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REPORT ON INVESTIGATION OF TAILPLANE FLUTTER

Air Safety Investigation Branch

GAF 24 Nomad Aircraft
Serial Number 10
at Avalon,
Victoria,
on 6 August 1976

Technical Supplement

Special Investigation Report 77-1

AIR SAFETY INVESTIGATION BRANCH

Report on Investigation of Tailplane Flutter

GAF N24 Nomad Aircraft Serial Number 10 at Avalon, Victoria, on 6 August 1976

This report refers only to the results achieved by a specialist group set up specifically to explore the nature and source of the tailplane flutter which was evident in this accident. It is published as a separate document for those interested in the technical details of this aspect of the investigation. The report of the investigation of the accident has been separately published as Accident Investigation Report 77-1.

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1. INTRODUCTION

Nomad aircraft N24-10 was authorised to carry out Flight 128 on 6 August 1976 at Avalon, Victoria. In the course of this flight, the aircraft crashed and was destroyed. The accident investigation team charged with the task of investigating all aspects of the accident was divided into various groups and subgroups, the Flutter Subgroup being part of the Engineering Group.

The terms of reference of the Flutter Subgroup were 'to investigate the flutter characteristics of the aircraft in its accident configuration'. This is the report of the subgroup to the Engineering Group Leader and is written in accordance with the stated terms of reference.

2. PURPOSE OF THE FLIGHT

The N24 Nomad has encountered problems with longitudinal stability at the 20° flap setting. Certification requirements demand that the aircraft exhibit suitable stability and control feel. In particular, it must possess the characterstic that, with the aircraft trimmed at a prescribed speed, any substantial speed change results in a stick force clearly perceptible to the pilot, i.e. the stick force/speed curve must have a positive gradient. This characteristic was demonstrated by the N24 for the 10° and 40° flap settings but, in the opinion of the Chief Test Pilot, the stick force gradient was unacceptable at the 20° flap setting. Measured stick forces showed a very low gradient at low speed.

While the longitudinal stability problem may not affect Australian certification of the N24, it was considered important to solve the problem for a developed version of the aircraft. Accordingly, the Government Aircraft Factories (G.A.F.) made and flight tested a series of modifications to the tailplane. These included:

(a) changing the tab gearing ratio,

(b) extending the tailplane leading edge,

(c) fitting vortex generators to both upper and lower surfaces of the tailplane,

(d) fitting boundary layer fences to the tailplane near the root.

None of these modifications had any measurable effect on the stick force gradients and further modifications were made to the tabs.

The Nomad tailplane is fitted with anti-balance geared tabs, i.e. the angular motion of the tabs has the same sign as that of the tailplane. On the N24 production tailplane, these tabs extend outboard from the root cut-out over a semispan of 69 in. Flights made to test the various tab modifications and the associated tailplane configurations are as follows:

Flight 93 — standard tabs (69 in) with 1-inch T strips fitted to the tab trailing edge.

Flight 94 — as for Flight 93 but with 1-inch T strips also fitted to the tailplane trailing edge.

Flight 96 — standard tabs with 1-inch T strips fitted to the tailplane trailing edge only.

Flight 97 — as for Flight 96 but with T strips increased to 2 inches.

Flight 100 — tabs lengthened by 16 in to a semi-span of 85 in. No T strips fitted.

Flight 101 — tabs lengthened by a further 16 in to full span (101 in). No T strips fitted.

Flight 128 — full span tabs with 2-inch T strips fitted to the tab trailing edge.

For the purposes of this report, the tabs are designated standard, extended and full span and their dimensions are shown in Fig. 1.

The modifications associated with Flights 93–101 made no measurable change to the stick force gradients, and the purpose of Flight 128 was to measure the stick force gradient at 20° flap with full span tabs and 2-inch T strips.

3. FLIGHT FLUTTER CLEARANCE

The production N22 aircraft has been cleared by calculation and by flight testing up to speeds of 218 KIAS. At the time of the accident, the N24-10 had been granted a Permit to Fly which included maximum speeds of 120 KIAS with wing tip tanks full and 170 KIAS with tip tanks empty. This clearance was based on N22 experience, the application of the Broadbent Criterion (Ref. 1), and on additional flutter calculations which used results obtained from ground resonance tests on the standard N24 tailplane.

The Broadbent Criterion states that for the frequency parameter (ν) given by:

$$\nu = \frac{2\pi f \bar{c}}{v}$$

where f = expected flutter frequency, Hz
$\bar{c}$ = reference mean aerodynamic chord, ft
v = airspeed, f.p.s.

flutter need not be expected at values of:

$\nu > 1.0$ for main surfaces
$\nu > 1.5$ for control surfaces
$\nu > 2.5$ for tabs

This criterion is an empirical rule based solely on previous experience for the purpose of establishing whether preliminary flutter clearance can be obtained without detailed flutter analysis.

4. DESCRIPTION OF FLIGHT 128

Take-off was normal and the aircraft commenced a straight climb on its take-off heading of 264°M. At 106 KIAS and 220 ft altitude, the flight data recorder was switched off. While the aircraft maintained a straight climb, eyewitnesses on the ground observed the tailplane tabs to be fluttering and an unidentified component to separate from the aircraft. Aircraft conditions at the time were estimated as approximately 100 KIAS and 800 ft altitude with flaps and undercarriage retracted. Several pieces of wreckage were subsequently recovered from a position below the flight path and these were identified as pieces of skin and a section of T strip from the port tailplane.

These events were described by Witness 16 in the following terms. 'After passing us, we could see that the elevators were flapping or vibrating very rapidly, far too fast for it to be caused by the pilot pushing on his controls. The tab section was fluttering very quickly and the whole elevator was also moving up and down but did not seem to be doing so as quickly. . . . About half a minute after this, the Nomad banked gradually over to the left and started to turn towards the south.' Witness 18 commented: 'The aircraft was about over the main strip . . . when the flaps on the back of the horizontal part of the tail, on both sides, suddenly began to flutter rapidly. It was just like a rag flapping in a strong wind. The climb didn't change but some 5–10 sec later a dark object fell off from the plane. . . . The plane kept climbing away and appeared quite normal for about another minute. Then the plane started to turn to the left, towards the south, in a level turn.'

During a post-accident interview, the Flight Test Engineer gave the following description: '. . . while we were still climbing out, we had this buzz . . . we had this brrr for about five seconds I'd guess and the nose pitched down and positively . . . It was flutter all right, I'm sure of that. The thing that was absolutely astounding was that it was below 120 knots... and also the fact that we'd flown in very similar configurations to that before without any apparent problems.'

5. WRECKAGE FEATURES

During the inspection of the wreckage, the following significant features were noted.

(a) Both sides of the tailplane had failed under the action of alternating loads.

(b) The top static stop of the tailplane exhibited a series of heavy impact marks.

(c) At the lightening holes aft of the spar, most internal ribs of the port tailplane had fractured as under repeated reversed rib bending.

(d) The aft web of the tailplane spar centre section had buckled as under the action of a large torsion load.

(e) Both tailplane tabs had sustained severe damage at their inboard ends, that on the port side being sufficient to separate the tab from its control rod.

These features are consistent with a large amplitude oscillation of the tailplane and its attached anti-balance tabs.

6. FLUTTER ANALYSIS

From the eyewitness reports and from the evidence of the wreckage, it was clear that flutter of the tailplane and tabs occurred during the accident sequence. Whether flutter initiated the sequence or whether it was initiated by some prior failure remained to be established. This required a detailed investigation into the flutter characteristics of the aircraft's tailplane and tabs in the accident configuration.

A flutter program had been developed by G.A.F. in order to study the flutter characteristics of the Nomad aircraft. This program utilises programs of unsteady aerodynamics developed by R.A.E. and A.R.L. Normally when performing flutter calculations, the mode of vibration describes the motion of the complete aircraft, and aerodynamics appropriate to this overall motion are used. In this instance, this was only possible for the lower frequency modes since the tandem surface aerodynamic program was not reliable for values of frequency parameter greater than 3.0.

As a result, two types of flutter model were used, one for low frequency and one for high frequency. In the low frequency models, the total motion of the aircraft was accounted for in the definition of generalised masses, and aerodynamic forces which included the effects of wing, tailplane and tab aerodynamics were used. These were generated by the R.A.E. program designated PO7B.

For the high frequency models, the motion of tailplane and tabs only were considered and the presence of the wing, fuselage etc. was ignored. The aerodynamics used were generated by the A.R.L. program R36022 which calculated only the forces on the tailplane and tabs in the absence of the wing. This program has no restriction on frequency parameter.

Subsequent to the accident, the G.A.F. flutter program was modified to take account of the full span tabs by factoring the inertial and aerodynamic terms appropriate to the tabs by the ratio of tab spans. The inertial contribution of the trailing edge T strips was included but their effect on aerodynamics was ignored. Results obtained showed a critical flutter speed in the region of 120–130 KEAS for zero structural damping. While these results were suggestive, they could not be accepted as conclusive because the aerodynamics did not include the effect of T strips and because of the uncertainties inherent in the factoring process used. Further, as stated above, the aerodynamic program was unreliable for frequency parameters greater than 3.0. Accordingly, a research program was undertaken to obtain better structural and aerodynamic representations of the aircraft for incorporation in the flutter models.

7. STRUCTURAL REPRESENTATION

The results obtained from earlier ground resonance testing of the N24 fitted with a standard tailplane are reported in Ref. 2. For convenience, a summary of these results is included in this report; see Tables 1 and 2. In these tables, the first fuel condition is main wing tanks half full with auxiliary tanks empty, while the second fuel condition is similar but with auxiliary tanks full.

A comprehensive program of ground resonance testing was carried out at A.R.L. on a new tailplane configured as for Flight 128. For these tests, the tailplane control circuit was simulated by a rigid link attached to a flexure pivot. With standard tabs fitted to the tailplane, the stiffness of the simulated circuit was adjusted by varying the length of the flexure pivot, to give a frequency of 11.1 Hz in the tailplane rotation mode. This was the frequency of this mode measured in the N24 ground resonance tests; Table 1. Similarly, the tab control circuit was simulated by a rigid link and flexure pivot. The stiffness of this simulated circuit was adjusted to provide the same coupled tab/tailplane frequency of 28.3 Hz quoted in Table 2 for the antisymmetric tailplane torsion mode. Initially this adjustment proved difficult to achieve and the tests were made with the simulated circuit adjusted to give a frequency of 30.6 Hz in this mode (see Table 5).

With full span tabs set at zero incidence, measurements were made of coupled tab/tailplane modes with and without the tab T strips. Similarly, uncoupled tab modes were measured with the tailplane held rigid, and uncoupled tailplane modes were measured with the tabs removed. In order to examine the effect of incidence on tab restraint, additional measurements were made of certain coupled modes with the tabs set at a nose down incidence of 22°.

Subsequently, measurements of the tab control circuit stiffness were made on the wreckage of N24-10 and compared with similar measurements made on new production aircraft. The result obtained from N24-10 of 640 lb/in was comparable with the 800–900 lb/in obtained from production aircraft and the standard design figure of 700–800 lb/in used by G.A.F. However, a similar measurement made on the resonance test specimen indicated a tab control circuit stiffness of 1250 lb/in, i.e. approximately double that of N24-10. This high stiffness was thought to be caused by excessive friction in the torque tube bearing housings. Incorporating a trim jack in the tab control circuit resulted in some improvement but, because of the poor simulation of the tab control circuit stiffness in the laboratory tests, some additional resonance tests were carried out on an actual aircraft. The results obtained were then used to correct the laboratory test results where necessary.

The results obtained from these tests are given in Tables 3–6. It will be observed that the effect of the more realistic mounting of the tailplane and the tab/tailplane control circuits has been to reduce the measured frequency of the tab rotation modes by amounts up to 5 Hz. Adding the trailing edge T strips reduced the frequency of both coupled and uncoupled modes by approximately 3–5 Hz. The effect of variation in tab incidence was insignificant. The results given in Tables 3–6 were used as a basis for the structural representations contained in the flutter models.

8. AERODYNAMIC REPRESENTATION

The unsteady aerodynamic data used by G.A.F. are based on theories developed by Dr G. Long (Ref. 3) and P. Farrell of A.R.L. and Dr D. E. Davies (Ref. 4) of R. A. E. Farnborough. These theories are restricted to attached flow and are based on the assumption of infinitely thin lifting surfaces. They cannot be used reliably to predict the forces on a surface with T strips. Accordingly, it was necessary to measure the effects of T strips on a wind tunnel model and to adjust the theoretical data accordingly.

A surplus Nomad tailplane (from N22-02) was obtained from G.A.F. and modified to make a two-dimensional wind tunnel model for testing in the A.R.L. 9′ x 7′ tunnel. The tailplane was held rigidly at zero incidence by two vertical walls 5 ft apart and the tab was oscillated by shakers attached, through long pushrods, to each end of the tab. The pressure distribution was measured at up to 47 stations around the centreline section. Each pressure tapping was connected to an acoustic scanning valve for pressure measurement. The chordwise stations of the pressure tappings are given in Table 7 and photographs of the model mounted in the tunnel are shown in Figs 2 and 3.

As a check on the method, a series of experiments was carried out without T strips fitted and the results obtained compared with theoretical values. Good agreement was obtained over the frequency parameter range of 1.6 to 4.8. In all tests, the tab was oscillated to an amplitude of $\pm 1°$, the frequencies of oscillation were 5, 10, 20 and 30 Hz, and two tunnel speeds of 80 and 100 knots were used.

These tests were repeated with a 2-inch T strip attached to the trailing edge of the tab. Some results obtained from both series of tests, with and without T strips, are presented in Figs 4–7 where the effects of frequency parameter and T strips can be easily seen. A 1-inch T strip was also tested and the effect of tab deflection investigated.

The main effect of the T strips, 1-inch or 2-inch, is to increase the aerodynamic stiffness derivatives and to reduce the damping derivatives. The effect of tab deflection was insignificant. The results obtained for the 2-inch T strips are summarised in Table 8. Similar results were obtained for the 1-inch T strips, i.e. the results are not sensitive to the T strip width for a range in width from 1 to 2 inches.

In order to apply these results, a correction matrix was prepared to modify the theoretical pressure distributions to agree with the measured values. This was a two-dimensional correction only and the spanwise distribution was assumed to be as theory predicts.

The aerodynamic coefficients obtained and used in the flutter calculations are therefore the result of two distinct processes. The computer programs are used to predict the pressure distribution, then this distribution is multiplied by the correction matrix to obtain the desired values. These values are still classed as theoretical since the absolute values of pressure are determined theoretically and the wind tunnel correction matrix is only used as a qualitative correction. Therefore, the values as used are again adjusted for viscous and three-dimensional effects by multiplying all the aerodynamic coefficients by a factor FT. Based on a two dimensional correction only, this factor would be around 0.6–0.8. Considering previous G.A.F. steady state flight test and steady state theoretical values, it is thought that FT = 0.5 is a good approximation.

9. FLUTTER MODELS

Tailplane models which incorporated the tabs were formulated in the following two categories:

(a) low frequency symmetric tailplane model,

(b) high frequency antisymmetric tailplane model.

The two models were separated because of the difficulties experienced in calculating unsteady aerodynamics applicable to both the high frequency and the low frequency cases (see Section 6). The models are so arranged that the frequency of uncoupled tab and tailplane modes are appropriate rather than coupled tab/tailplane modes.

9.1 Low frequency models

Two low frequency flutter models were formulated which combined the symmetric tailplane modes with symmetric tab modes. The flutter models comprise tailplane symmetric rotation at 11 Hz, tailplane symmetric bending at 17.3 Hz and symmetric rotation of the tabs at varying frequency.

The first low frequency model used single surface aerodynamics throughout, while in the second model tandem surface aerodynamics were used to calculate the generalised forces in the tailplane bending modes only. Thus the second model makes use of aerodynamics better described as hybrid since single surface aerodynamics in two modes, tab and tailplane rotation, are combined with tandem surface aerodynamics in the third.

The low frequency models included provision for flexible tab modes. However, the effect of tab flexure on flutter speed proved to be insignificant and this provision was excluded from later calculations.

9.2 High frequency model

The high frequency flutter model formulated combines the antisymmetric tailplane mode with antisymmetric tab modes. The flutter model comprises tailplane antisymmetric torsion at 33.8 Hz with antisymmetric rotation of the tabs again at varying frequency. Single surface aerodynamics are used throughout. Again, provision is made for flexible tab modes but, because of their insignificant effect on calculated flutter speeds, this provision was excluded from later calculations.

10. RESULTS

For the aircraft in its accident configuration, viz. fitted with T strips 2 inches wide which weighed a total of 0.7 lb, calculations of flutter speed were made for various values of tab frequency (OMTT). As stated in Section 8, the aerodynamic coefficients are multiplied by a factor FT. A value of FT = 0.5 is the best estimate for the N24 but the effect of parameter variation was studied by allowing FT to vary between 0.5 and 1.0.

Selection of the most appropriate level of structural damping for the flutter calculations is largely a matter of experience. Levels of structural damping are expressed as percentages of the critical damping, i.e. the damping which reduces a disturbance to zero in the shortest time. From damping measurements made during earlier ground resonance tests, Tables 1 and 2, a structural damping ratio of 2–4% could be expected to be appropriate to the Nomad tailplane. Accordingly, the flutter calculations were set up using a nominal structural damping of 2% for both tailplane and tabs, and this nominal value was factored by a structural damping factor SDF. The effect of variation in structural damping was studied by allowing SDF to vary between zero and 1.0.

The results obtained using the two low frequency models are shown in Figs 8 and 9. With the tailplane restrained from deforming in bending, two asymmetric tab modes were measured at 19.0 Hz and 26.3 Hz (Table 3). The appropriate purely symmetric or antisymmetric tab frequency for use in the model will lie within these limits and hence 19–26 Hz is the frequency range of practical interest. Figures 8 and 9 show that over this range in OMTT flutter does not occur unless the structural damping is reduced to zero.

The structural damping of a standard tab has been determined from decay rates measured in ground resonance tests as 6%. A full span tab with the greater friction generated by its longer piano hinge would not be expected to have less structural damping than this. Further, since the structural damping of the tailplane must, in practice, be greater than zero, the possibility of flutter occurring in this low frequency mode may be discounted.

The results obtained using the high frequency model are shown in Fig. 10. For this model, the nominal structural damping was increased to the more realistic value of 5% for the tabs and maintained at 2% for the tailplane. The results show that for the parameter values FT = 0.5, SDF = 1.0, flutter does occur over the range in aircraft speed of 102–113 KEAS corresponding to the tab frequency range of 19–26 Hz. Increasing the factor on aerodynamic forces to 1.0 decreased the flutter speed, while doubling the structural damping resulted in only a small increase in flutter speed.

These results are shown in greater detail in Fig. 11. For the parameter values SDF = 1.0 and OMTT = 22 Hz (the nominal mid range value), the flutter speed decreases from 103 KEAS to 90 KEAS as the factor on aerodynamics increases from 0.5 to 0.7, the maximum value of FT likely in practice. Little emphasis should be placed on the precise flutter speed obtained for any given set of parameter values. However, it is clear that flutter of the tailplane and tabs does occur at a speed of 90–115 KEAS for all combinations of parameter values of practical interest. The limiting and most likely values of flutter speed are given in Table 9 to facilitate comparison with other aircraft configurations.

The flutter mode is characterised by antisymmetric torsion of the tailplane combined with tab rotation. Most of the torsion occurs in the tailplane centre section and there is little tailplane bending. As such, the mode is closely compatible with the damage observed on the tailplane and tabs of N24-10.

The growth rate for the set of parameter values FT = 0.5, SDF = 1.0 and OMTT = 22 Hz corresponding to curve 2 of Fig. 10 is shown in Fig. 12. This is a typical example of the growth rates applicable to the curves of Figs 10 and 11. For this particular case, the critical flutter speed is 103 KEAS (zero decay rate) at a frequency parameter of 4.5. As shown in Fig. 12, the growth rate increases rapidly with speed and, in consequence, the onset of flutter would be rapid. For example, a speed increment of 2 KEAS produces a growth rate of 1%. From Fig. 12, the number of cycles required for the oscillation to double in amplitude is:

$$\frac{0.11}{0.01} = 11 \text{ cycles}$$

For a frequency parameter of 4.5, the flutter frequency from Section 3 is:

$$\frac{4.5 \times 103 \times 1.69}{2\pi \times 4.33} = 29 \text{ Hz}$$

Therefore, time to double amplitude = 0.38 sec.

While this particular example applies to a single point on the curves of Figs 10 and 11, a similar situation would exist for all points within the range of practical interest. Given the short time to double amplitude, it may be presumed that a pilot would have little chance of recognising the development of flutter in time to take appropriate corrective action before the flutter became catastrophic.

Some frequency parameters corresponding to the calculated flutter speeds are shown on the curves of Figs 10 and 11. It will be seen that flutter occurs at frequency parameters in excess of 4.0. This is well above the limiting frequency parameter indicated by the Broadbent Criterion.

11. JUSTIFICATION OF ANALYSIS

In order to check the mathematical model used, it was considered advisable to determine the flutter speeds of other aircraft configurations using this model and to compare these with actual flight data. This work was confined to the high frequency model described in Section 9.2.

11.1 Full span tabs with small T strips

This configuration was not flown but envisages an aircraft configuration similar to the accident configuration with the 2-inch T strips of N24-10 replaced by 1-inch T strips with a nominal mass of 0.35 lb. For this case, the tab frequency applicable to large T strips was fed into the program and internal adjustments made to reduce the tab inertia to a value appropriate to the smaller T strips. The values of OMTT shown in the results, Figs 13 and 14, are for tabs with 2-inch T strips. When applied to 1-inch T strips, they constitute a reference frequency only rather than an actual tab frequency.

The results shown in Fig. 13 are similar to those shown in Fig. 10 for the 2-inch T strips. For the reference frequency of 20 Hz, slightly lower flutter speeds are obtained with the 1-inch T strips but the flutter speed increases more rapidly with increasing frequency. For the parameter values considered most likely, viz. SDF = 1.0, OMTT = 22 Hz, flutter occurs at approximately 106 KEAS for FT = 0.5, i.e. 3 KEAS above that for the large T strips. As for the previous case, the flutter speed decreases with increasing values of FT but, in contrast with the previous case, flutter does not occur for values of FT < 0.3 (see Fig. 14.)

11.2 Full span tabs without T strips

The aircraft was flown to a maximum speed of 118 KIAS in this configuration.

The results obtained for this configuration are shown in Fig. 15. Again, the tab frequency (OMTT) shown is a reference frequency only and not the actual tab frequency. For the most likely parameter values of OMTT = 22 Hz and SDF = 1.0, flutter does not occur at any speed up to 250 KEAS for FT = 1.0. Curves of flutter speed for lower values of FT are to the left of those shown in Fig. 15, indicating that the configuration is free from flutter for all values of FT $\leqslant 1.0$.

11.3 Extended tabs without T strips

The aircraft was flown in this configuration up to a maximum speed of 120 KIAS.

The results obtained for this configuration are shown in Fig. 16. In this figure the actual tab frequency is shown as OMTT and, because of the lower tab inertia, the frequency range of practical interest is estimated as 28.5–34.0 Hz. The results show that the configuration is free from flutter for all speeds below 150 KEAS for parameter values FT $\leqslant 1.0$ and SDF $\geqslant 2.0$.

11.4 Standard tabs with large T strips

The aeroplane was not flown in this configuration. The configuration envisages tabs of standard span (138 in) fitted with 2-inch T strips.

The tab frequency shown as OMTT in Fig. 17 is the tab frequency without T strips. As such, it should be regarded as a reference frequency only and not the actual tab frequency. The reference frequency of practical interest is in the range 33–38 Hz. The results shown in Fig. 17 indicate that flutter occurs at 115 to 140 KEAS for FT = 0.5 and SDF in the range 1.0 to 2.0. As with previous cases, the flutter decreases with increasing values of FT.

11.5 Standard tabs with small T strips

The aeroplane was flown in this configuration up to a maximum speed of 120 KIAS.

The results obtained for this configuration are shown in Fig. 18. The same tab reference frequency is used as in the preceding case. For the most likely parameter values of FT = 0.5 and SDF = 1.0, flutter occurs at 115 KEAS at a reference frequency (OMTT) of 33 Hz, the lower limit of the range of practical interest. As OMTT increases, the flutter speed also increases until, at the upper limit of the range (38 Hz), no flutter occurs. Assuming the midpoint of the range to be the most likely value of OMTT, the most likely flutter speed is 125 KEAS.

11.6 Standard tabs without T strips

This is the standard tab configuration used on production Nomad aircraft. These aircraft have been flown to a maximum speed of 218 KIAS.

The results obtained for this configuration are shown in Fig. 19 and indicate that the aircraft is flutter free for all parameter values of practical interest.

12. DISCUSSION

The flutter analysis described in this report contains a number of simplifying assumptions. Many of these are concerned with the aerodynamics used in the flutter models. In the high frequency model, the effect of the wing on the aerodynamic forces acting on the tailplane is ignored. The aerodynamics of both high and low frequency models makes no detailed allowance for fuselage and fin interference effects and all tab aerodynamic coefficients are factored equally. Nevertheless, the results obtained from the flutter models are consistent with flight test experience on a wide range of tab/tailplane configurations. This consistency justifies a high level of confidence in the flutter models.

The analysis shows that, in the accident configuration, flutter of the tailplane and tabs could be expected at a speed between 90 KEAS and 115 KEAS depending upon the parameter values used. Because of the approximations contained in the analysis, these calculated values are only approximate and a tolerance of perhaps $\pm$ 10 KEAS should be applied. This flutter critical situation arises from the inertia and aerodynamic effects of T strips added to the trailing edge of the tailplane tabs. By comparison, the original clean tab configuration is essentially flutter free for all tab spans investigated.

There is little difference between 1-inch and 2-inch T strips in terms of aerodynamic effect. The generally lower flutter speed of configurations fitted with 2-inch T strips, compared with 1-inch, is derived mainly from the increased inertial effects of the larger T strips. However, the difference in flutter speed is relatively small and both sizes of T strip are flutter critical. In this context it is noteworthy that a configuration which combined tabs of standard span with 1-inch T strips was flown to a maximum speed of 120 KIAS, which is marginally below the flutter speed of 125 KEAS calculated in this analysis.

Flutter occurs at a frequency parameter between 4.0 and 6.4 which is very high compared with the limiting value of 2.5 specified by the Braodbent Criterion. This is not unique and there is a previous case reported in the literature where flutter associated with an unconventional trailing edge device occurred at a frequency parameter of 2.9 (Ref. 5).

It is unlikely that the Broadbent Criterion could be used as a reliable guide in the development program of the N24–10. In retrospect, the calculations show that the criterion was highly unreliable as evidenced by the large difference in frequency parameter obtained.

Previous flight test experience on the different configurations of the development program, which included some occurrences of tab flutter, indicated that flutter was unlikely at speeds close to 100 knots. Any flutter calculations made for these configurations would have been based on conventional aerodynamic theories and parameter variations made to investigate the sensitivity to flutter of various unknown factors. No theory existed that could reliably predict the additional aerodynamic forces generated by the trailing edge T strips. This investigation has shown that these aerodynamic forces are far in excess of what reasonably could have been estimated.

In retrospect, as a result of the large change in aerodynamic forces, a flutter clearance based on all of the above considerations would not have provided an adequate guide to the safe operating speed.

13. CONCLUSIONS

The investigation has led the subgroup to the conclusion that flutter could be expected in the accident configuration at speeds below 120 KEAS. It is probable that tab/tailplane flutter was the primary cause of the accident. The mode involved is consistent with the tailplane damage experienced by the aircraft and the 'most probable' calculated flutter speed agrees well with the aircraft speed at the onset of airframe damage. Flutter would occur at a relatively high frequency parameter and would be characterised by such a rapid increase in amplitude that a pilot could not be expected to take appropriate corrective action in the short time available to prevent structural damage to the tailplane.

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Table 1

SUMMARY OF MEASURED NATURAL FREQUENCIES FOR FIRST FUEL CONDITION
N24 NOMAD WITH STANDARD TAILPLANE

Mode	*Natural frequency (Hz)*	*Damping (% critical)*
Antisymmetric wing bending	6.97	3.2
Symmetric wing bending	6.99	1.7
Rudder rotation	6.99	2.9
Roll of fin and tailplane	7.29	1.7
Engine horizontal	7.91	2.5
Symmetric wing bending	9.47	2.9
Symmetric aileron rotation	10.29	3.4
Antisymmetric wing bending	10.52	2.1
Rigid-body tailplane rotation	11.11	4.6
Horizontal fuselage bending	12.12	1.8
Symmetric wing and tailplane bending	13.88	2.4
Antisymmetric wing bending	15.24	3.1
Engine horizontal	15.98	5.8
Symmetric tailplane bending	17.32	1.7
Antisymmetric wing torsion	19.09	3.1
Fuselage vertical bending	20.10	3.1
Antisymmetric aileron bending	22.31	2.8
Wing strut lateral bending	22.41	—
Rudder–tab rotation	31.32	—
Rudder and tab bending	37.22	—
Rudder–tab torsion	69.83	—

Table 2

SUMMARY OF MEASURED NATURAL FREQUENCIES FOR SECOND FUEL CONDITION
N24 NOMAD WITH STANDARD TAILPLANE

Mode	*Natural frequency (Hz)*	*Damping (% critical)*
Symmetric wing bending	4.63	1.1
Antisymmetric wing bending	5.94	3.7
Symmetric wing bending	7.72	2.6
Antisymmetric wing bending	8.67	2.7
Symmetric wing and tailplane bending	13.34	4.1
Antisymmetric wing bending	14.22	6.4
Symmetric wing bending	15.36	1.3
Symmetric wing and tailplane bending	16.77	2.0
Antisymmetric wing torsion	17.31	3.3
Fuselage vertical bending	19.7	2.7
Antisymmetric tailplane torsion	28.3	5.3

Table 3

RESONANCE TESTS ON N24 TAILPLANE WITH FULL SPAN TABS
TAILPLANE MOUNTED ON AIRCRAFT

Mode	*Natural frequency (Hz)*	
	With T strips	*Without T strips*
Rigid-body tailplane rotation	9.2	9.2
Symmetric tailplane bending	16.2	16.4
Antisymmetric tab rotation	21.3	23.3
Symmetric tab rotation	26.5	29.3
Antisymmetric tailplane torsion	35.5	39.3
Antisymmetric tab rotation with tailplane restrained in bending	19.0	—
Symmetric tab rotation with tailplane restrained in bending	26.3	—

Table 4

RESONANCE TESTS ON N24 TAILPLANE WITH FULL SPAN TABS
LABORATORY TESTS WITH TAB TRIM JACK IN CIRCUIT

Mode	*Natural frequency (Hz)*	
	With T strips	*Without T strips*
Antisymmetric tab rotation	24.9	28.5
Antisymmetric tailplane torsion	35.8	39.1
Uncoupled antisymmetric tab rotation	27.7	34.2

Note: Tabs in mean position

Table 5

RESONANCE TESTS ON N24 TAILPLANE WITH FULL SPAN TABS
TABS IN MEAN POSITION WITHOUT TAB TRIM JACK

Mode	*Natural frequency (Hz)*	
	With T strips	*Without T strips*
Rigid-body tailplane rotation	11.1	—
Antisymmetric tab rotation	25.2	30.6
Symmetric tab rotation	29.6	—
Antisymmetric tailplane torsion	39.3	44.5
Independent tab torsion	54.9	58.3
Independent tab overtone torsion	—	75.9
Uncoupled antisymmetric tab rotation	—	33.0
Uncoupled symmetric tab rotation	30.3	32.8
Uncoupled tailplane torsion	—	33.9*

* Measured with tabs removed

Table 6

RESONANCE TESTS ON N24 TAILPLANE WITH FULL SPAN TABS
TABS AT 22° INCIDENCE WITHOUT TAB TRIM JACK

Mode	*Natural frequency (Hz)*	
	With T strips	*Without T strips*
Antisymmetric tab rotation	—	29.5
Antisymmetric tailplane torsion	—	44.5

Table 7

CHORDWISE LOCATION OF PRESSURE TAPPINGS IN WIND TUNNEL MODEL

Fraction of chord	
Upper surface	*Lower surface*
0.042	0.041
0.079	0.082
0.115	0.118
0.173	0.175
0.240	0.242
0.317	0.319
0.388	0.394
0.481	0.481
0.551	0.553
0.651	0.654
0.690	0.692
0.767	0.768
0.798	0.798
0.833	0.835
0.842	0.844
0.875	—
0.887	0.888
0.895	0.897
0.911	0.915
0.929	0.934
0.946	0.948
0.964	0.968
0.983	0.982
0.990	0.990

Table 8

COMPARISON OF UNSTEADY AERODYNAMIC DERIVATIVES FOR 2-DIMENSIONAL MODEL WITH AND WITHOUT T STRIPS

Derivative	$\nu \approx 1.6$			$\nu \approx 3.1$			$\nu \approx 4.8$			$\nu \approx 5.9$	
No.	*No strips*	*1" strips*	*2" strips*	*No strips*	*1" strips*	*2" strips*	*No strips*	*1" strips*	*2" strips*	*No strips*	*2" strips*
1	—0.536	—0.961	—1.082	—0.541	—0.853	—0.979	—0.608	—0.886	—1.057	—0.685	—1.043
2	—0.290	—0.575	—0.635	—0.304	—0.533	—0.608	—0.344	—0.562	—0.659	—0.376	—0.631
3	—0.0034	—0.017	—0.021	—0.0032	—0.015	—0.019	—0.0032	—0.014	—0.019	—0.0029	—0.016
4	0.016	0.134	0.137	—0.046	0.012	0.014	—0.055	—0.024	—0.018	—0.071	—0.052
5	—0.032	0.009	0.013	—0.046	—0.018	—0.021	—0.051	—0.033	—0.031	—0.059	—0.053
6	—0.0017	—0.0014	—0.0013	—0.0017	—0.001	—0.001	—0.0018	—0.0013	—0.001	—0.0019	—0.0015

Derivative 1 = lift due to tab rotation (in-phase)
2 = leading edge moment due to tab rotation (in-phase)
3 = hinge moment due to tab rotation (in-phase)
4 = lift due to tab rotation (in-quadrature)
5 = leading edge moment due to tab rotation (in-quadrature)
6 = hinge moment due to tab rotation (in-quadrature)

Table 9

SUMMARY OF RESULTS FOR HIGH FREQUENCY MODEL

Configuration	*Calculated flutter speed for various parameter combinations KEAS* — *Least stable*	*Most stable*	*Most probable*
Standard tabs			
— no T strips	No flutter	No flutter	No flutter
— small T strips	82	No flutter	125
— large T strips	84	140	115
Extended tabs			
— no T strips	140	No flutter	No flutter
Full span tabs			
— no T strips	130	No flutter	No flutter
— small T strips	68	No flutter	106
— large T strips	73	132	103

Note: No flutter indicates that the configuration is free from flutter at speeds below 250 KEAS.

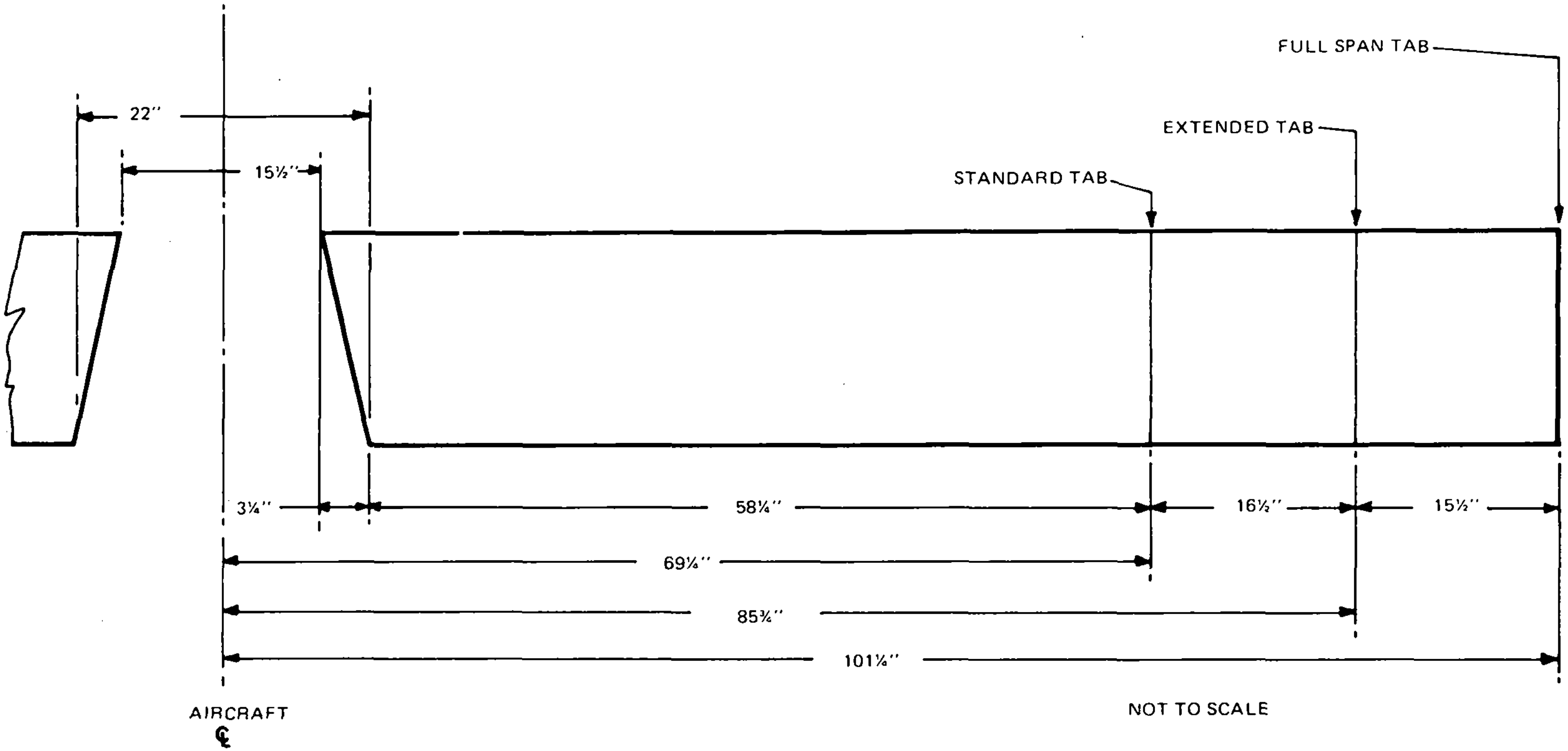

Fig. 1 NOMAD TAB GEOMETRY.

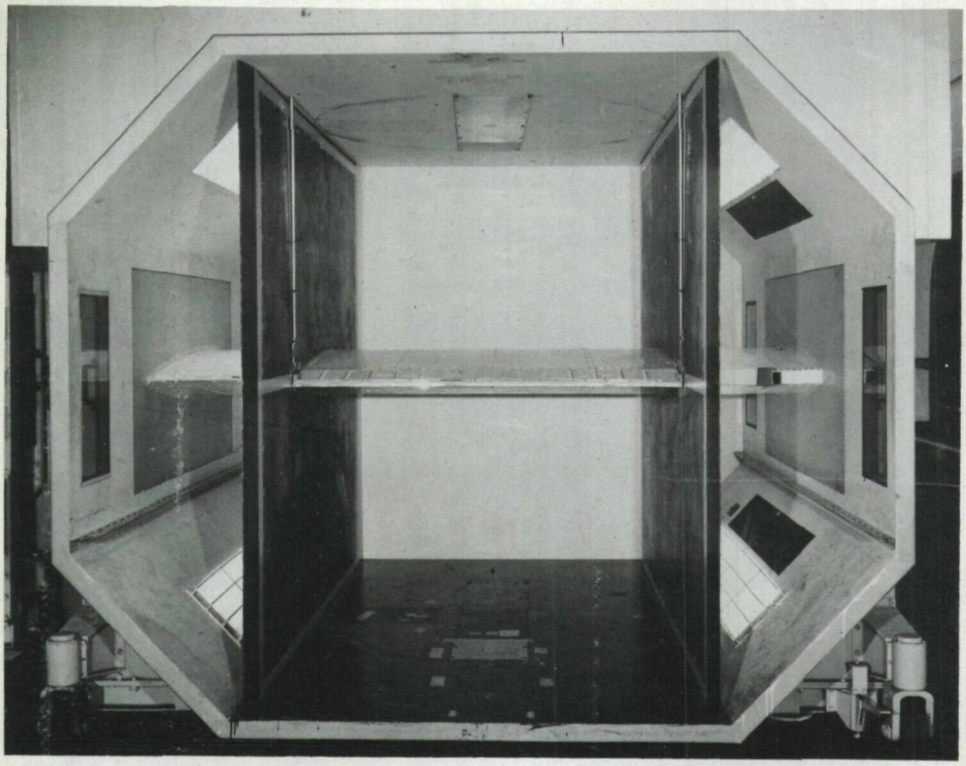

Fig. 2 WIND TUNNEL MODEL MOUNTED IN WORKING SECTION OF TUNNEL.

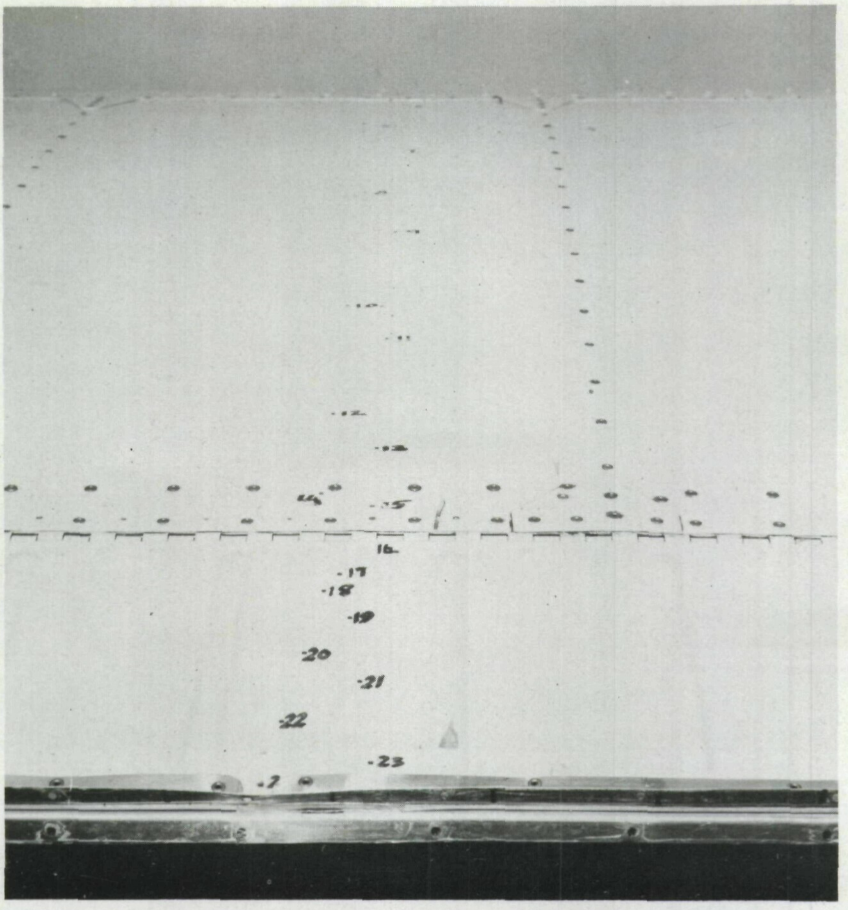

Fig. 3 WIND TUNNEL MODEL SHOWING UPPER SURFACE PRESSURE TAPPINGS.

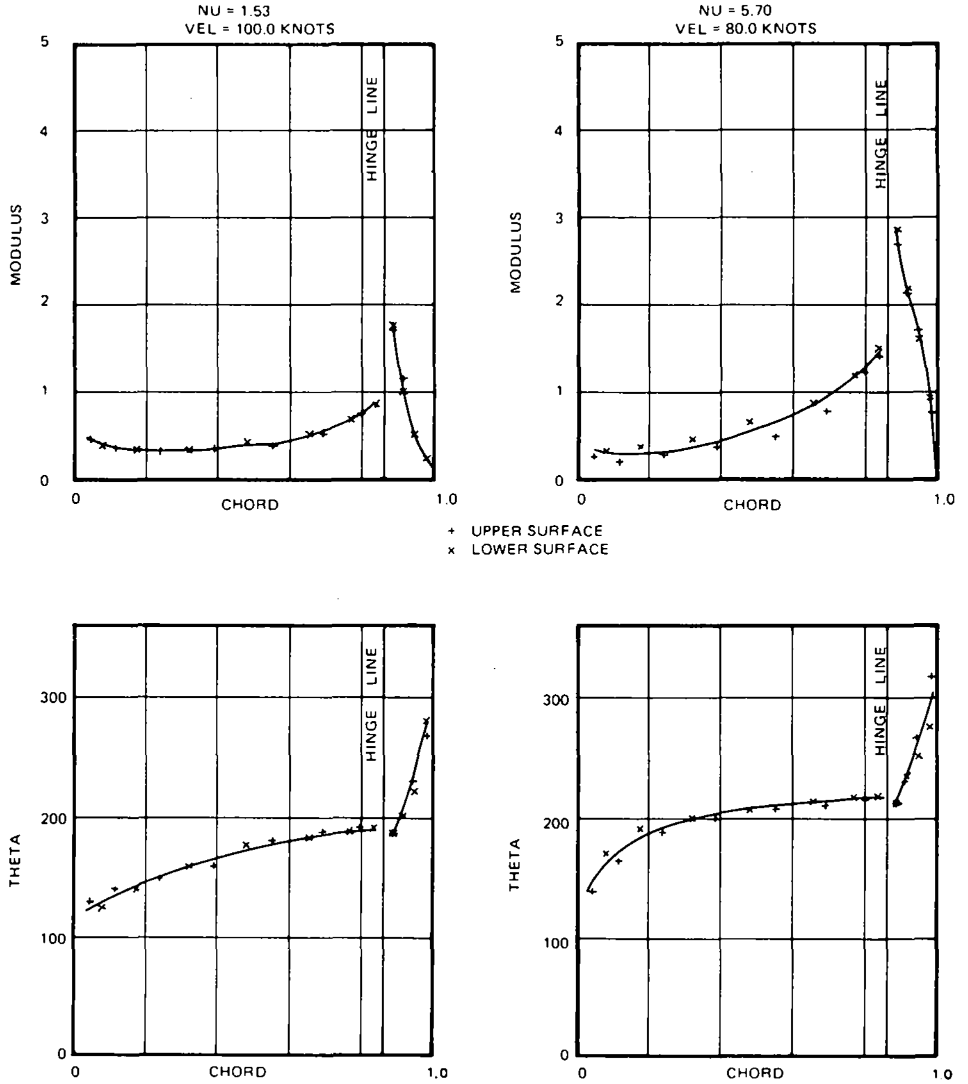

Fig. 4 CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION NO T STRIPS.

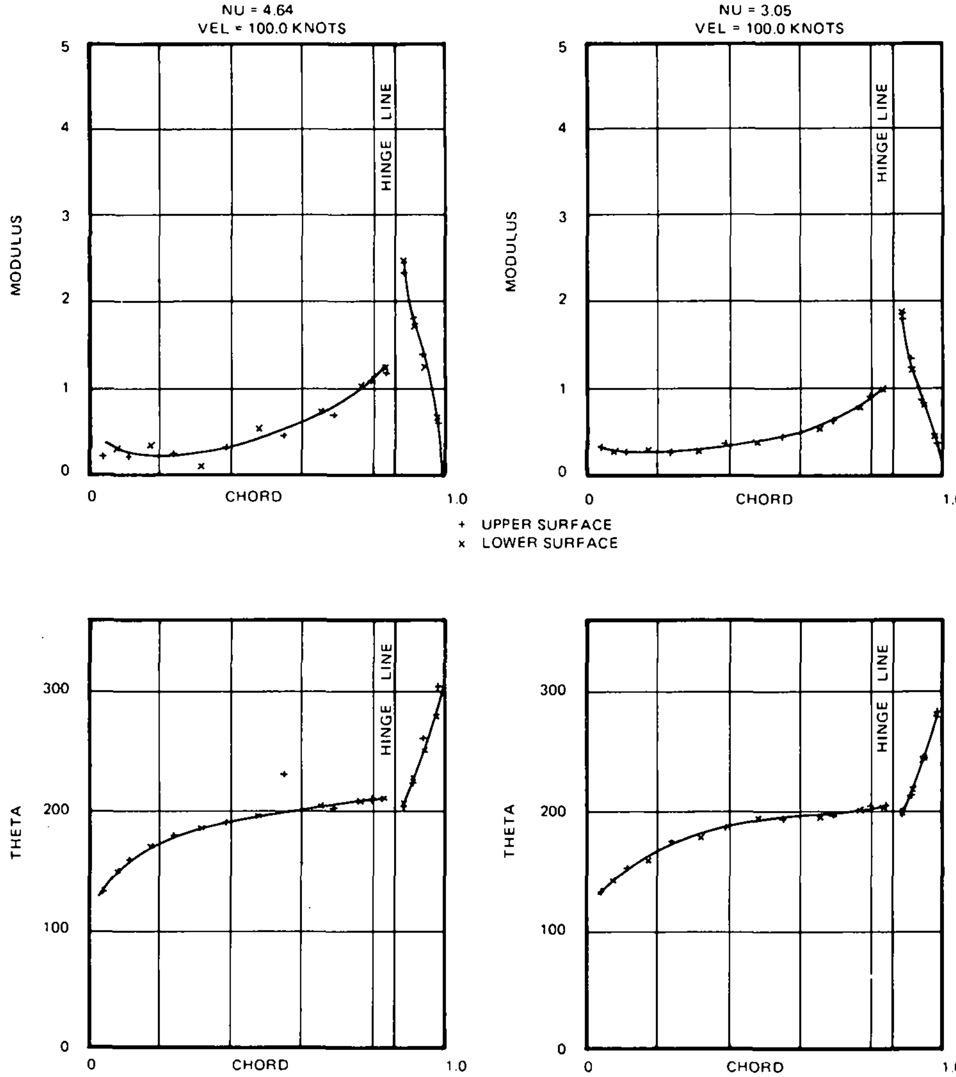

Fig. 5 CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION NO T STRIPS.

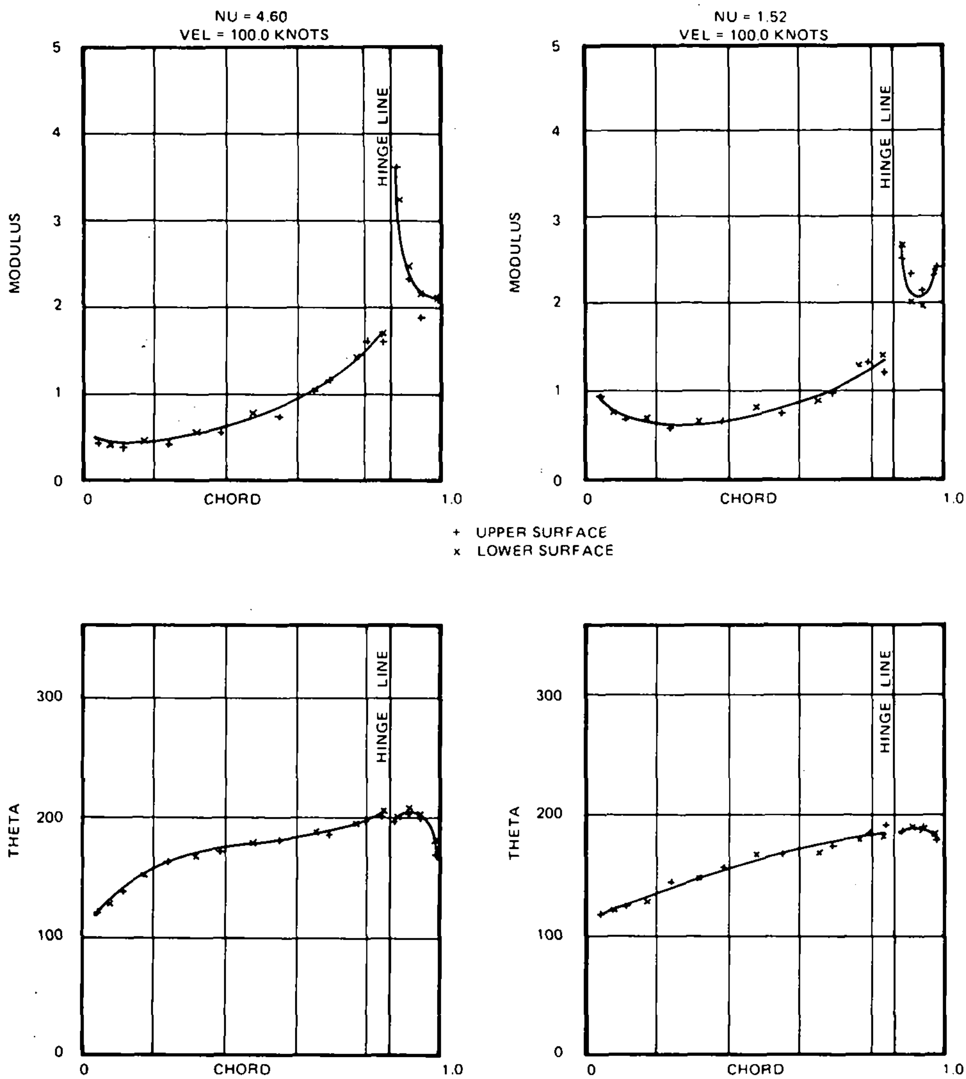

Fig. 6A CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION LARGE T STRIPS.

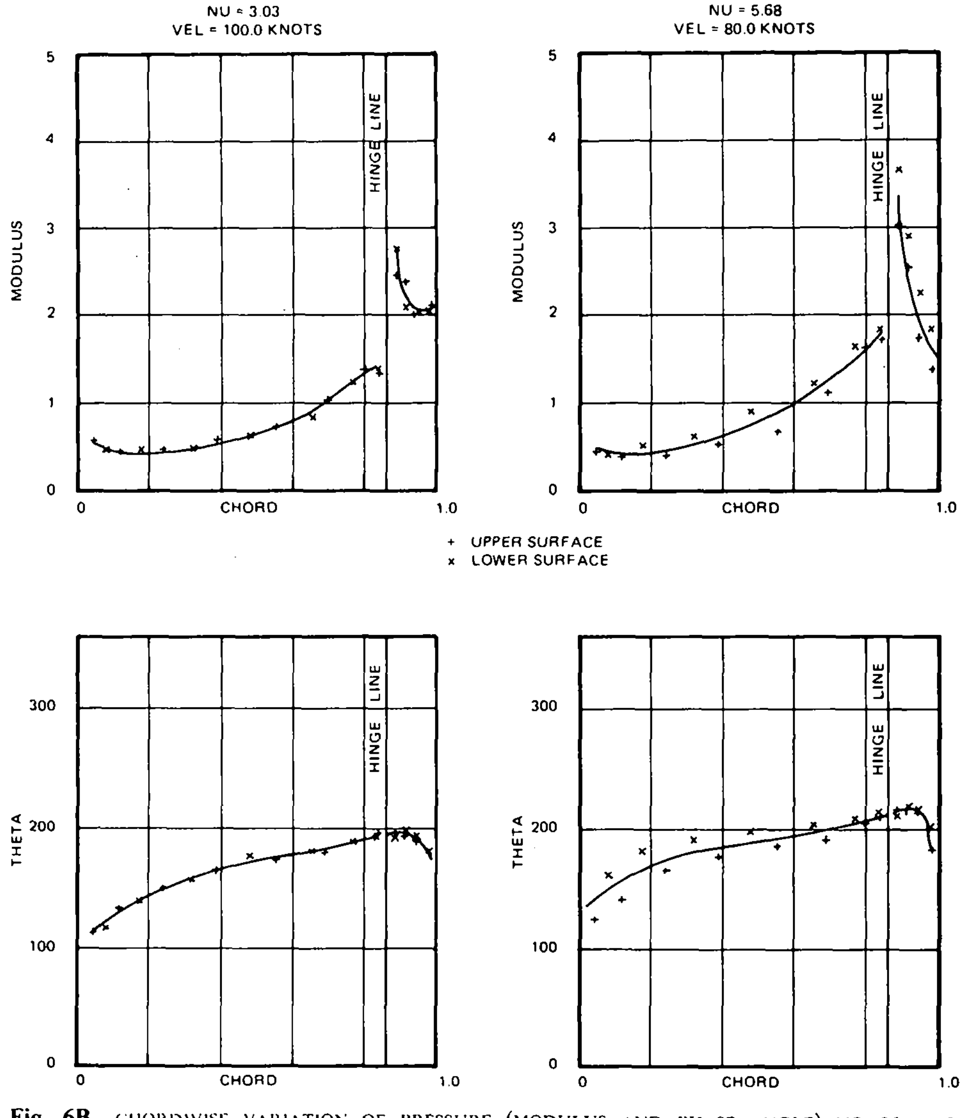

Fig. 6B CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION LARGE T STRIPS.

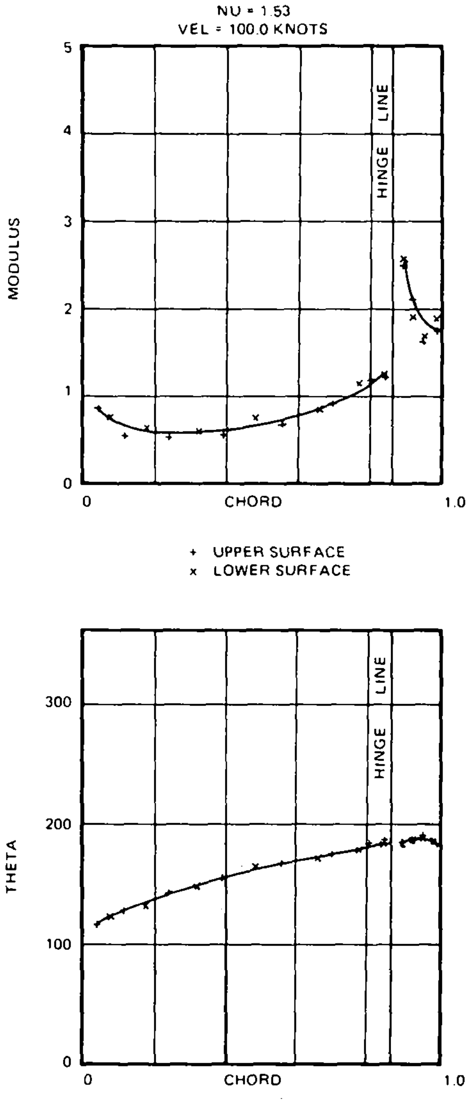

Fig. 7A CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION SMALL T STRIPS.

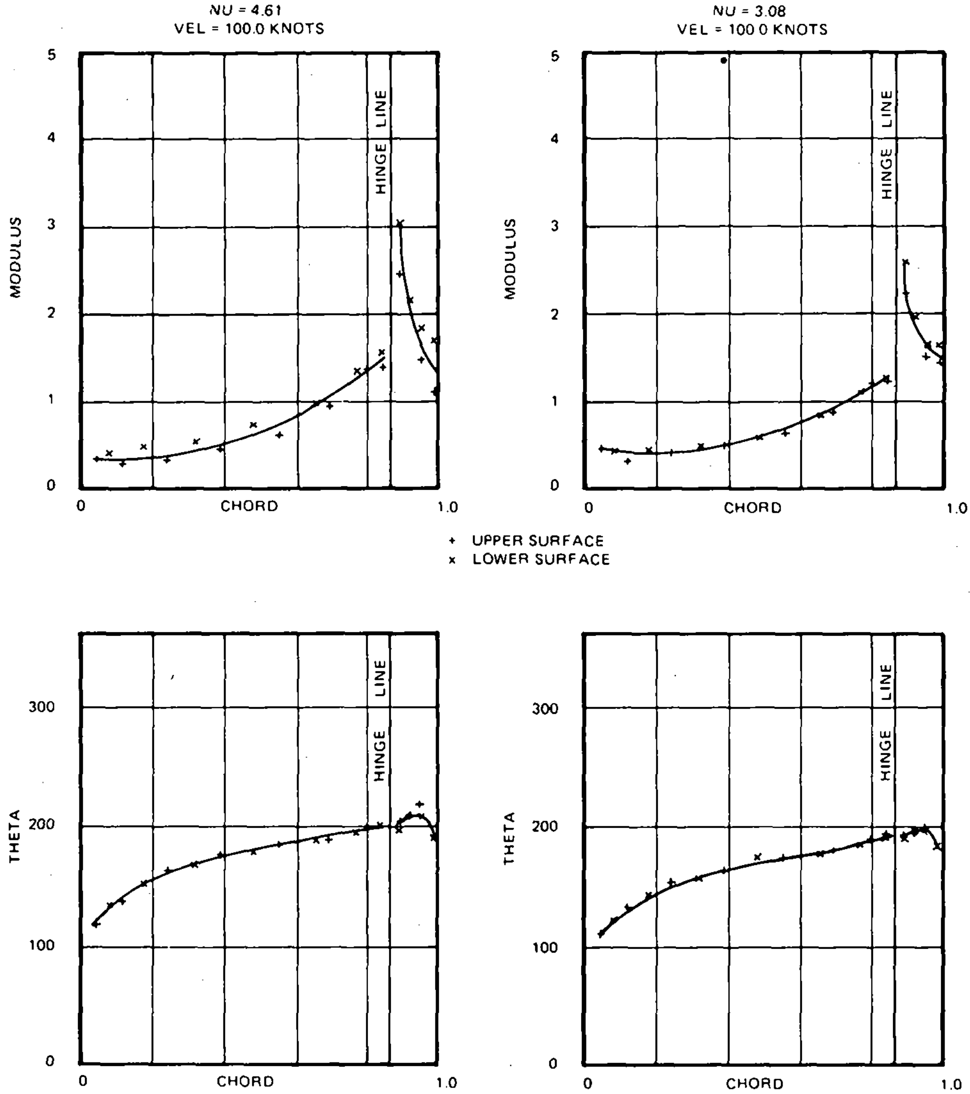

Fig. 7B CHORDWISE VARIATION OF PRESSURE (MODULUS AND PHASE ANGLE) NO CONTROL DEFLECTION SMALL T STRIPS.

LOW FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	11.0	0.51	0
2	11.0	0.49	1.0
3	11.0	1.00	1.0
4	9.0	1.00	1.0
5	9.0	0.51	1.0

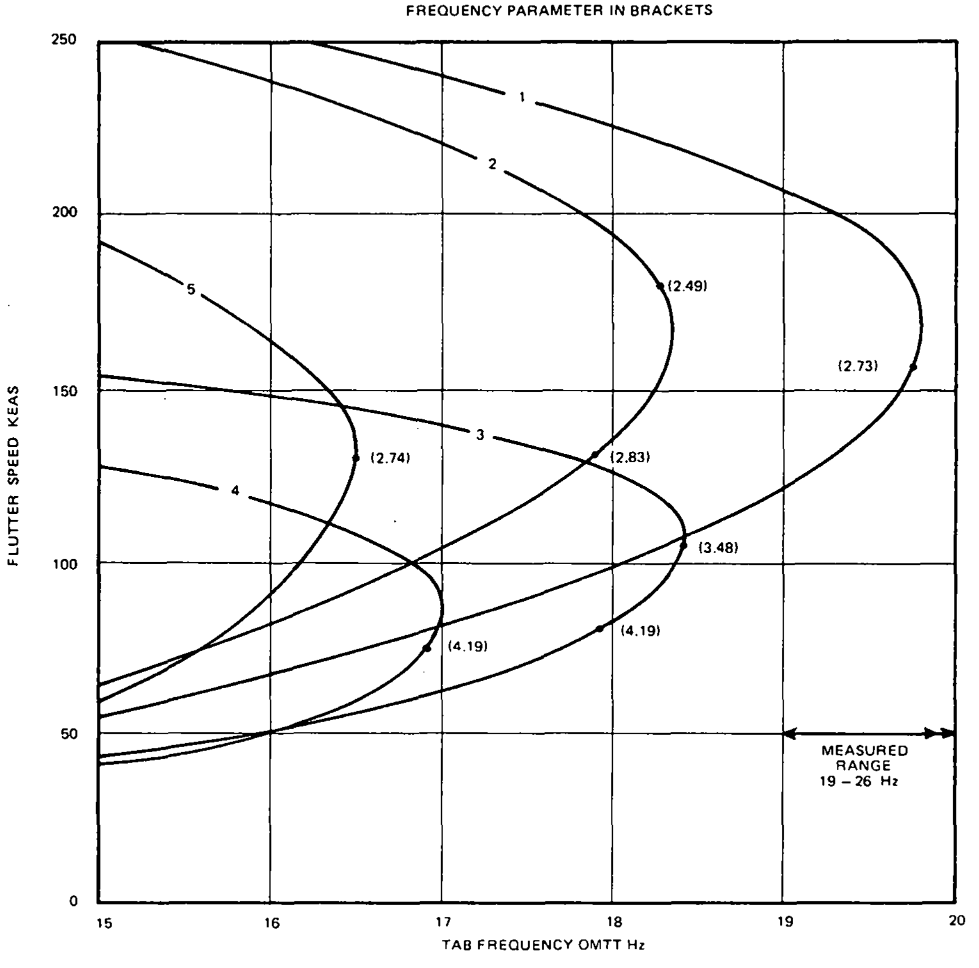

Fig. 8 FULL SPAN TABS WITH LARGE T STRIPS.

LOW FREQUENCY MODEL

HYBRID AERODYNAMICS

Curve	OMT	FT	SDF
1	11.0	0.5	0
2	11.0	0.5	1.0
3	11.0	1.0	1.0

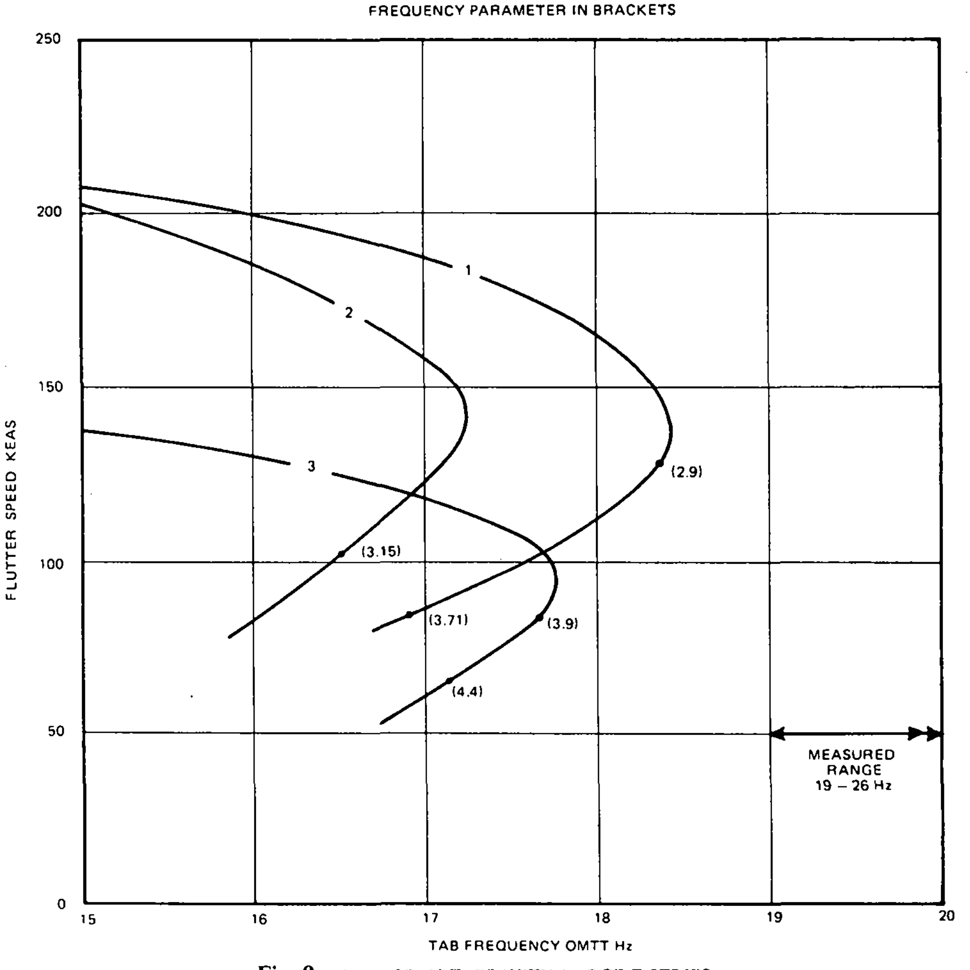

Fig. 9 FULL SPAN TABS WITH LARGE T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	1.0	2.0
4	33.8	1.0	1.0

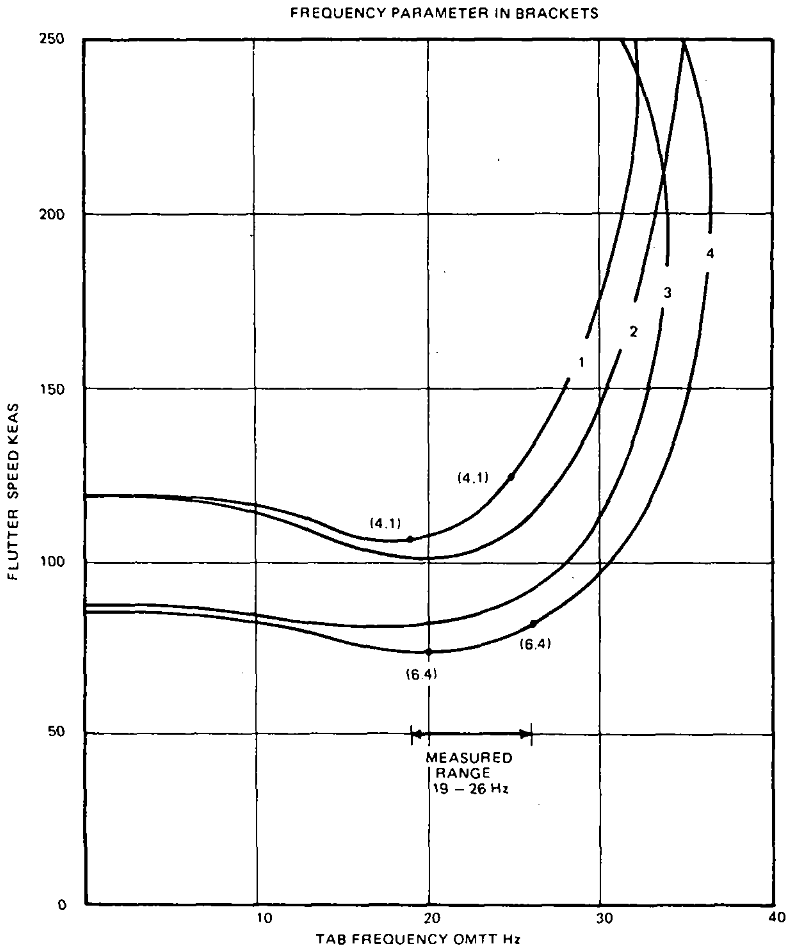

Fig. 10 FULL SPAN TABS WITH LARGE T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	OMTT	SDF
1	33.8	26.0	2.0
2	33.8	26.0	1.0
3	33.8	19.0	2.0
4	33.8	19.0	1.0

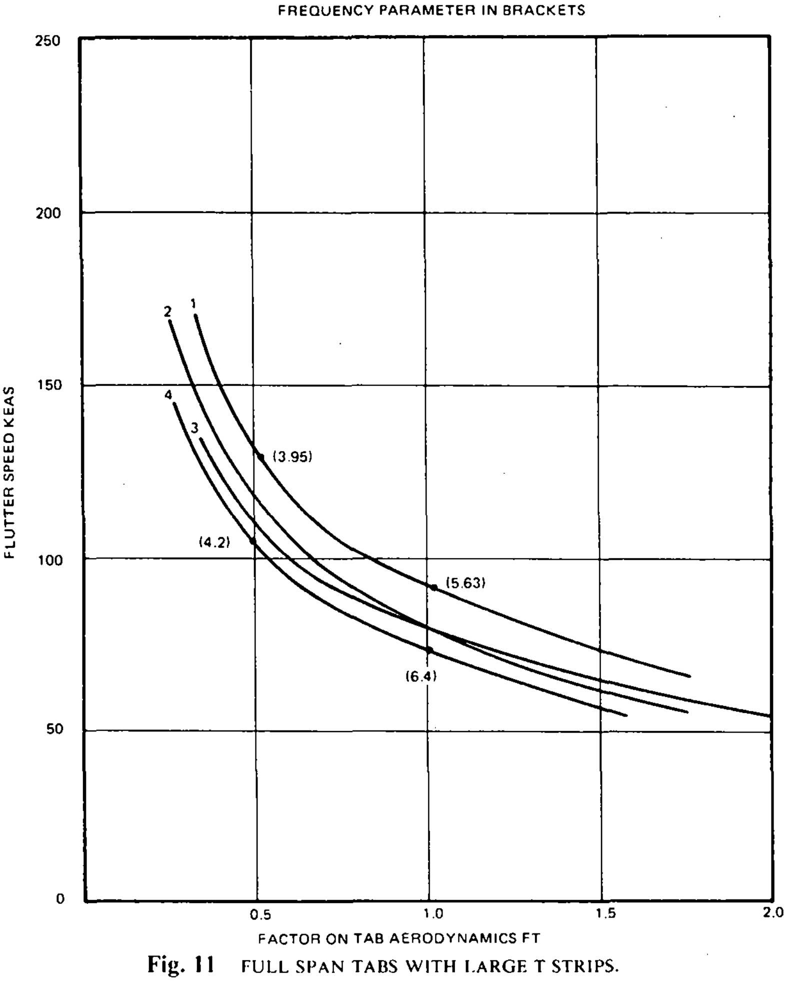

Fig. 11 FULL SPAN TABS WITH LARGE T STRIPS.

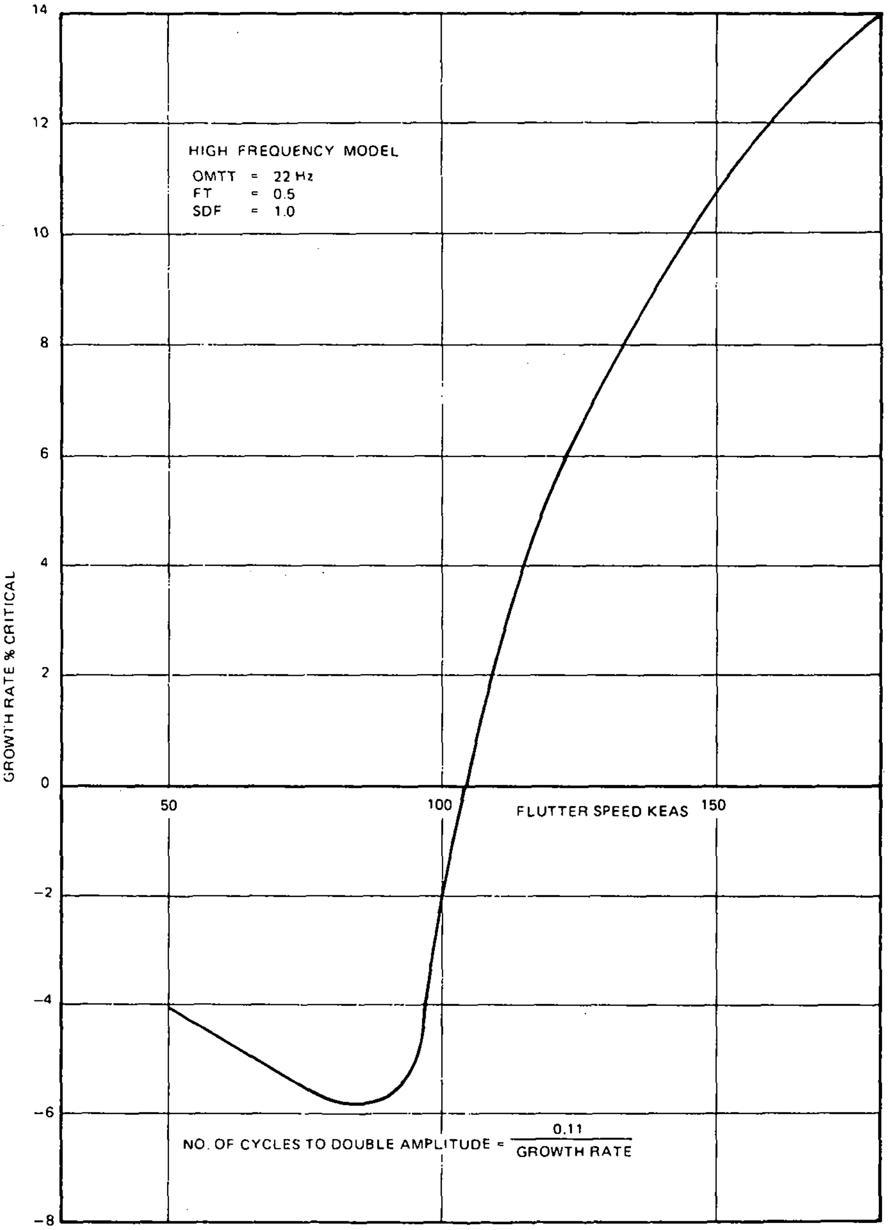

Fig 12 FULL SPAN TABS WITH LARGE T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	1.0	2.0
4	33.8	1.0	1.0

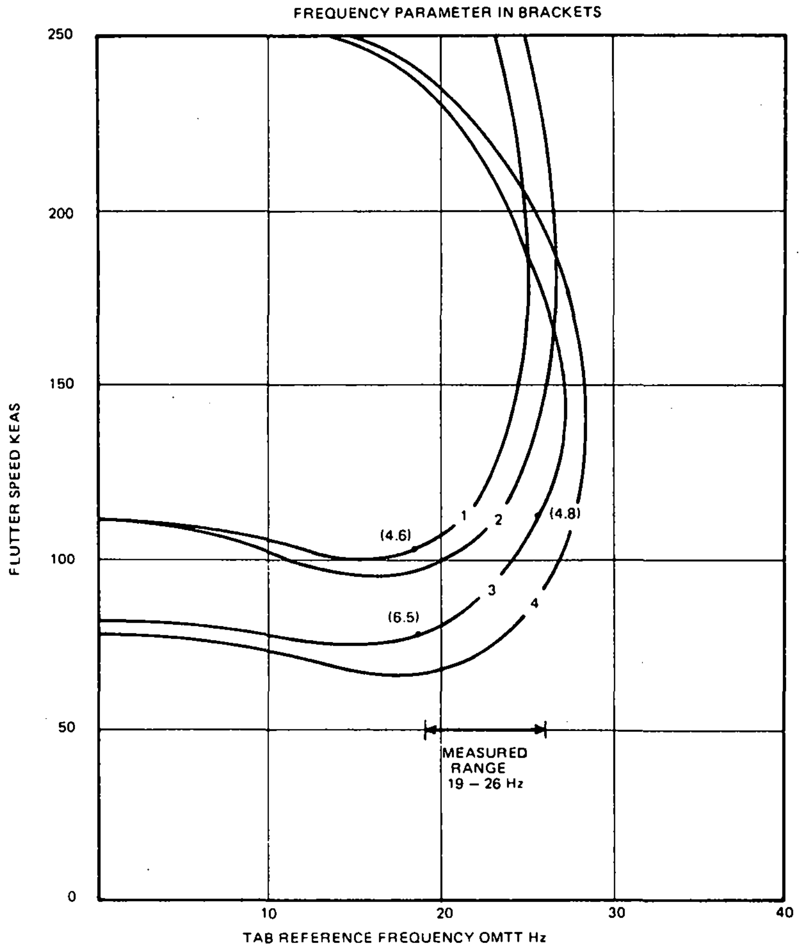

Fig. 13 FULL SPAN TABS WITH SMALL T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	OMTT	SDF
1	33.8	26.0	2.0
2	33.8	26.0	1.0
3	33.8	19.0	2.0
4	33.8	19.0	1.0

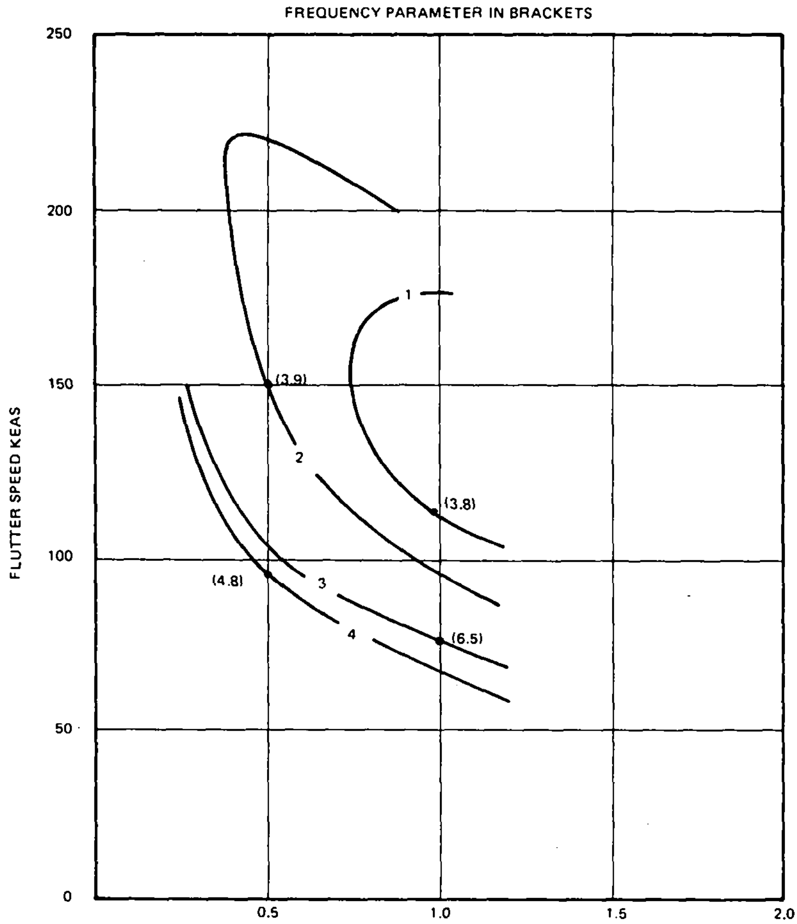

Fig. 14 FULL SPAN TABS WITH SMALL T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	1.0	2.0
2	33.8	1.0	1.0

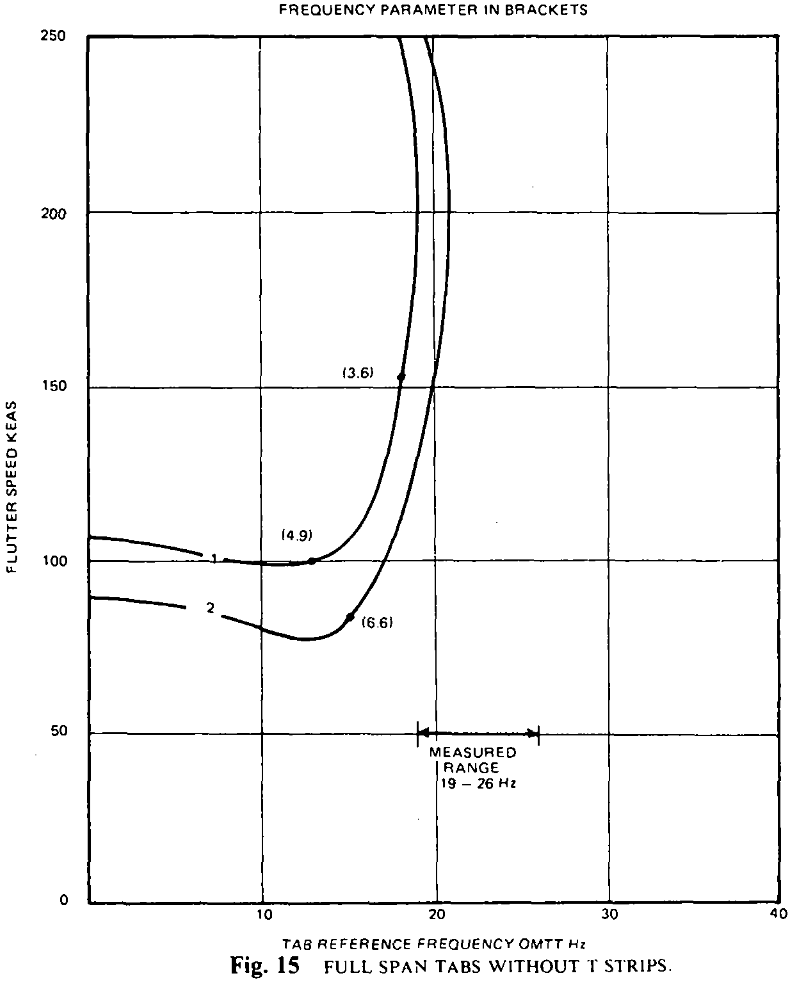

Fig. 15 FULL SPAN TABS WITHOUT T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	1.0	2.0
4	33.8	1.0	1.0

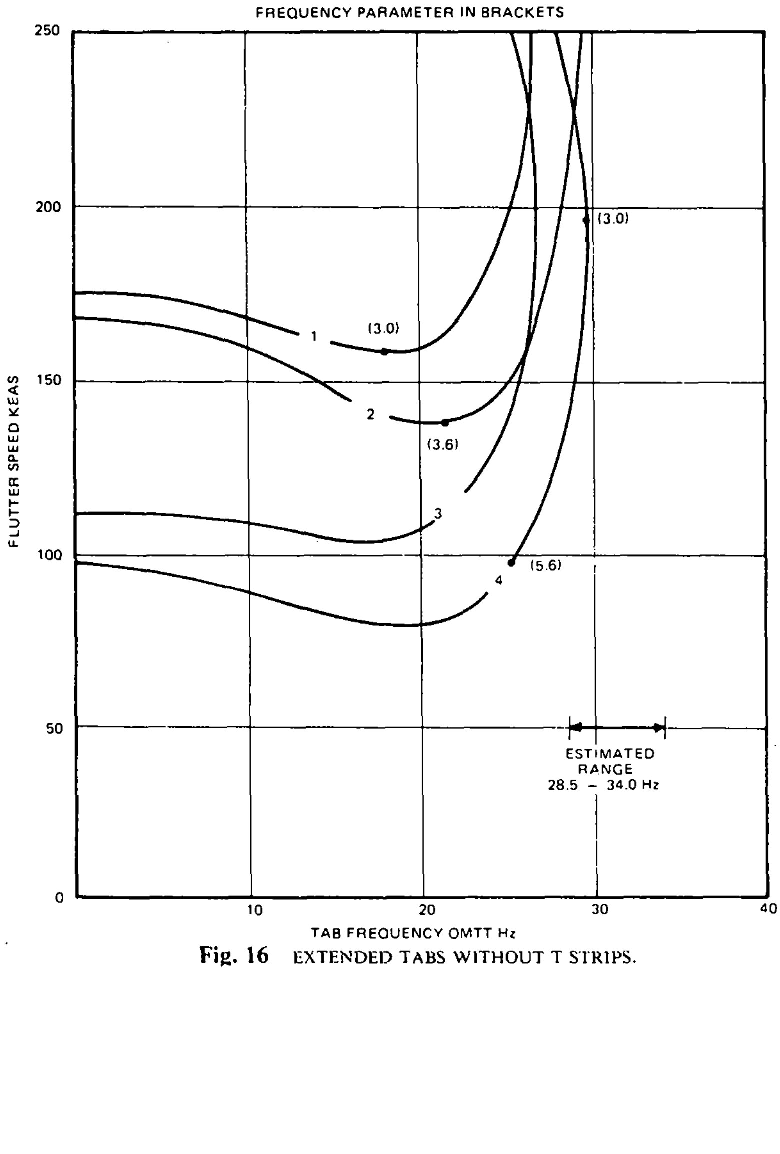

Fig. 16 EXTENDED TABS WITHOUT T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	1.0	2.0
4	33.8	1.0	1.0

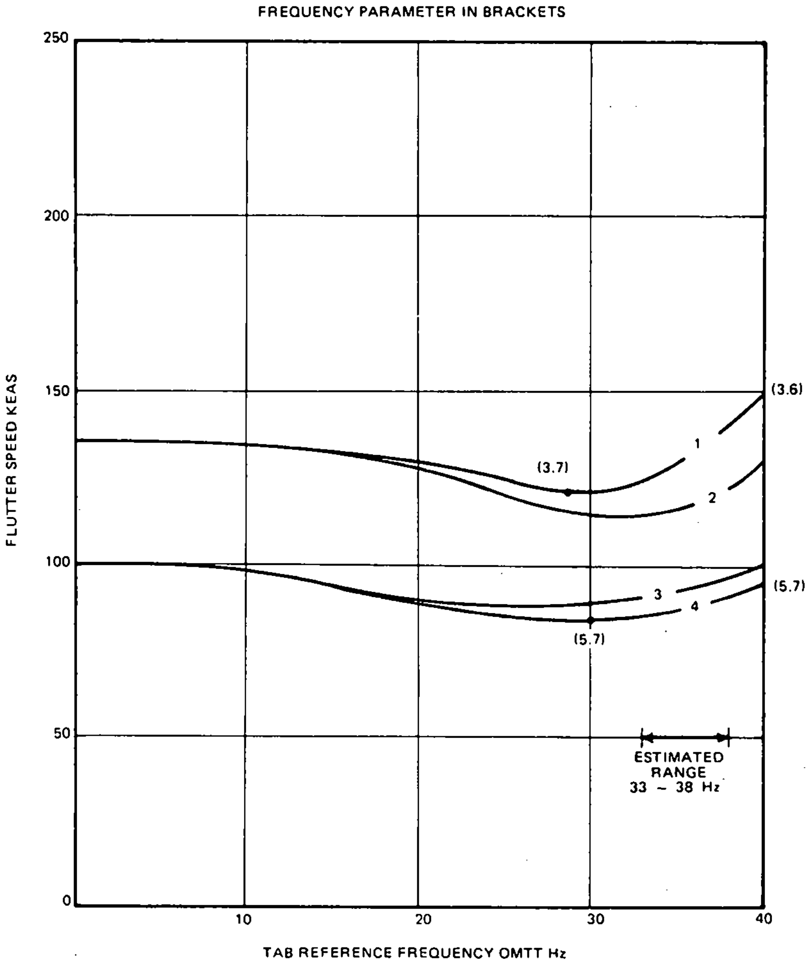

Fig. 17 STANDARD TABS WITH LARGE T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	1.0	2.0
4	33.8	1.0	1.0

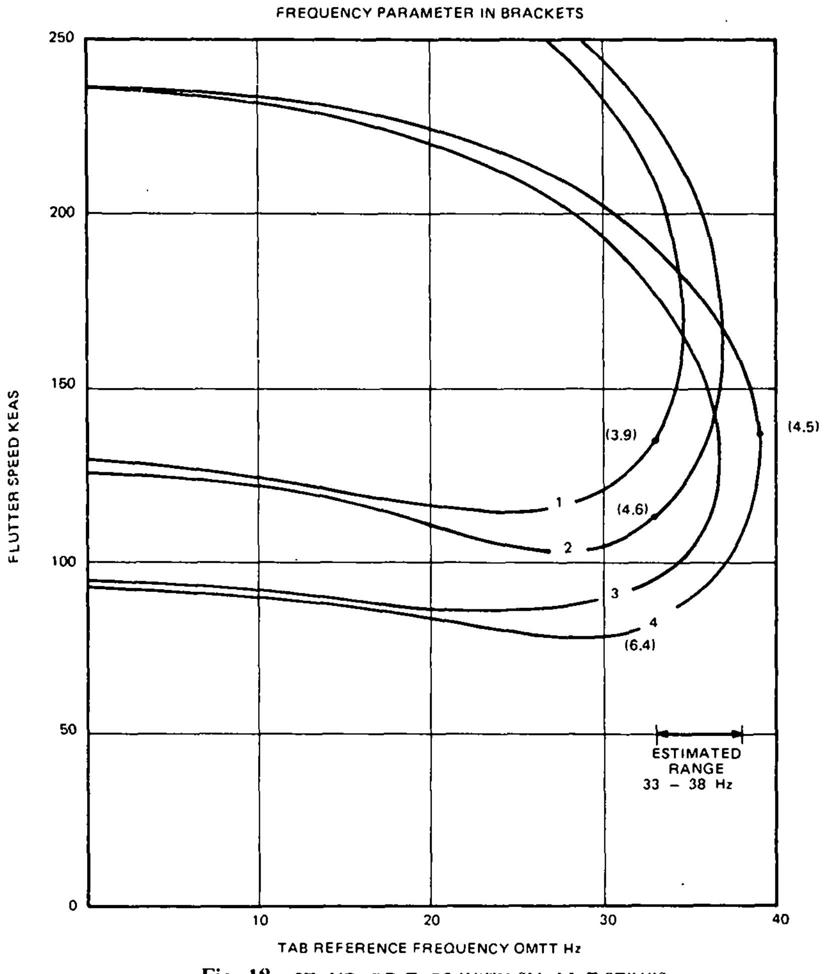

Fig. 18 STANDARD TABS WITH SMALL T STRIPS.

HIGH FREQUENCY MODEL

SINGLE SURFACE AERODYNAMICS

Curve	OMT	FT	SDF
1	33.8	0.5	2.0
2	33.8	0.5	1.0
3	33.8	0.5	0
4	33.8	1.0	2.0
5	33.8	1.0	1.0

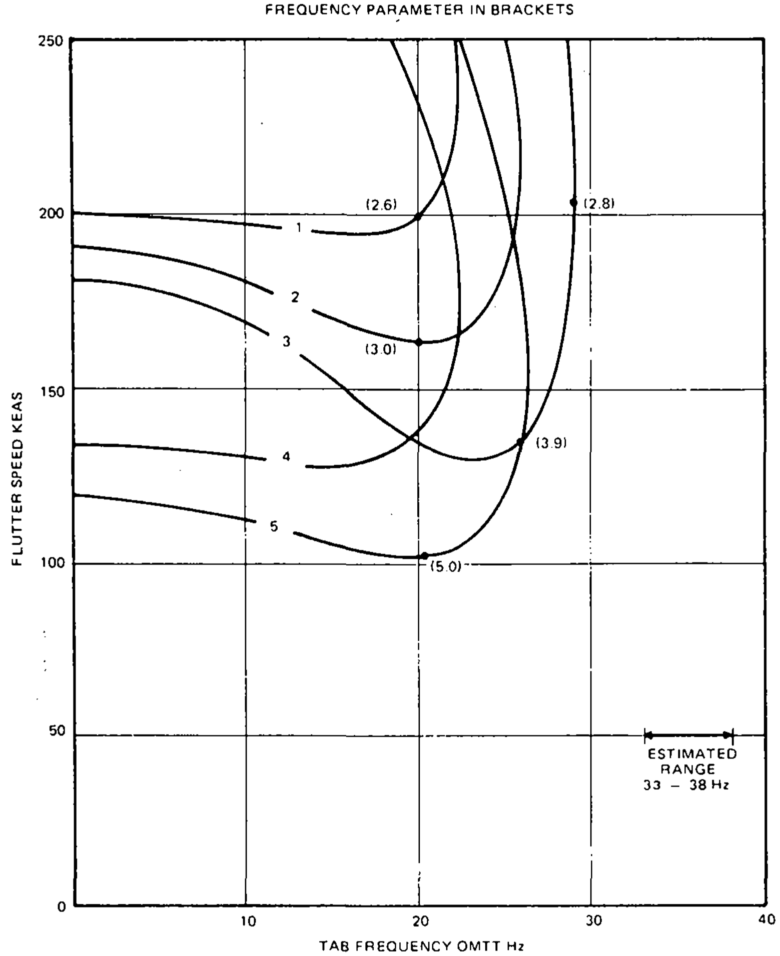

Fig. 19 STANDARD TABS WITHOUT T STRIPS.