this analysis is

$$\sqrt{nF(n)} = p/q(\varepsilon)^{\frac{1}{2}}$$

where p = pressure fluctuation in a frequency band f at frequency f_1

q = $\frac{1}{2}\rho V^2$ kinetic pressure

and ε = analyser bandwidth ratio $\Delta f/f$.

The tunnel unsteadiness function $\sqrt{nF(n)}$, see Ref.2, was measured on the side wall of the closed working section or the top and bottom slotted working section of the wind tunnel. There is some evidence that these measurements approximated pressure fluctuations on the centre line of the wind tunnel which would obviously be preferred for this analysis. It is convenient to relate the model response to the tunnel unsteadiness at a Mach number where the tunnel unsteadiness is highest and most precisely measured. This is generally in the range from M = 0.75 to 0.85 in a transonic wind tunnel, and this is also the range where the severity of buffeting on civil and military aircraft is generally of most importance. However it is advisable to avoid transonic shocks on the model at low angles of incidence and this means that the speed selected to relate the model response with the tunnel unsteadiness should be below the critical Mach number for the wing. As mentioned above, it is essential that at low angles of incidence the model is free of significant sources of local excitation.

The precise relationship between the tunnel unsteadiness in the working section and the model response at low angles of incidence is not clear. Perhaps fluctuations in the angle of incidence on the centre line of the tunnel, rather than pressure fluctuations, should be measured, although these spectra are probably related in some way. These spectra may not be related however if, for example, pressure waves coming from the fan or compressor remote from the working section are planar in the working section[8], because planar pressure waves are unlikely to generate any significant response at the wing fundamental mode. Hence sharp peaks in the tunnel unsteadiness spectrum associated with fans or compressors remote from the working section should not be used to establish the datum level of tunnel unsteadiness. However, in order that tests made in different tunnels may be compared, it is necessary to assume that the value of $\sqrt{nF(n)}$ for the unsteadiness of the tunnel flow bears some fixed relationship to the response of the model at low incidence.

Models can be used for this buffet prediction hypothesis and for the classic method[3,4,5] because they have approximately the correct reduced frequency as the full-scale aircraft, i.e.

$$f_1 \bar{c} \text{ (model)}/f_1 \bar{c} \text{ (aircraft) is approximately equal to } 1$$

and because the wing buffeting is predominantly at the wing fundamental frequency (see Table 1).

3 DETAILS OF ANALYSIS

Fig.1 shows a typical curve of unsteady wing-root strain signal at the wing fundamental frequency f_1, plotted against angle of incidence (taken from Ref.1). If these signals are divided by the appropriate kinetic pressure $q = \frac{1}{2}\rho V^2$, we have, if the flow is insensitive to changes in Reynolds number,

$$\text{wing-root strain signal}/q = C_B(M,\alpha) \tag{1}$$

where $C_B(M,\alpha)$ is a dimensional function of Mach number M which is independent of q at a given M and angle of incidence, if the total damping of the wing fundamental mode is constant[9]. Before the onset of flow separations on the model, most of the curves in Ref.1 and numerous tests in other wind tunnels[10] show that $C_B(M,\alpha)$ is constant equal to $C_B(M,\alpha = 0)$. This is the portion of the model response caused by the tunnel unsteadiness $\sqrt{nF(n)}$ at the appropriate Mach number and the same frequency f_1. If we assume

$$\left.\begin{aligned} C_B(M,\alpha = 0^\circ) &= K\sqrt{nF(n)} \\ \text{then} \qquad C'_B(M,\alpha = 0^\circ) &= \frac{1}{K}\,C_B(M,\alpha = 0^\circ) = \sqrt{nF(n)} \quad , \end{aligned}\right\} \tag{2}$$

where $C'_B(M,\alpha = 0^\circ)$ is dimensionless and $1/K$ is a scaling factor.

This scaling factor is different for every model. It depends on the mass and stiffness distribution of the model, the sensitivity of the strain gauges and the total damping in the fundamental mode. Unfortunately these factors are often not quoted in many buffeting experiments. If the same* scaling factor $1/K$ is applied to the coefficient $C_B(M,\alpha = 0)$ for all other Mach numbers the dimensionless model-response $C'_B(M,\alpha = 0)$ can be directly compared to the tunnel unsteadiness $\sqrt{nF(n)}$. If the scaling factor $1/K$ is also applied to the coefficients $C_B(M,\alpha)$ above buffet-onset, curves of $C'_B(M,\alpha)$ are obtained. Fig.1 shows a typical example. The level $C'_B(M,\alpha = 0)$ represents the tunnel unsteadiness and the model response to that unsteadiness. The subsequent increase in $C'_B(M,\alpha)$ as the angle of incidence increases gives a measure of the integrated pressure fluctuations arising from the wing buffet pressures and

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* It is not necessary to assume the same scaling factor $1/K$ for all Mach numbers. However the assumption of a constant scaling factor provides a severe test of the hypothesis and does effectively allow the best overall match between the tunnel unsteadiness and the model response over a range of Mach numbers.

of the model response to this excitation. Having used the tunnel unsteadiness $\sqrt{nF(n)}$ to establish a datum buffeting scale, this signal must now be subtracted to give the true buffeting level in the absence of tunnel unsteadiness. If the tunnel unsteadiness does not exceed the criteria in Ref.2 there should be no correlation between the tunnel unsteadiness and the wing buffeting and so we can calculate a corrected buffeting coefficient

$$C_B''(M,\alpha) = \sqrt{C_B'(M,\alpha)^2 - C_B'(M,\alpha = 0^\circ)^2} \quad . \tag{3}$$

The angle of incidence at which $C_B''(M,\alpha)$ first differs from zero is buffet onset. Contours of buffeting coefficients are then readily obtained as a function of Mach number and angle of incidence or lift coefficient.

Fig.2 shows a fair correlation between $C_B'(M,\alpha = 0)$ and $\sqrt{nF(n)}$ for most of the models discussed, implying that a simple relationship between the model response and the tunnel unsteadiness is justified and that the damping of the wing fundamental mode does not change much with Mach number. The wind tunnels used include 3 with slotted working sections and 2 with perforated working sections. The poor correlation between $C_B'(M,\alpha = 0)$ and $\sqrt{nF(n)}$ for model D in the RAE 3ft × 2.2ft tunnel is exceptional and implies that the sidewall pressure fluctuations in this case were grossly misleading as regards fluctuations in angle of incidence on the centre line. When these tests were repeated recently in the larger ARA tunnel, where the tunnel unsteadiness on the centre line is known precisely, much better correlation of $C_B'(M,\alpha = 0)$ and $\sqrt{nF(n)}$ was obtained; these curves are also shown in Fig.2.

Indirect verification of the hypothesis is provided by some recent measurements on a research configuration with a high aspect-ratio wing of leading-edge sweep $\Lambda = 27^\circ$. Two models of similar scale were tested at the same Reynolds number with a slightly different transition fix, having different degrees of structural damping, different wing frequencies (90 Hz and 140 Hz) and thus different values of the reference unsteadiness, $\sqrt{nF(n)}$. Both models gave almost identical buffeting contours (Fig.3).

4 COMPARISON OF MODEL BUFFETING CONTOURS AND FLIGHT PENETRATION BOUNDARIES

Figs.4 to 12 show contours of buffeting coefficient C_B'' versus lift coefficient C_L for 9 aircraft models from the flight buffet onset to maximum penetration boundaries. Table 1 derived from these figures shows C_B'' appropriate to maximum penetration and comments on the influence of Reynolds number from the buffet onset and the development of flow separations. For the transport aircraft models (A, B) the buffeting limit corresponds with $C_B'' = 0.006$.

For the fighter aircraft models (C to J) the heavy buffeting limit is higher than for transport aircraft and corresponds with

$$C''_B = 0.012 \text{ to } 0.016 \quad .$$

For the fighter aircraft there is considerable scatter from the flight buffet onset boundary to the $C''_B = 0.004$ contour. Hence for fighter aircraft the following buffeting criteria are suggested:

Buffet onset	C''_B	=	0
Light buffeting	C''_B	=	0.004
Moderate buffeting	C''_B	=	0.008
Heavy buffeting	C''_B	=	0.016.

5 SIGNIFICANCE OF BUFFETING COEFFICIENTS

The order of magnitude of the fluctuating normal force coefficient, C_N rms, on a model with a high aspect ratio unswept wing due to flow separations ought to be given by the corresponding fluctuating pressure-coefficient, which should in turn be of the same order as C''_B, i.e.

$$C_N \text{ rms} = O(C''_B) = O(0.016) \quad . \tag{4}$$

The total rms normal force contours for 7 NACA aerofoils under widely differing buffet conditions are given by Polentz [6] and appear to satisfy equation (4) as the following table shows*.

	Polentz buffet intensity	Present buffeting criteria
	C_N rms	C''_B
Onset	0.005	0
Light	0.010	0.004
Moderate	0.020	0.008
Heavy	0.040	0.016

* Polentz took buffet onset as C_N rms = 0.005, the same level as the tunnel unsteadiness signal and the maximum discrimination of his measurements. The tunnel unsteadiness level for these tests apparently satisfied the criteria specified in Ref.2.

Similarly Fig.13 shows that the maximum fluctuating normal force, C_N rms, at a low frequency parameter, on a series of delta wings at vortex breakdown conditions[7] varies from $\sqrt{nG(n)}$ = 0.008 to 0.010 for $\Lambda = 45^o$ to $\sqrt{nG(n)}$ = 0.014 to 0.019 for $\Lambda = 70^o$. Hence equation (4) appears to be valid for these two extreme classes of wings with different separated flows; the heavy buffeting limit can thus be given a general physical significance. It is interesting to note that the light buffeting limit suggested for fighter aircraft, $C_B'' = 0.004$, is of the same magnitude as the maximum pressure fluctuations associated with an attached turbulent boundary layer ($0.002 < \sqrt{nF(n)} < 0.003$).

6 DISCUSSION

The correlations established between buffeting contours and maximum flight penetration in Figs.4 to 12 are surprising because it might reasonably be expected that the severity of buffeting in flight would be based on the dimensional level of vibration (either estimated by the pilot or measured by an accelerometer), rather than a dimensionless buffeting coefficient. There are two alternative explanations for the correlations established. Either

(1) the severity of wing buffeting is not really the limiting factor so that the pilots of fighter or strike aircraft tend to fly right up to a handling boundary, such as pitch/up (as on aircraft E and F) or stalling (as on aircraft C). This handling boundary might coincide with the heavy buffeting contour. Or,

(2) the pilot may instinctively include in his assessment buffeting a 'q' factor, as he tends to do in the application of steady loads to the aircraft.

If he does introduce a 'q' factor, pilot-defined boundaries for light, moderate and heavy buffeting at constant altitude would be uniformly spaced above the buffet onset boundary where Mach number effects are small, and correspond with constant values of pressure-fluctuation coefficients measured in the tunnel and hence of buffeting coefficients, C_B'' (cf. Fig.14 for the Venom aircraft with the sharp-leading-edge, Ref.11).

The pilots of transport aircraft generally sit further from the nodal points of the wing fundamental mode than pilots of fighter or strike aircraft and would not wish to approach a handling boundary, even if sufficient thrust was available. Thus for transport aircraft the maximum penetration coefficient $C_B'' = 0.006$ seems more reasonable than the value of 0.016 for fighter aircraft. This limit for maximum buffet penetration for transport aircraft of $C_B'' = 0.006$ is based on measurements on only two models and may need to be revised as additional tunnel/flight comparisons become available for this class of aircraft.

Although the present hypothesis is believed to offer a quick estimate of buffet penetration limits for transport and fighter type aircraft from tunnel measurements of unsteady wing-root strain, the method of Refs.3, 4 and 5 is still needed to compare tunnel and flight buffet loads. Both these methods must assume the absence of significant Reynolds number effects from model to full scale, although there is no doubt that the complex mixed flows which generally appear during buffet penetration are likely to be somewhat scale sensitive, particularly at transonic speeds. In addition both methods assume that in flight the buffet manoeuvre is stabilized (or steady in a statistical sense). In fact this can be rarely true for the buffet penetration of transport aircraft and is quite difficult to achieve even on fighter aircraft.

7 CONCLUSIONS

Buffeting coefficients appropriate to the maximum flight penetration of wing buffeting for both transport and fighter type aircraft have been deduced from the comparison between flight observations and tunnel measurements of unsteady wing-root strain using models. The buffeting coefficients thus deduced may now be used for predictions of buffet penetration limits for future aircraft. These predictions will be particularly useful during comparative tests for projects with alternative wing designs.

The necessary buffeting coefficients are derived rapidly from the unsteady wing-root strain measurements. The tunnel unsteadiness (which must be known) is used as a given level of aerodynamic excitation to calibrate the model response at the wing fundamental frequency; a detailed knowledge of the structural characteristics of the model is thus not required.

However, as in many other types of test using models significant scale effects can occur between model and full-scale. The use of buffeting coefficients as a criterion also implies a degree of similarity between the type of structure used on the aircraft involved in the analysis and on the particular aircraft under review. In addition the hypothesis itself involves many assumptions which are not readily verifiable, so some care is needed in its application.

Table 1

ASSESSMENT OF BUFFET PENETRATION CRITERIA

Aircraft type	Model	Wing frequency f_1		C''_B for maximum flight penetration	Reynolds number effects	
		(Hz)	$\frac{(f_1\ c)\ m}{(f_1\ c)\ a}$		Buffet onset	Separation development
Transport	A	287	1.26	0.004-0.006	Yes - small	Large
	B	360	1.48	0.006	Yes - small	Unknown
Fighter/Strike	C	580	1.42	0.014	No	Unknown
	D	260	0.84	0.014-0.008	No	Unknown
	E	526	1.50	0.012	No	Large effect inferred from pitch-up differences
	F	665	1.15	0.006	Yes - small	Very large
	G	204	1.58	0.012	Yes - large	Unknown
	H	283	0.75	0.010	Yes - large	Unknown
	I	323	1.50	No heavy buffeting	Yes - large	Significant
	J (Unpublished)	155	1.22	0.016	Yes - large	Unknown

SYMBOLS

$\bar{c}$	average wing chord
C_B, C'_B, C''_B	buffeting coefficients equations (1), (2) and (3)
C_L	lift coefficient
C_N	normal force coefficient
C_N rms	rms normal force coefficient
f_1	wing fundamental frequency Hz
$1/K$	transformation factor equation (2)
$\sqrt{nF(n)}$	tunnel unsteadiness at frequency $f_1 = p/q(\varepsilon)^{\frac{1}{2}}$
$F(n)$	contribution to $\overline{p^2}/q^2$ in frequency band Δf
$G(n)$	contribution to C_N rms in frequency band Δf
M	Mach number
n	$f_1 w/V$ frequency parameter
p	pressure fluctuation in tunnel at frequency f_1
$\bar{p}$	rms pressure
$q/ = \frac{1}{2}\rho\ V^2$	kinetic pressure
R	Reynolds number on $\bar{c}$
V	velocity
w	tunnel width
ε	analyser bandwidth ratio $\Delta f/f$
α	angle of incidence
ρ	density

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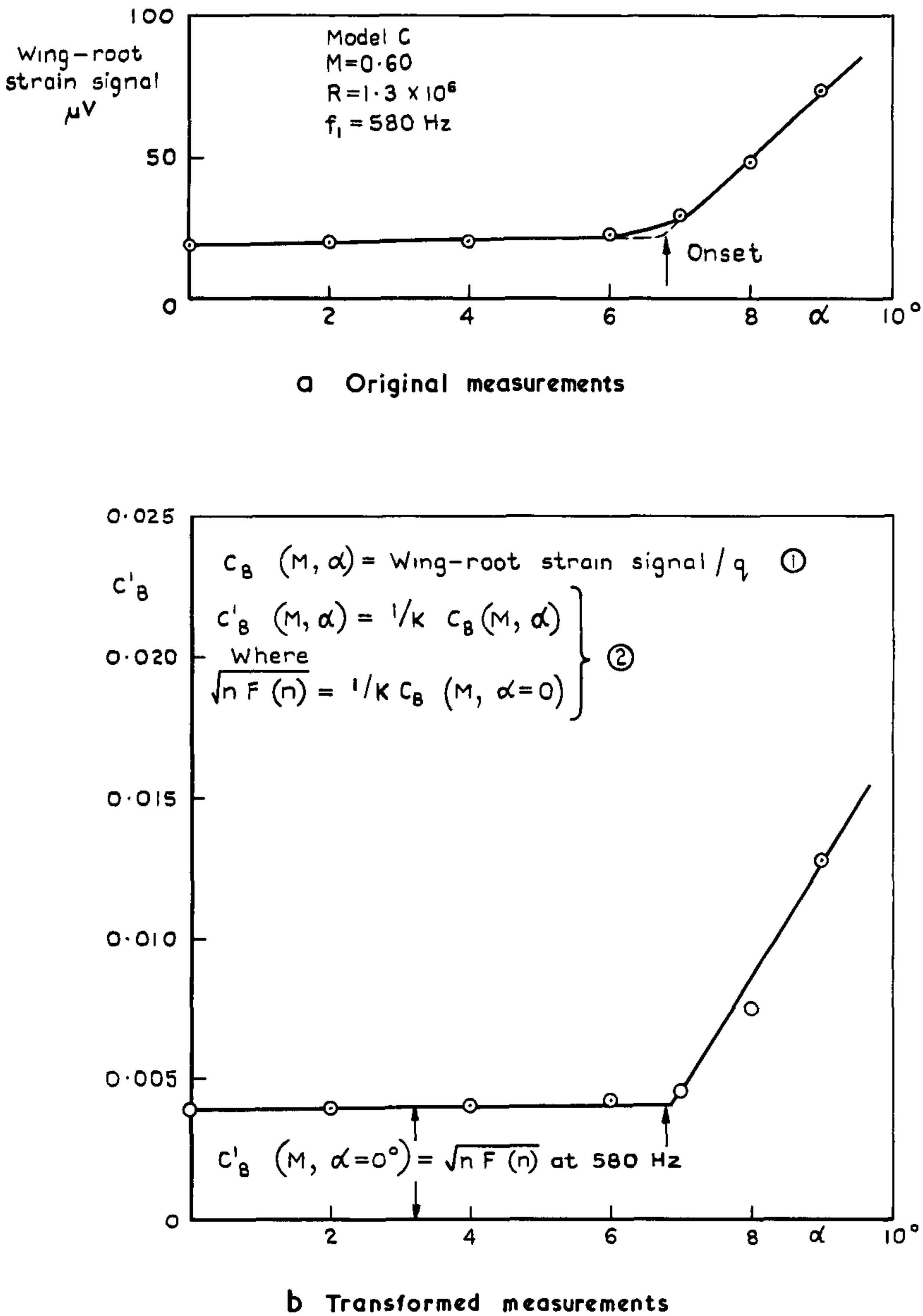


Fig.1a&b Definition of buffeting coefficients

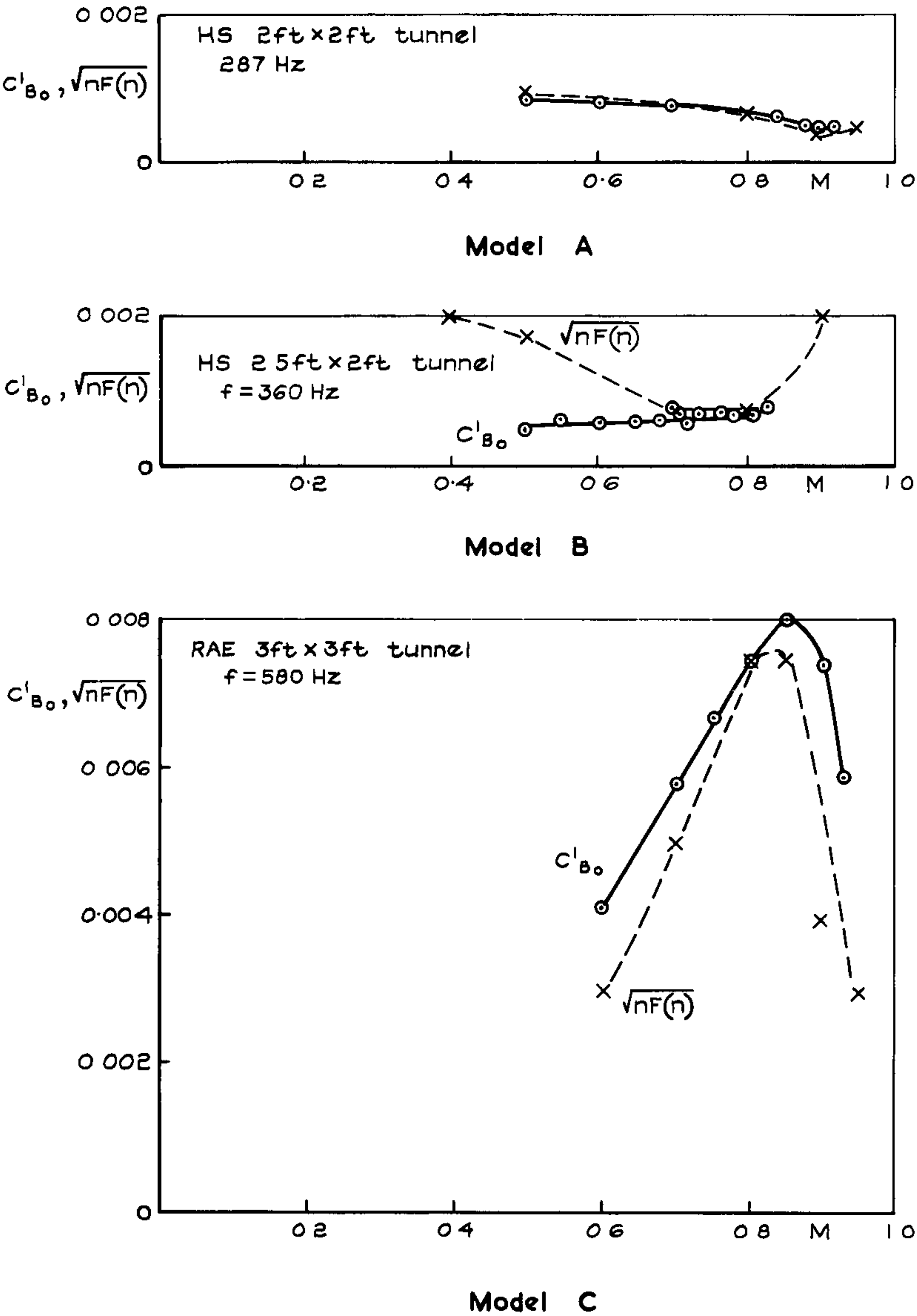
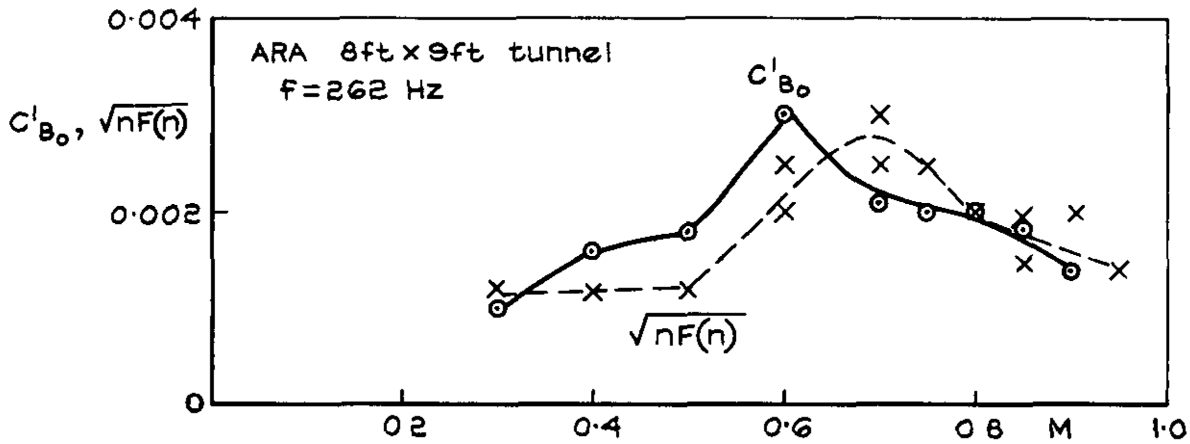
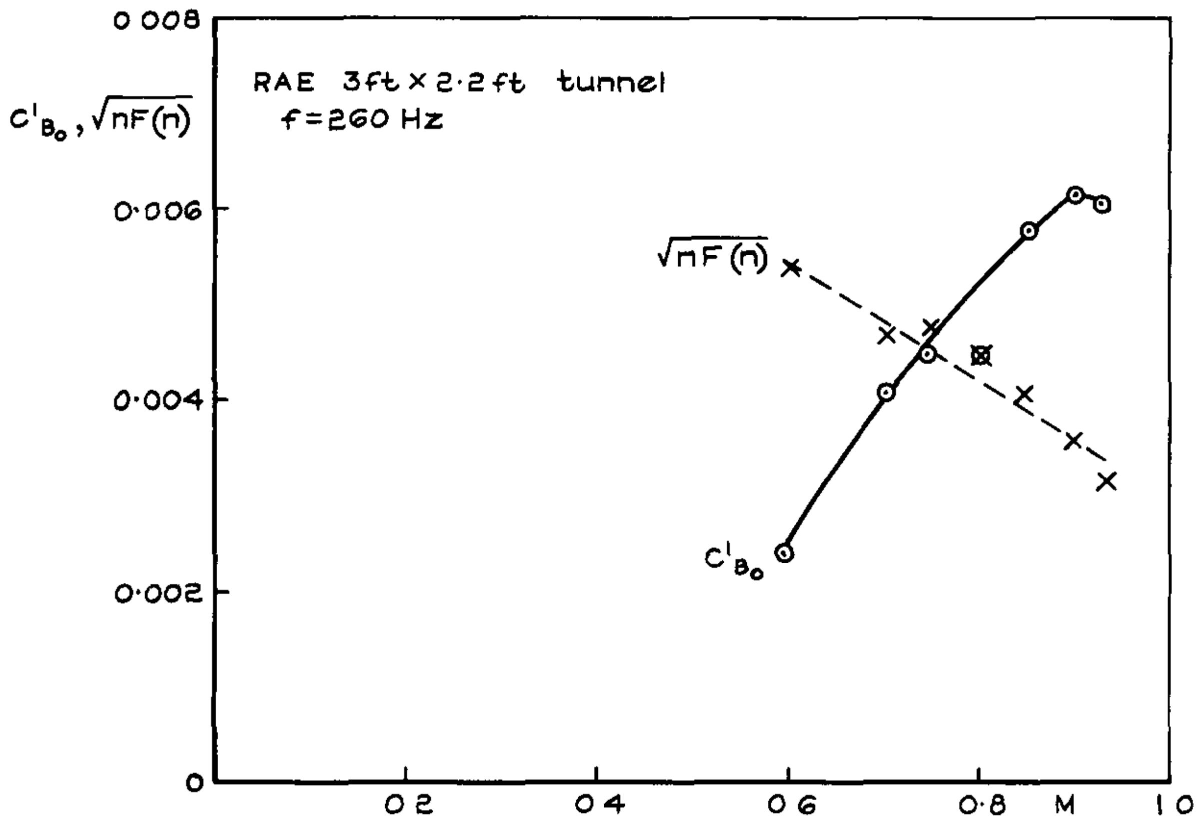


Fig. 2 Variation of C'_{B_0} and $\sqrt{nF(n)}$ with Mach number for different models

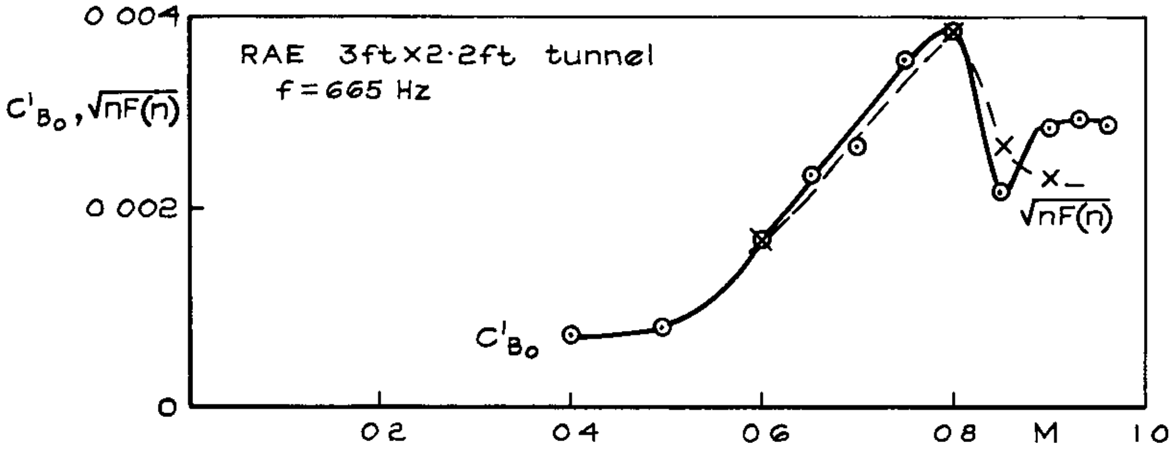


Model D

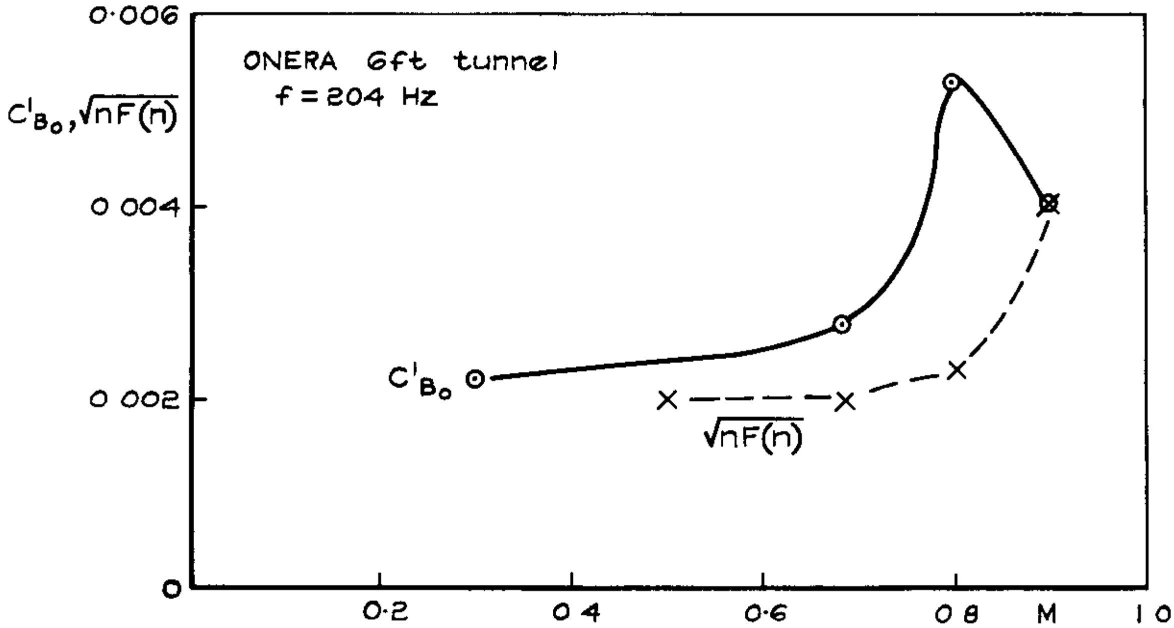


Model D

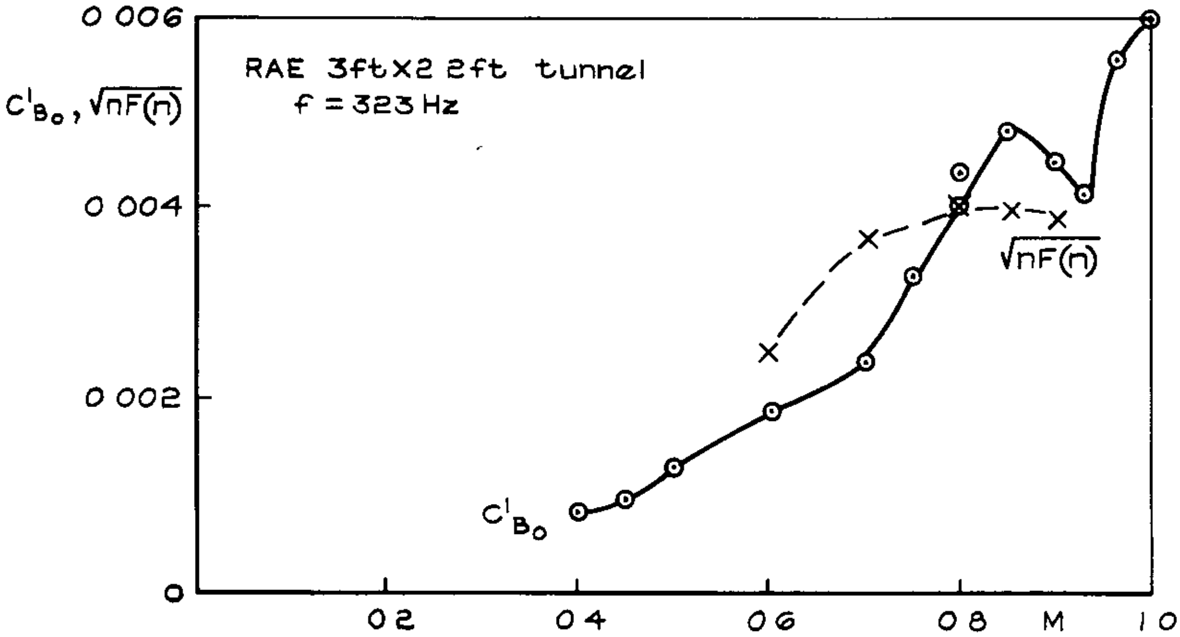
Fig. 2 cont Variation of C'_{B_0} and $\sqrt{nF(n)}$ with Mach number for different models



Model F



Model G



Model I

Fig. 2 concld Variation of C'_{B_0} and $\sqrt{nF(n)}$ with Mach number for different models

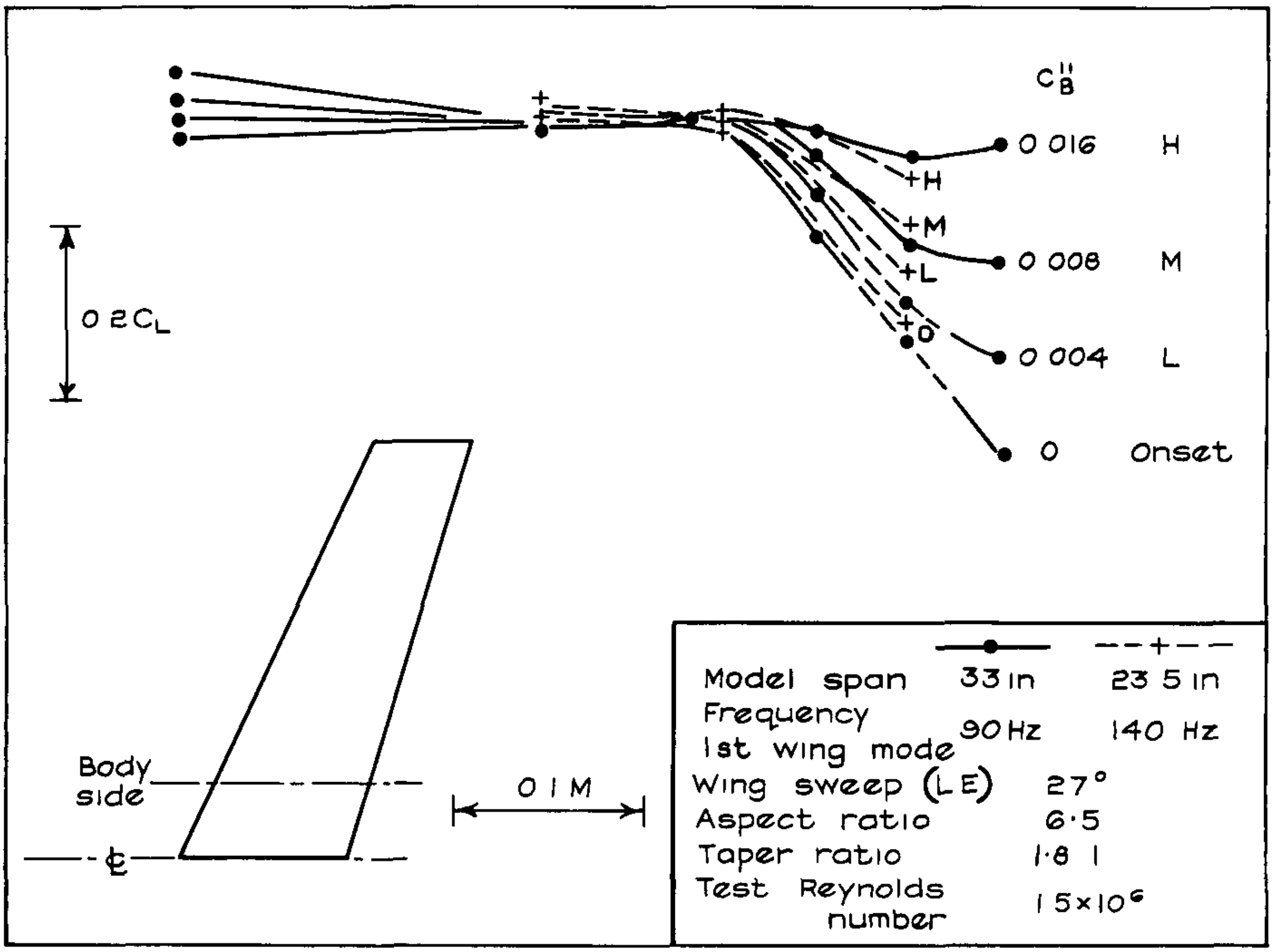


Fig. 3 Contours of buffeting for two similar models of differing scale

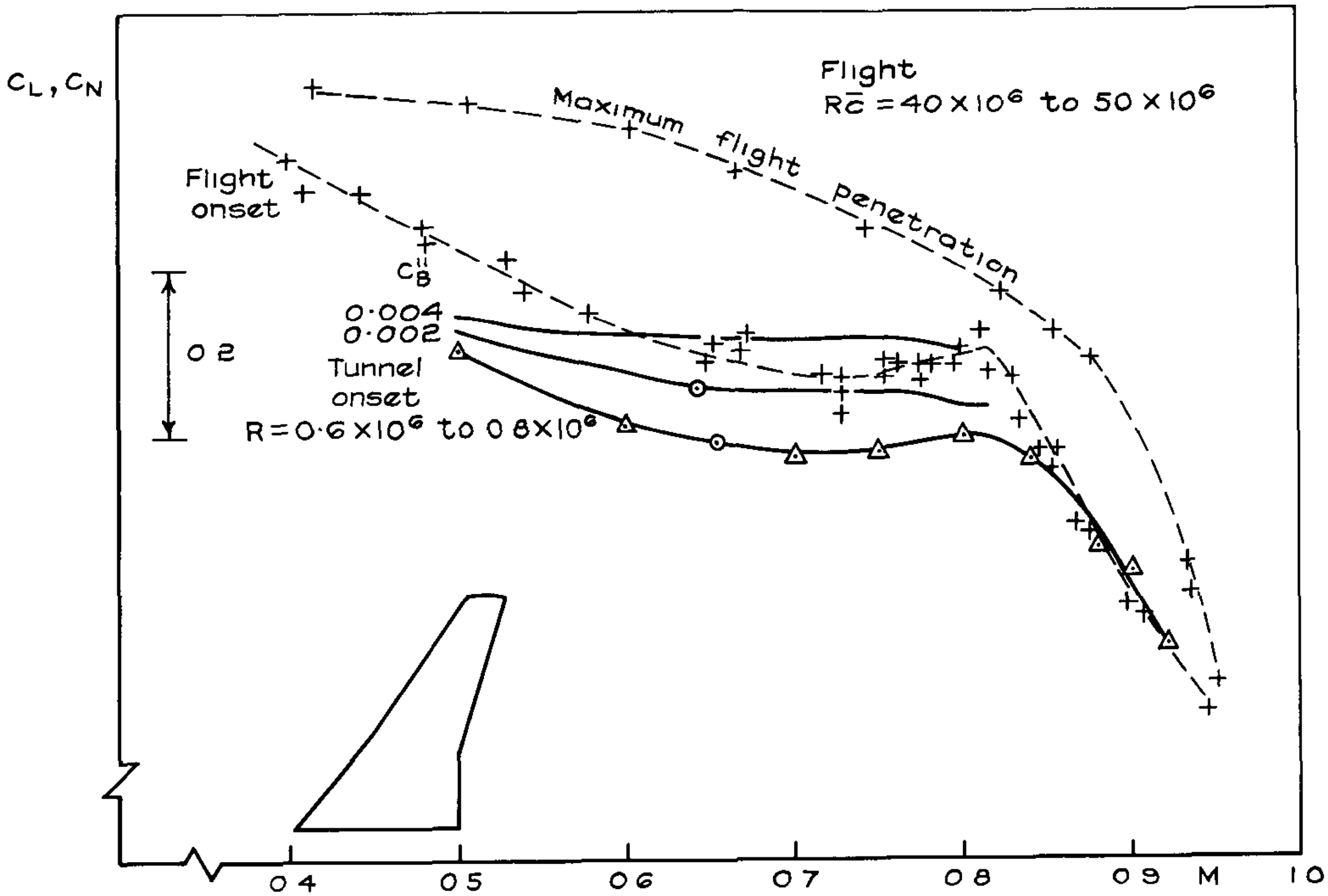


Fig. 4 Aircraft A: contours of buffeting

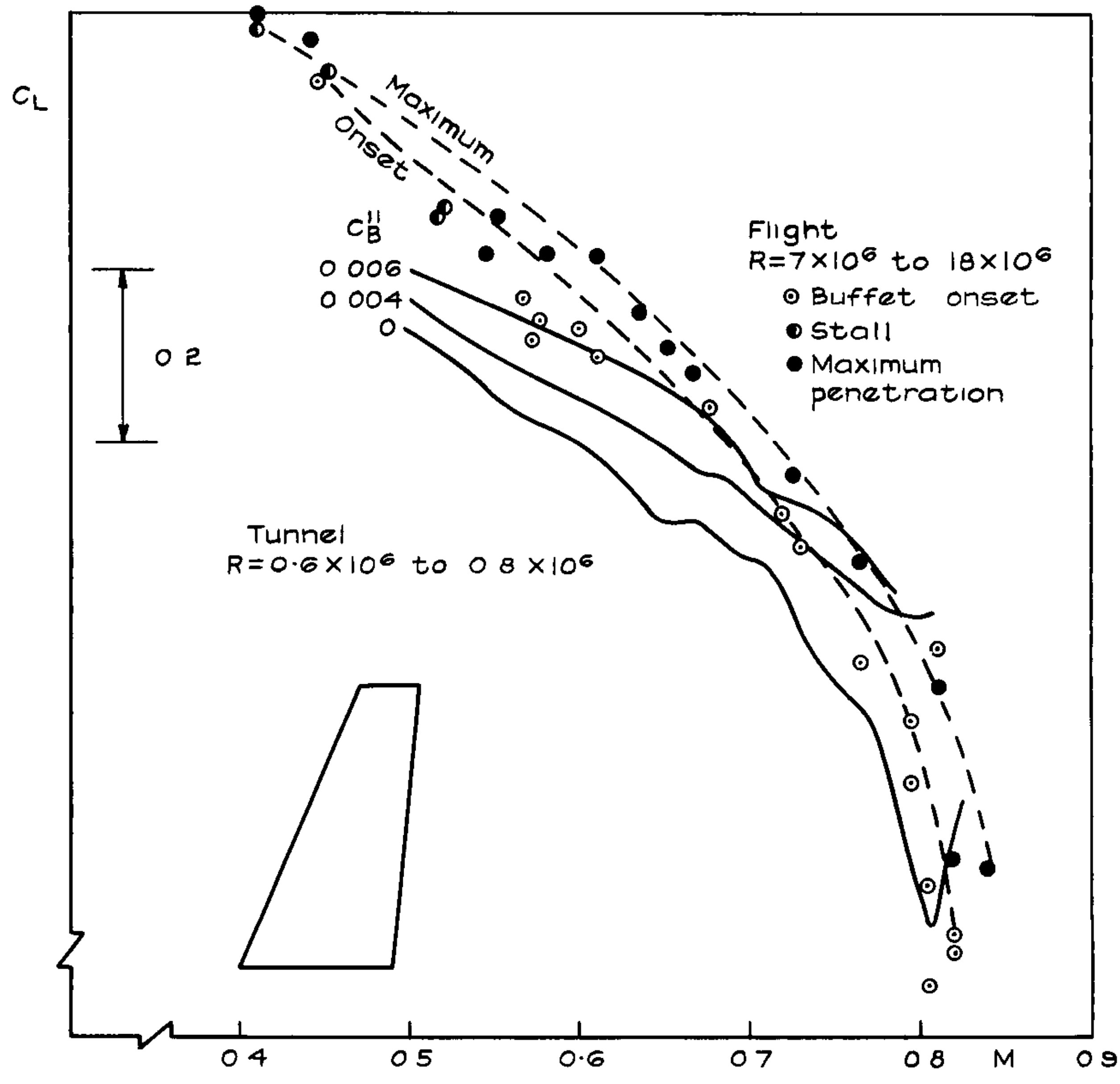


Fig.5 Aircraft B : contours of buffeting

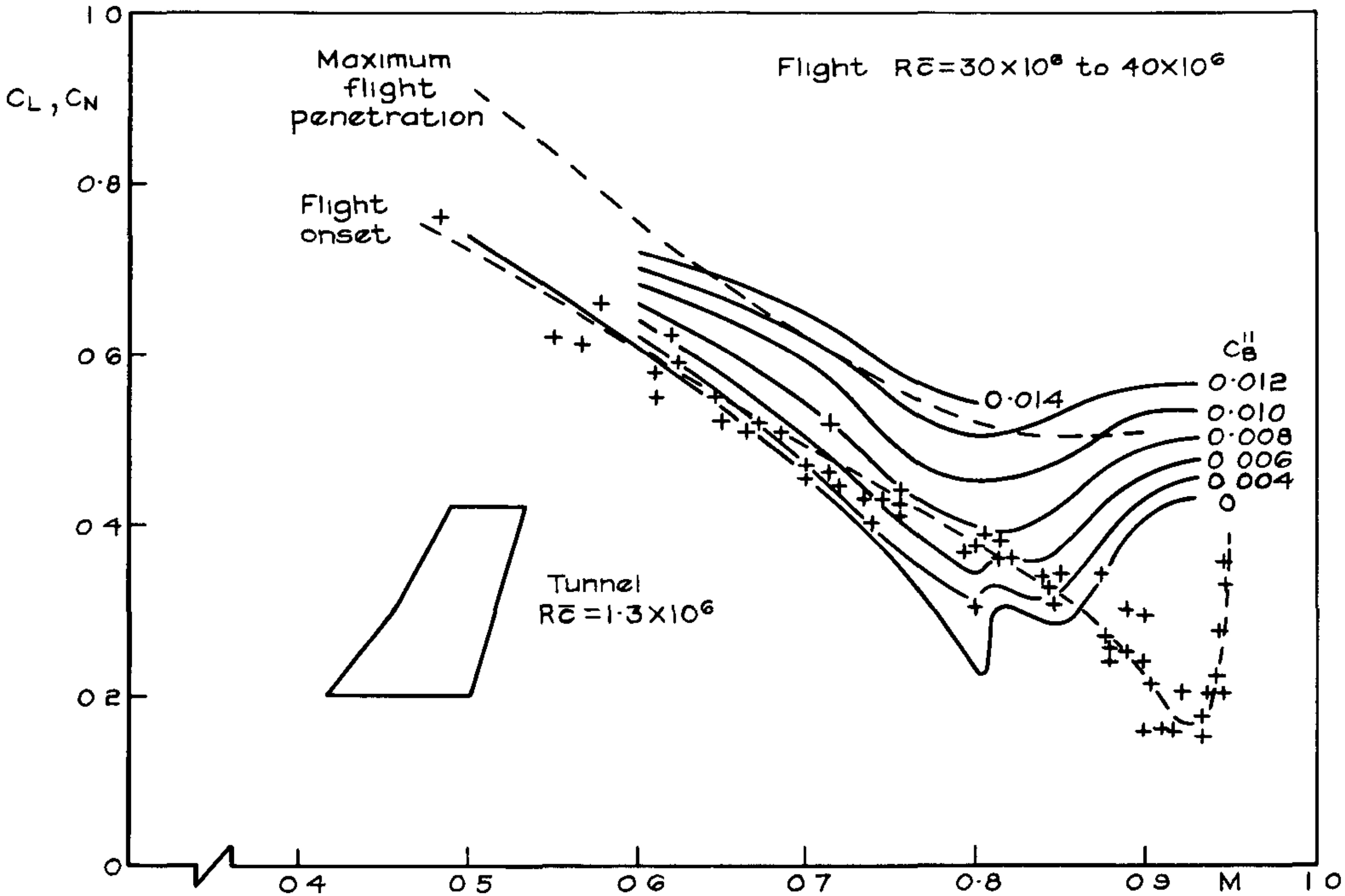


Fig. 6 Aircraft C : contours of buffeting

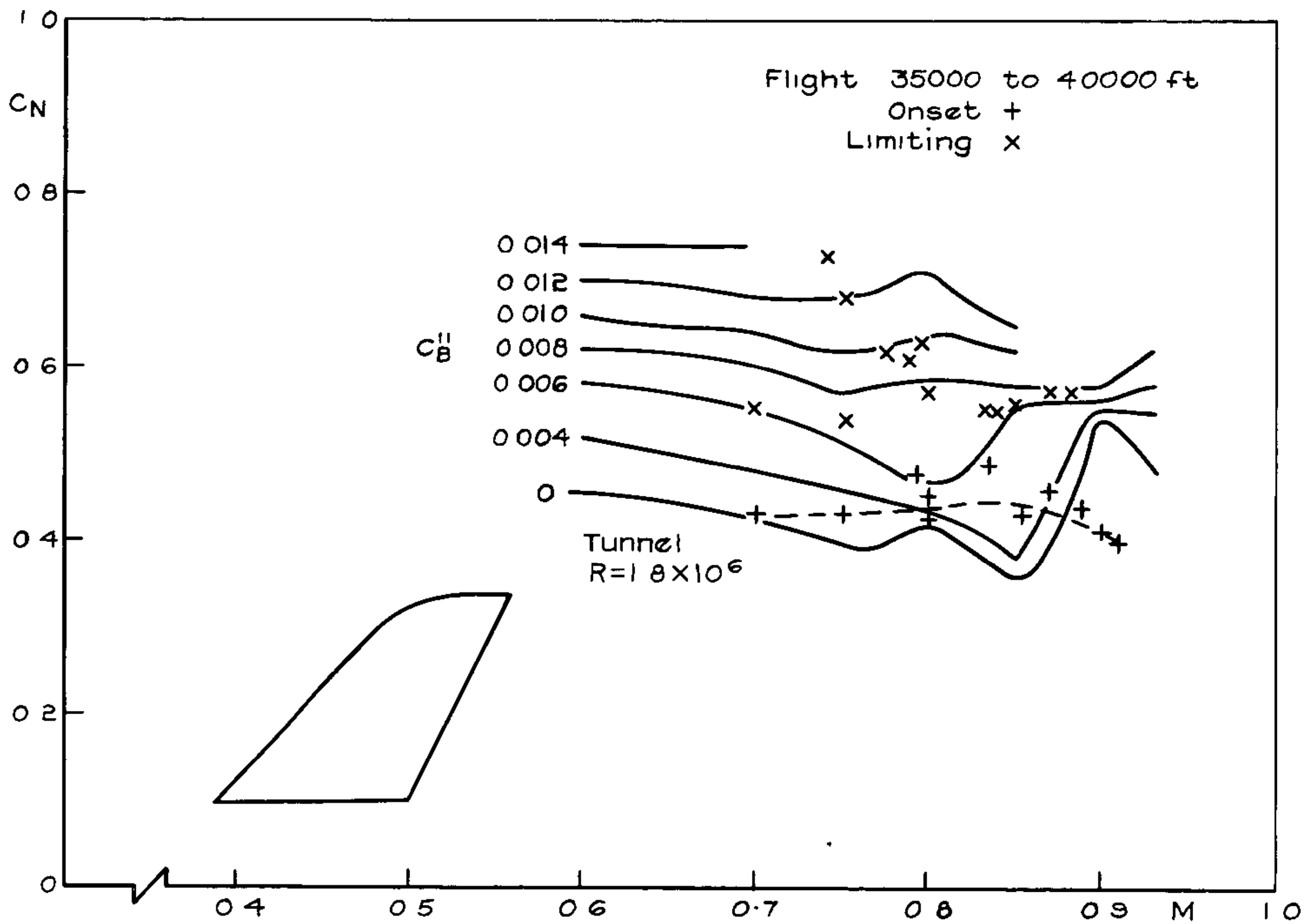


Fig.7 Aircraft D : contours of buffeting

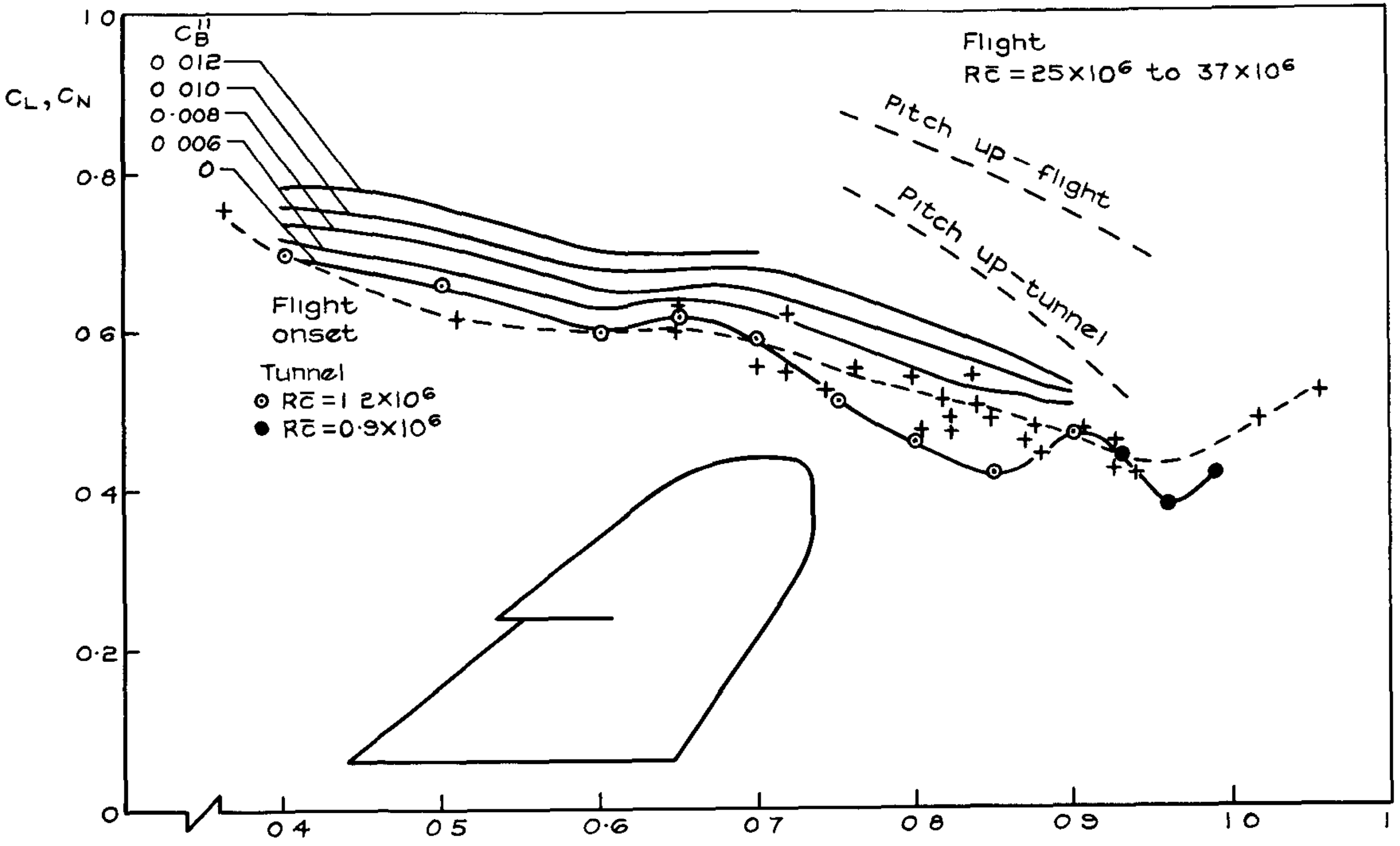


Fig. 8 Aircraft E: contours of buffeting

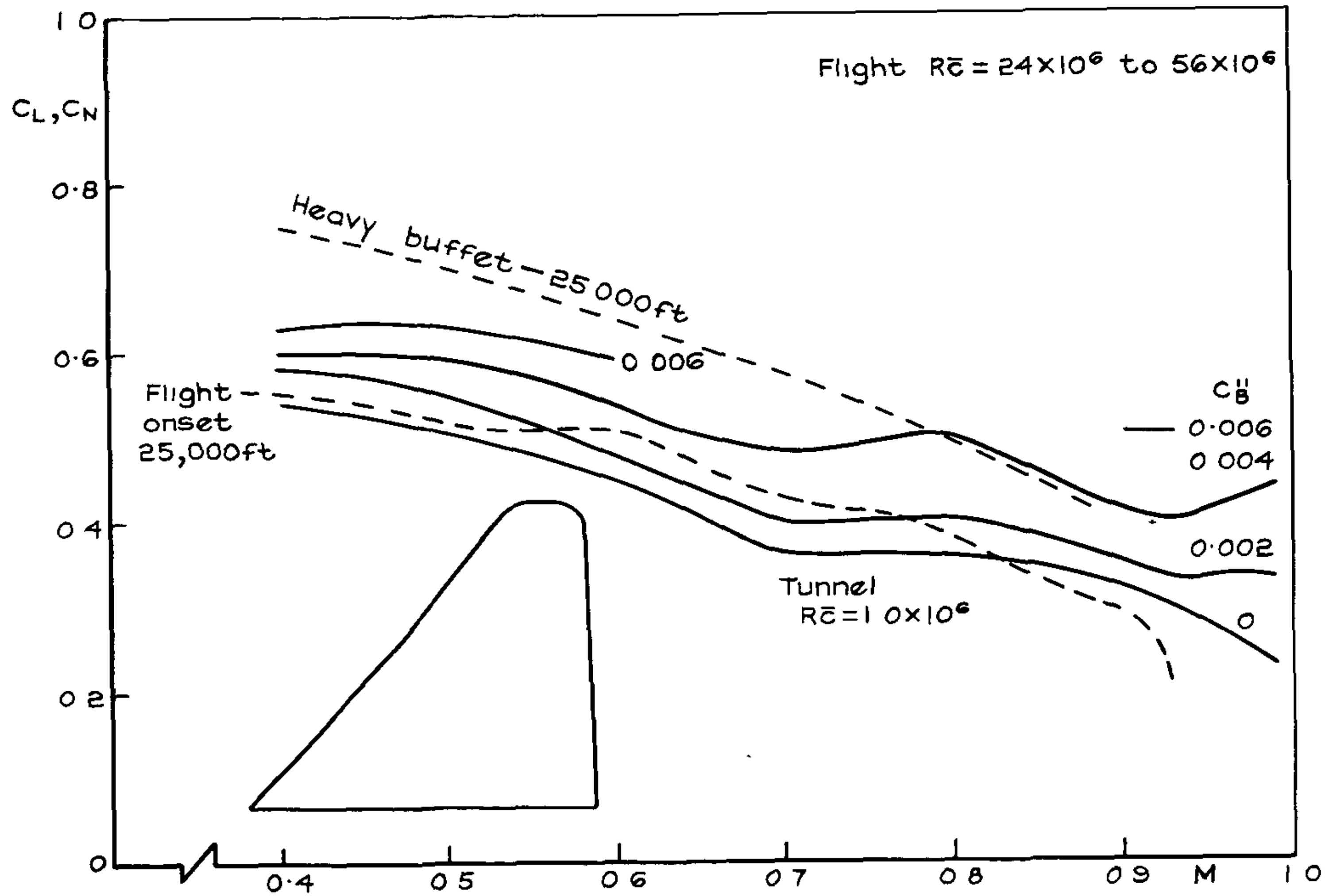


Fig.9 Aircraft F: contours of buffeting

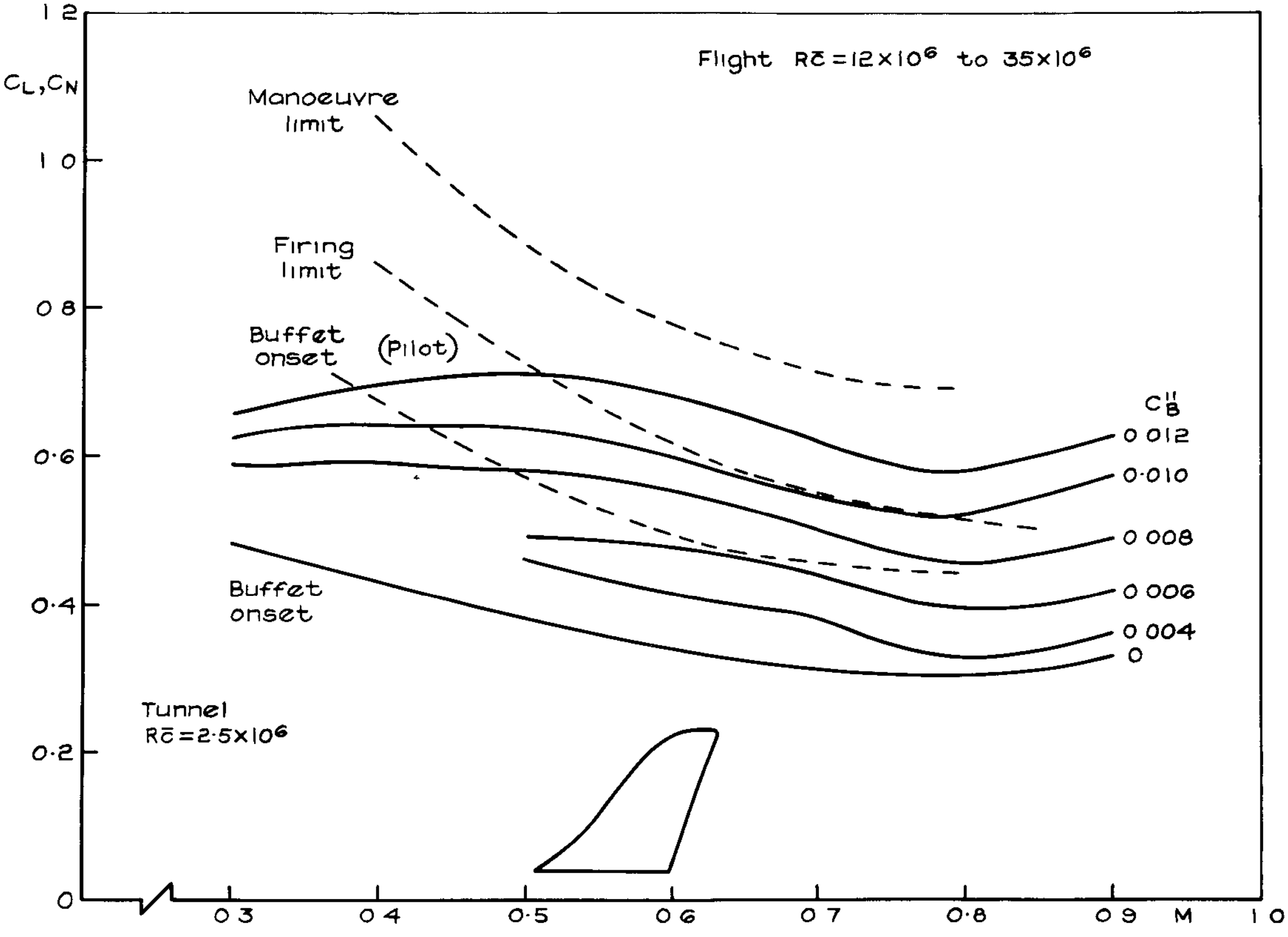


Fig. 10 Aircraft G : contours of buffeting

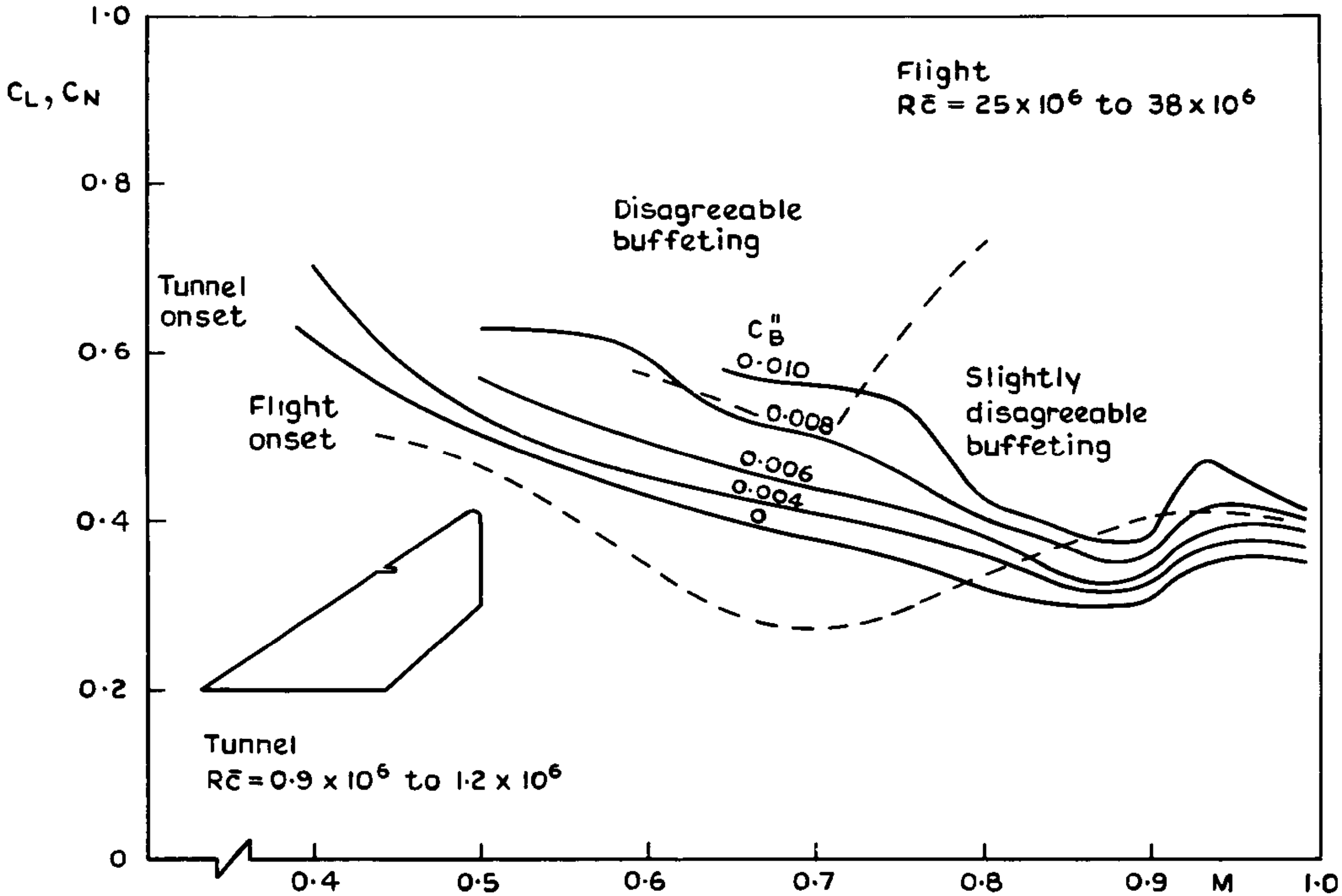


Fig.11 Aircraft H: contours of buffeting

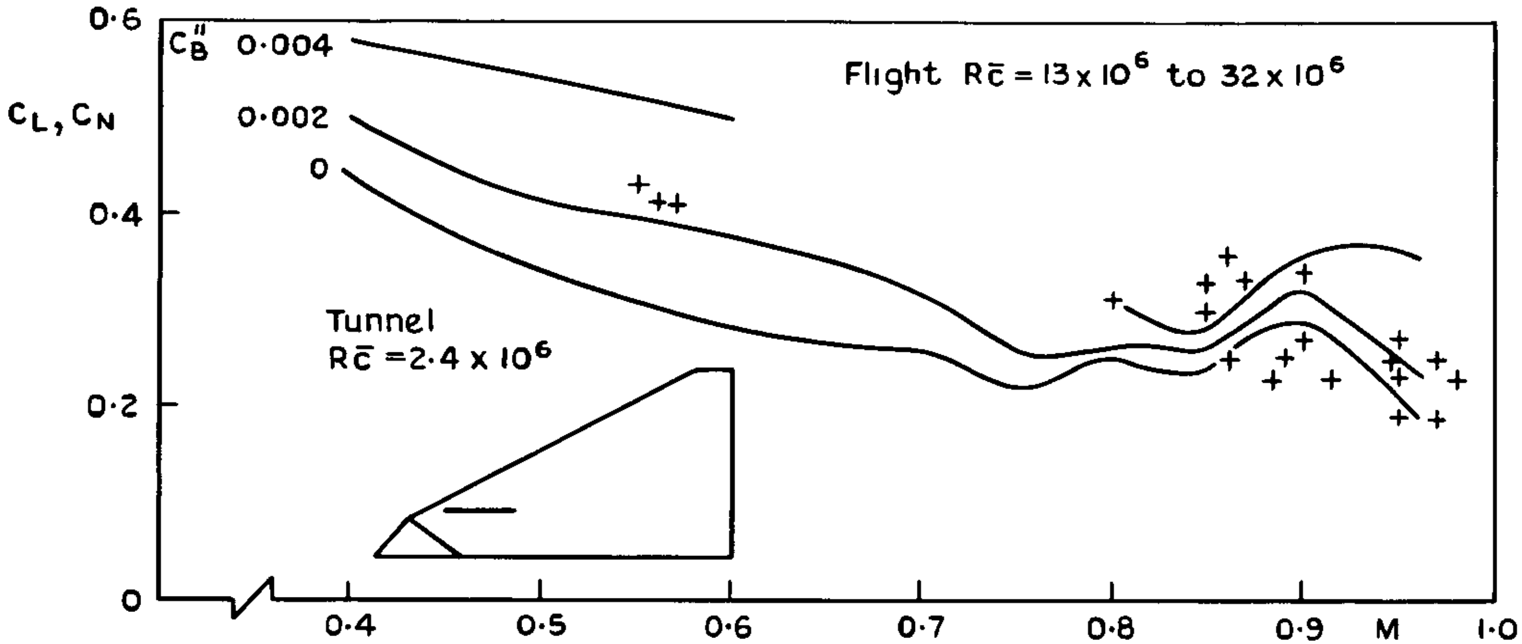


Fig.12 Aircraft I : contours of buffeting

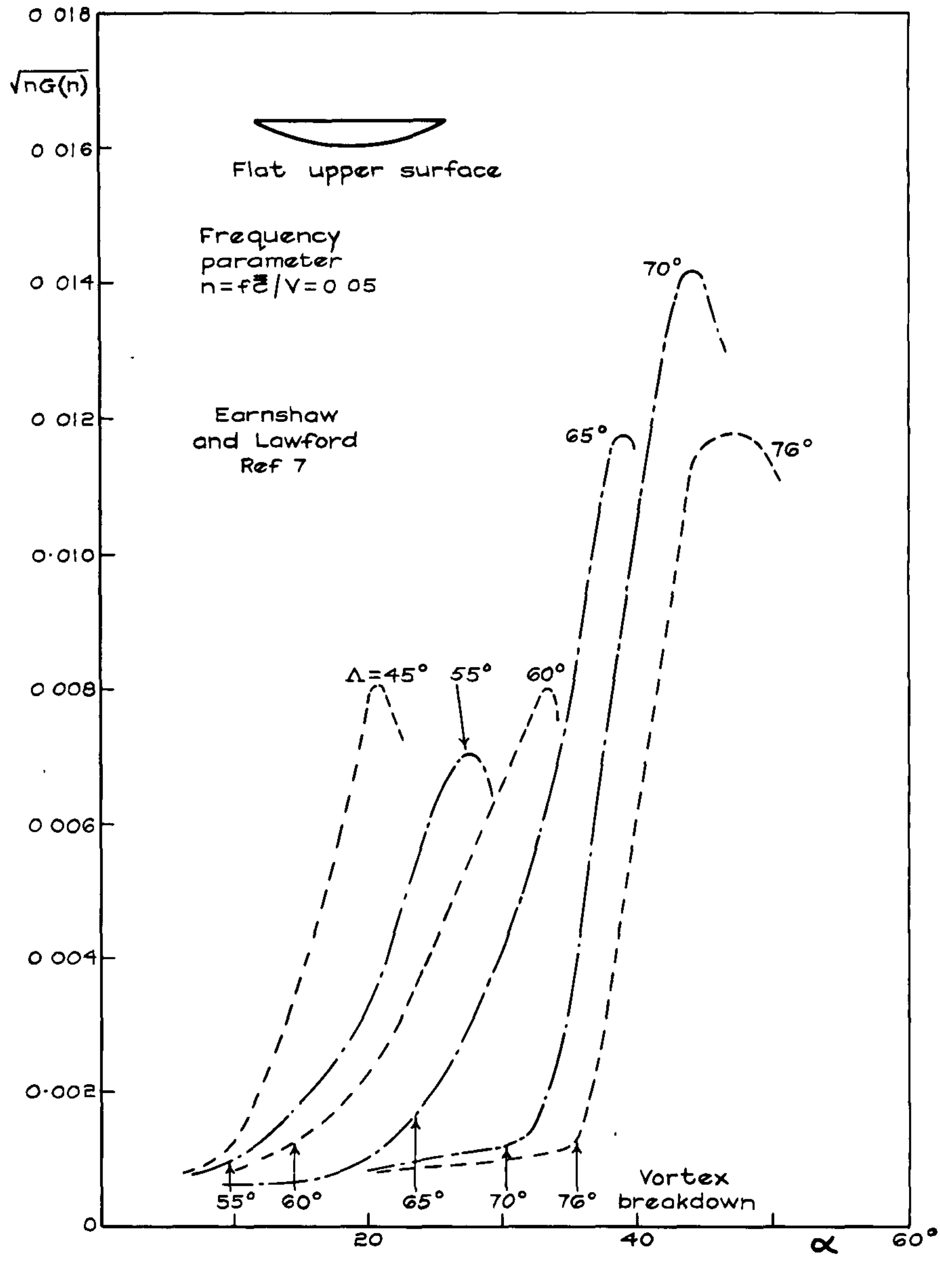


Fig.13 Variation of fluctuating normal force coefficient with angle of incidence

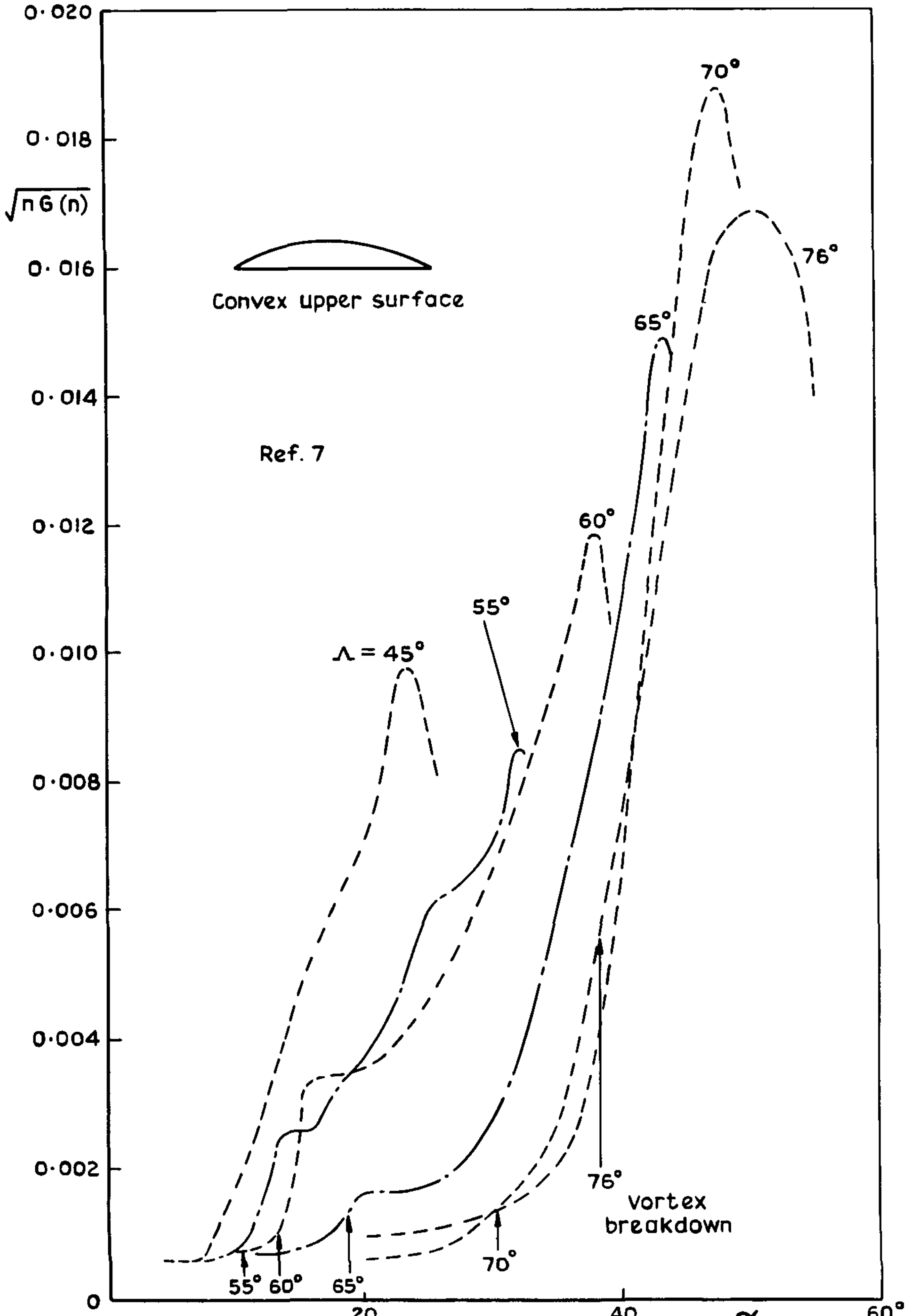

0·020
0·018
$\sqrt{nG(n)}$
0·016
Convex upper surface
0·014
Ref. 7
0·012
0·010
0·008
0·006
0·004
0·002
0
20
40
60°
α
70°
76°
65°
60°
55°
Λ = 45°
55°
60°
65°
70°
76°
Vortex
breakdown

Fig. 13 contd

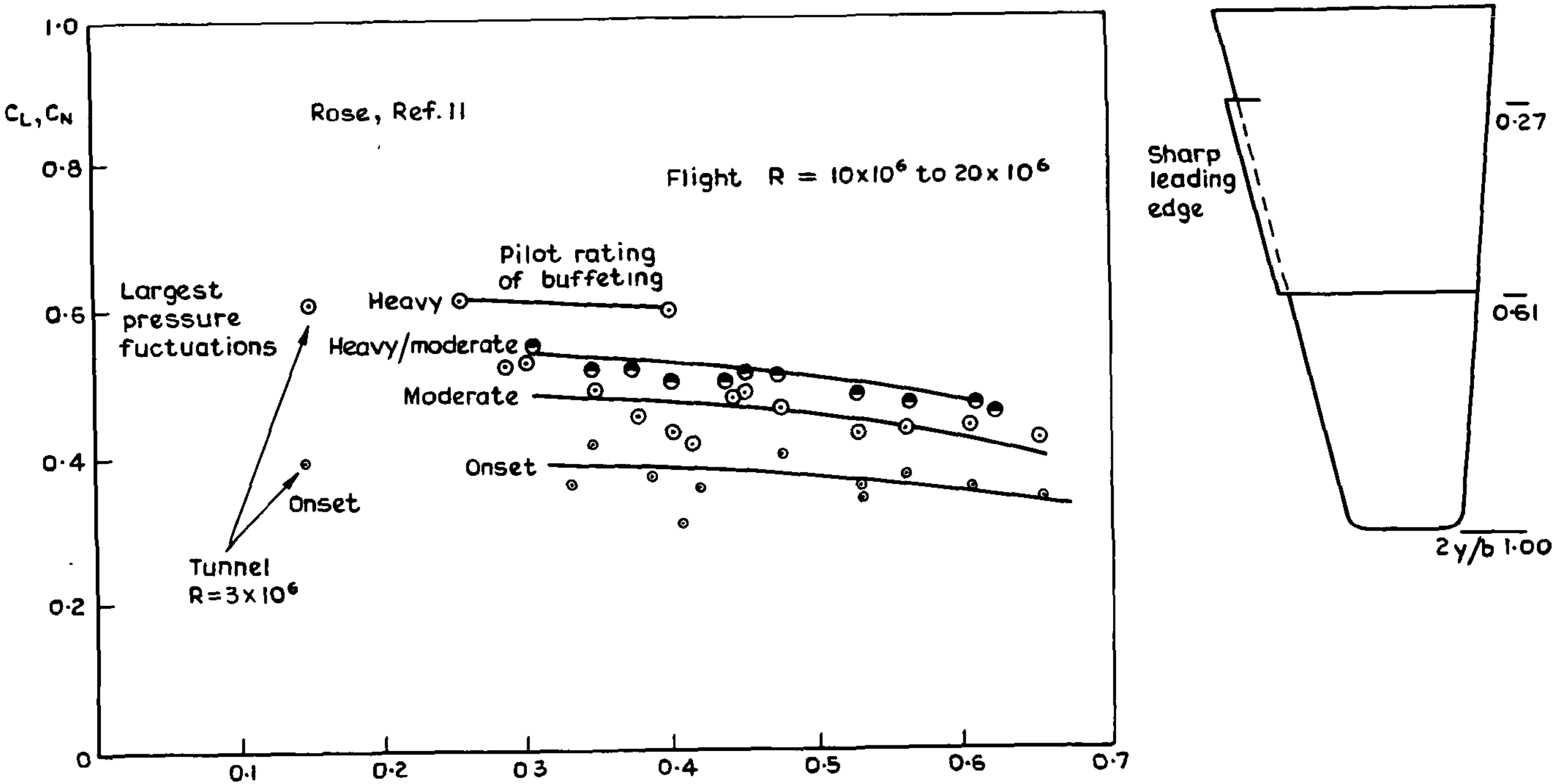


Fig.14 Venom aircraft with sharp leading-edge

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