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**A PRELIMINARY STUDY OF THE
EFFECTS OF VORTEX DIFFUSERS (WINGLETS)
ON WING FLUTTER**

By Robert V. Doggett, Jr., and Moses G. Farmer

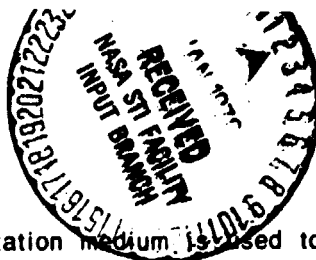
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SUMMARY

Some experimental flutter results are presented for a simple, flat-plate wing model and for the same wing model equipped with two different upper surface vortex diffusers over the Mach number range from about 0.70 to 0.95. Both vortex diffusers had the same planform, but one weighed about 0.3 percent of the basic wing weight, whereas the other weighed about 1.8 percent of the wing weight. The addition of the lighter vortex diffuser reduced the flutter dynamic pressure by about 3 percent; the heavier vortex diffuser reduced the flutter dynamic pressure by about 12 percent. The experimental flutter results are compared at a Mach number of 0.80 with analytical flutter results obtained by using doublet lattice and lifting surface (kernel function) unsteady aerodynamic theories.

INTRODUCTION

Currently there is considerable interest in reducing aircraft fuel consumption. One way to reduce aircraft fuel usage is through improved aerodynamic efficiency. Some recent work at the Langley Research Center has indicated that significant reductions in induced drag-due-to-lift can be achieved by the addition of small nearly vertical wing-like surfaces called vortex diffusers (sometimes referred to as winglets) at the tip of the main wing. Some results from vortex diffuser studies are presented in references 1 and 2. An attractive feature of vortex diffusers is that they can not only be incorporated in new aircraft designs but also have the potential for use as a modification to current designs. However, the addition of vortex diffusers to current designs does raise the question of what are the structural and dynamic implications. A specific question that must be addressed is the effects of vortex diffusers on flutter. Consequently, some wind-tunnel flutter model studies were made in the Langley transonic dynamics tunnel using a relatively simple cantilever, flat-plate wing model that was tested with and without upper surface vortex diffusers. The purpose of this paper is to present the results from this study. It should be pointed out that the latest vortex diffuser aerodynamic studies indicate the desirability of having both upper surface and lower surface vortex diffusers--a large one mounted rearward on the upper surface at the wing tip,

and a smaller one mounted forward on the lower usrface at the tip. Lower surface vortex diffusers were not included in the present study. The basic wing model used here had a planform representative of current subsonic transport designs. The same wing model was tested with and without two different vortex diffusers. The vortex diffusers were, like the wing, flat-plate models and weighed about 0.3 percent and 1.8 percent of the basic wing weight, respectively. Experimental flutter results are presented over the Mach number range from about 0.70 to 0.95. Some experimental results are compared with analytical results obtained using doublet-lattice and lifting surface (kernel function) unsteady aerodynamic theories.

SYMBOLS

b_r	reference semichord
f	frequency
f_f	flutter frequency
f_r	reference frequency, measured frequency of third natural mode
m	mass
q	dynamic pressure, $1/2 \rho V^2$
V	velocity
V_I	flutter-speed index parameter, $V/(b_r \omega_r \sqrt{\mu})$
v	reference volume
μ	mass-ratio parameter, $\frac{m}{\rho v}$
ρ	density
ω_r	reference circular frequency, $2\pi f_r$

Subscripts:

c	calculated
e	experimental

MODELS

Description

The basic wing model configuration used in this investigation was a semispan aspect ratio 6.37 wing with no dihedral, a leading-edge sweep of 38.2° , and a taper ratio of 0.20. Two other models, consisting of the basic configuration with an upper surface vortex diffuser, were tested in an effort to determine the vortex diffuser effects on the basic wing flutter characteristics. It should be pointed out that since the vortex diffusers used here were uncambered, nonlifting surfaces, only the planform aerodynamic effects and structural mass and stiffness effects of the diffusers were evaluated. The primary difference between the two vortex diffusers was in structural mass and stiffness. One weighed about 0.3 percent, and the other weighed about 1.8 percent of the basic wing weight. The two vortex diffuser configurations will be referred to hereafter as the light diffuser model and the heavy diffuser model, respectively. The vortex diffusers were mounted aft on the wing tip chord and were canted outward $17-1/2^\circ$ from a plane perpendicular to the plane of the wing. The vortex diffuser had a 39.9° leading edge sweepback, a 0.33 taper ratio, and a 5.00 aspect ratio.

A photograph of the heavy diffuser model mounted in the wind tunnel is presented in figure 1. Sketches giving the geometric properties of the wing and vortex diffuser are presented in figure 2.

The models were constructed of constant thickness aluminum alloy plate. The plate thicknesses were 0.4826 cm (0.190 in.) for the wing, 0.0813 cm (0.032 in.) for the light diffuser, and 0.4826 cm (0.190 in.) for the heavy diffuser. The leading edges of the plate models were rounded, and the trailing edges of the wing and heavy diffuser were beveled. The flat plate was extended inboard of the model root to provide a base for clamping the models in a cantilever fashion along the forward 80 percent of the root chord.

The basic wing was instrumented with electric resistance-type strain gages to measure dynamic response.

Physical Properties and Vibration

Characteristics

The total measured mass properties of the three models are presented in table I. The first four natural frequencies were measured for the basic wing and heavy diffuser models. The first three frequencies were measured for the light diffuser model. The measured values are given in table II along with the first five calculated natural frequencies of the basic wing and heavy diffuser models and the first seven calculated frequencies of the light diffuser model. The corresponding calculated natural mode nodal patterns are

presented in figure 3. Also included in the figure are the measured node lines for the first four basic wing model modes and the first three heavy diffuser model modes. The calculated and measured nodal patterns are very similar. The measured node lines were obtained by the 1G sand method. The calculated modal data were obtained by using the NASA Structural Analysis (NASTRAN) Computer Program (references 3 and 4). Quadrilateral structural finite elements (NASTRAN QUAD2) were used to model the structure. Ninety elements were used for the wing portion of all three models; 27 elements were used for the diffusers. The arrangement of the elements is shown in figure 4.

FLUTTER EXPERIMENTS

Wind Tunnel

This investigation was conducted in the Langley transonic dynamics tunnel. The tunnel has a 4.88m (16-foot) square test section with cropped corners. The tunnel is a slotted-throat, single-return wind tunnel equipped to use either air or Freon-12 as the test medium at stagnation pressures from near vacuum to about atmospheric at Mach numbers up to 1.2. Only Freon-12 was used for the present investigation. The tunnel is of the continuous-operation type and is powered by a motor-driven fan. Both test-section Mach number and density are continuously controllable. The tunnel is equipped with four quick-opening bypass valves which can be operated to rapidly reduce test section dynamic pressure and Mach number when flutter occurs.

Test Procedure

The same general procedure was used for all the tests. The determination of a typical flutter point proceeded as follows: With the tunnel evacuated to a low stagnation pressure, the fan speed was increased until the desired test-section Mach number was reached. The test-section Mach number was then held nearly constant, and the test-section density was gradually increased by bleeding Freon-12 into the tunnel through an expansion valve until flutter was reached. The test-section dynamic pressure and Mach number were then rapidly decreased by opening the four bypass valves. The actuation of the bypass valves also locked the tunnel instruments so that the tunnel conditions necessary to completely describe the flutter point could be recorded after precautions had been taken to save the model. The compressor speed was then decreased to a point well below the flutter condition, and the bypass valves were closed. This process was repeated several times to define the flutter boundary over the Mach number range of interest.

During each flutter condition the outputs from the bending and torsion resistance-wire strain gages mounted near the model root were recorded on a recording oscillograph. From these oscillograph records the flutter frequencies were determined. The first three natural frequencies were obtained for each model before and after each tunnel test to determine whether or not the model had been damaged.

FLUTTER ANALYSIS

Flutter calculations were made for all three models at 0.80 Mach number. The flutter equations in matrix notation were expressed in terms of generalized modal coordinates, and the traditional V-g method of solution, automated essentially as described in reference 5, was used. The calculated natural frequencies and mode shapes were used in the analysis. The first five modes were used for the basic wing and the heavy diffuser models; the first seven modes were used for the light diffuser model. Surface spline functions (ref. 9) were used to interpolate the calculated modal deflections to the modal displacements and streamwise slopes required to determine the unsteady aerodynamic forces. Calculations were made using both doublet-lattice unsteady aerodynamic forces (references 6 and 7) and subsonic lifting-surface theory (ref. 8). The doublet-lattice paneling arrangement consisted of 186 boxes on the wing and 72 boxes on the diffuser arranged as shown in figure 5. The locations of the 36 subsonic lifting-surface (kernel function) collocation points used are indicated by the solid circle symbols in figure 5. In the kernel function calculations no aerodynamic effects of the diffusers were included. Doublet-lattice calculations were made with and without diffuser aerodynamic effects included.

RESULTS AND DISCUSSION

The basic experimental flutter results are presented in figure 6 as the variations with Mach number of the mass-ratio parameter μ , of the flutter-frequency ratio f_f/f_r , and of the flutter-speed index parameter V_f . The mass-ratio parameter μ is defined as the ratio of the total model mass to the mass of a representative surrounding volume of test medium. The volume used here is that contained in the conical frustums generated by revolving each wing chord (and vortex diffuser chord) about its midpoint. These volumes were $6.926 \times 10^4 \text{ cm}^3$ (4226.4 in.^3) for the basic wing model and $6.946 \times 10^4 \text{ cm}^3$ (4238.8 in.^3) for both vortex diffuser configurations. The third measured natural frequency was used as the reference frequency f_r . The semichord at the basic wing three-quarter span station was used as the reference length b_r . This length was 9.36 cm (3.685 in.). The flutter-speed-index-parameter curves represent stability boundaries with the stable region below the curve. This parameter depends on the physical properties of the model, in particular the stiffness, and the atmosphere in which it operates. When plotted as the ordinate against Mach number, constant dynamic pressure lines are parallel to the Mach number abscissa.

No unusual trends are shown by the data presented in figure 6 for all three configurations studied. The flutter boundaries are similar to those usually observed, namely, a gradual decrease in flutter speed occurs as the subsonic Mach number is increased. Flutter data were not obtained at sufficiently high Mach numbers to define the minimum flutter speed which

usually occurs in the transonic regime.

A comparison of the flutter boundaries for all three models may be made by examining the data presented in figure 7 where the variations of flutter-speed-index parameter and flutter dynamic pressure with Mach number are shown. Note that the addition of the vortex diffusers to the basic wing did have an adverse effect on the flutter characteristics, the heavier the vortex diffuser the greater the effect. In general, the addition of the light and heavy vortex diffusers resulted in flutter dynamic pressure reductions over the Mach number range studied of about 3 percent and 12 percent, respectively.

Flutter analyses were made at $M = 0.80$ for all three model configurations by using kernel function and doublet lattice unsteady aerodynamic theories. The density values used in the calculations were obtained by interpolating the mass ratio curves in figure 6. The analytical results are presented in figure 8 as the variation of the ratio of flutter frequency to reference frequency and of dynamic pressure versus vortex diffuser weight relative to wing weight. The experimental results (plotted from the curves in figures 6 and 7 for $M = 0.80$) for this Mach number are also included in the figure. Kernel function results are presented where only wing unsteady aerodynamic forces were included. That is, only the structural effects of the vortex diffusers were included in the analysis. Doublet lattice results are presented both with and without vortex diffuser unsteady aerodynamic forces included. It should be noted that all of the analytical results are in good agreement with their corresponding experimental results (less than 10-percent variation in flutter frequency and less than 5-percent variation in dynamic pressure). However, only the kernel function results show the same trend that was found experimentally, namely, a decrease in flutter dynamic pressure with increasing vortex diffuser weight.

CONCLUDING REMARKS

The effects of the addition of two different upper surface vortex diffusers at the tip of a basic wing have been determined experimentally over the Mach number range from about 0.70 to 0.95 in the Langley transonic dynamics tunnel. The cantilever-mounted flat-plate wing had a planform representative of subsonic transport aircraft. The two flat-plate vortex diffusers had the same planform and differed from one another in mass and stiffness. One weighed about 0.3 percent of the basic wing weight, the other about 1.8 percent. The addition of the lighter vortex diffuser reduced the wing flutter dynamic pressure by about 3 percent; the addition of the heavier vortex diffuser produced about a 12-percent reduction. The experimental results were compared at $M = 0.80$ with calculated results obtained by using kernel function and doublet lattice unsteady aerodynamic theories. Although the individual calculated results were in good agreement with corresponding experimental results for all three model configurations, only the kernel function results showed the systematic decrease in flutter dynamic pressure found experimentally with increasing vortex diffuser weight.

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TABLE I
MODEL MASS PROPERTIES

Model	Wing Portion		Vortex Diffuser Portion		Vortex Diffuser Portion	
	kg	slugs	kg	slugs	kg	slugs
Basic wing	3.550	0.2433	----	----	3.550	0.2433
Light vortex diffuser	3.550	.2433	0.0113	0.0008	3.5613	.2441
Heavy vortex diffuser	3.550	.2433	.0630	.0043	3.6130	.2476

TABLE II
MODEL NATURAL FREQUENCIES (Hz)

Model	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5		Mode 6		Mode 7	
	f_e	f_c	f_e	f_c	f_e	f_c	f_e	f_c	f_e	f_c	f_e	f_c	f_e	f_c
Basic wing	5.8	5.9	26.4	26.8	51.4	52.9	66.9	69.8	(a)	114.9	(a)	(a)	(a)	(a)
Light vortex diffuser	5.7	5.8	25.8	26.2	51.1	50.7	(a)	53.8	(a)	68.3	(a)	114.5	(a)	130.6
Heavy vortex diffuser	5.4	5.5	24.0	24.0	50.5	51.5	58.7	60.4	(a)	107.0	(a)	(a)	(a)	(a)

(a) Not determined

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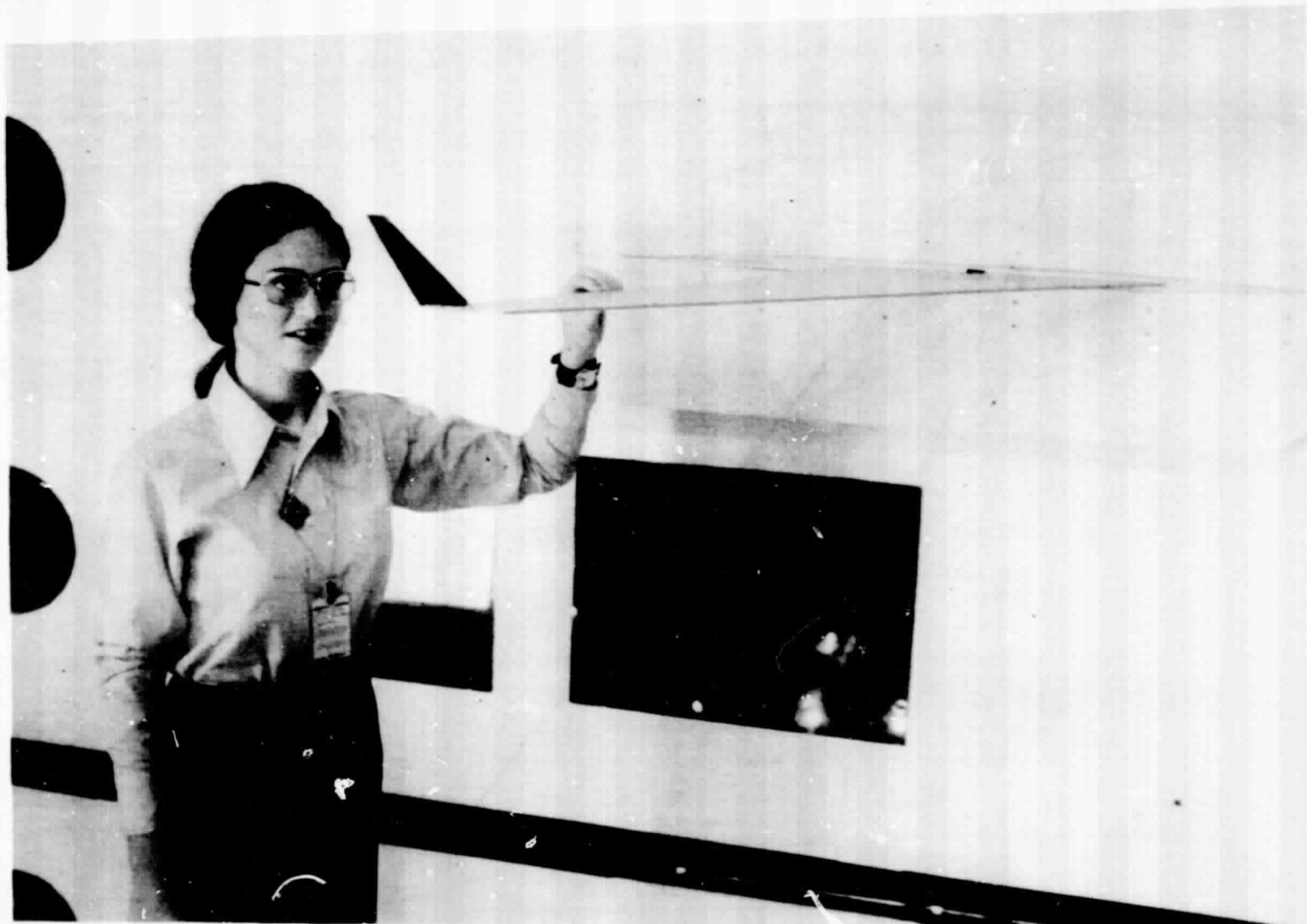
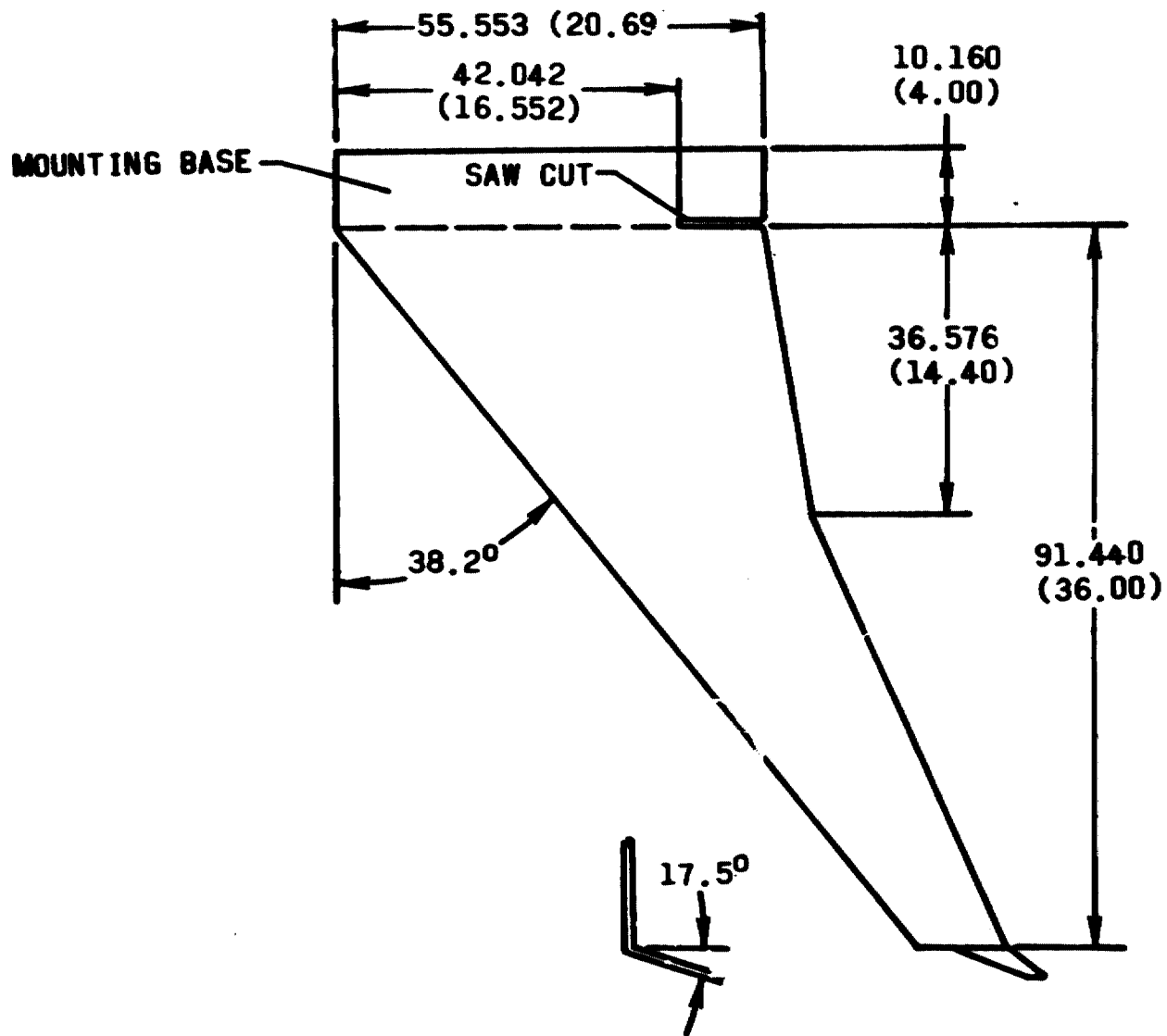
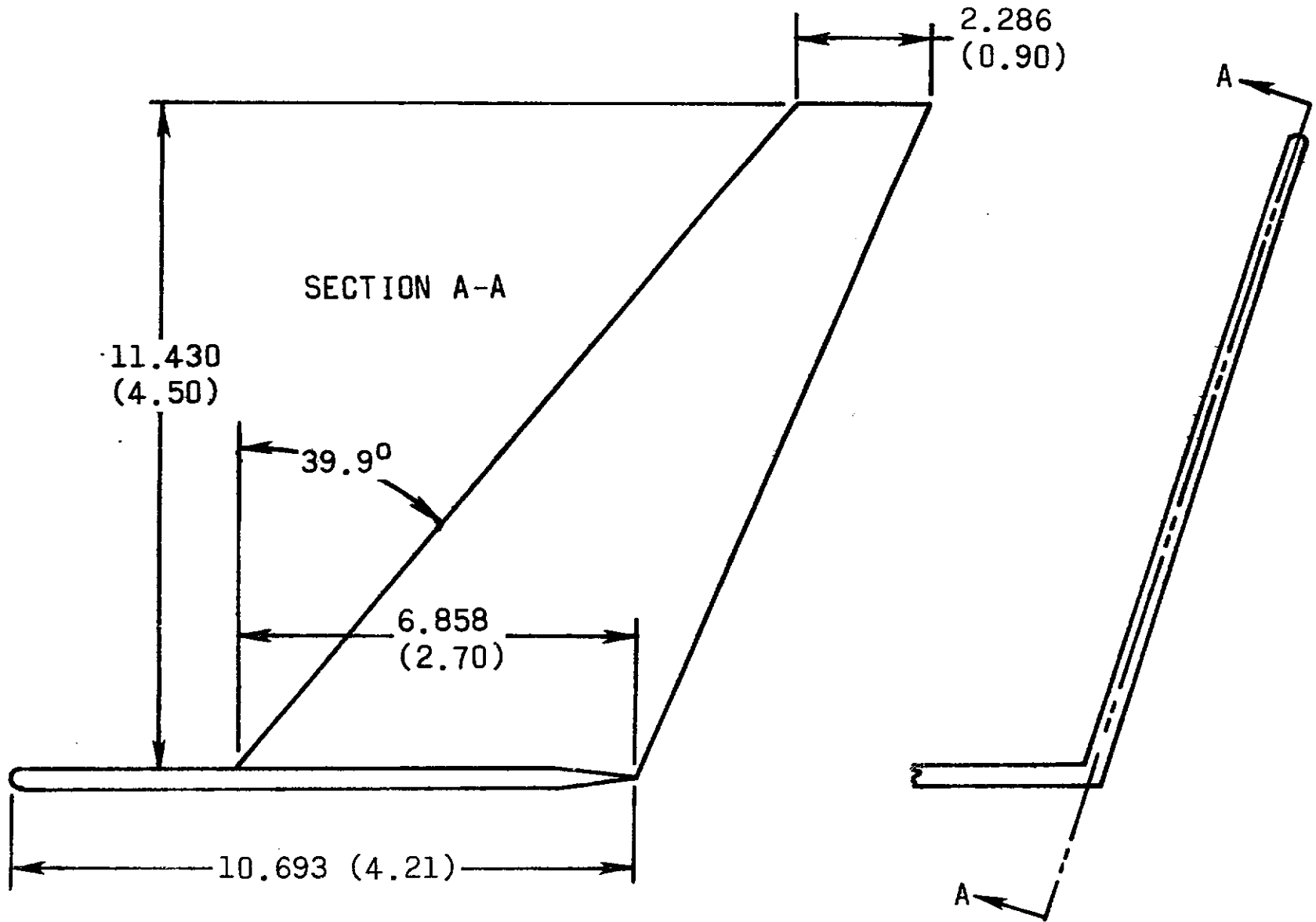


Figure 1.- Photograph of heavy diffuser model mounted in wind tunnel.



(a) General layout and wing details.

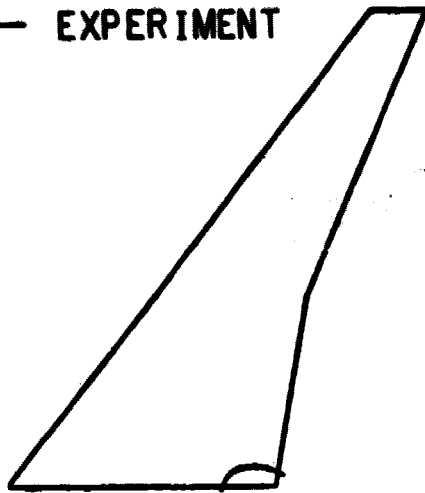
Figure 2.- Drawings of model configuration. Dimensions are in centimeters (inches).



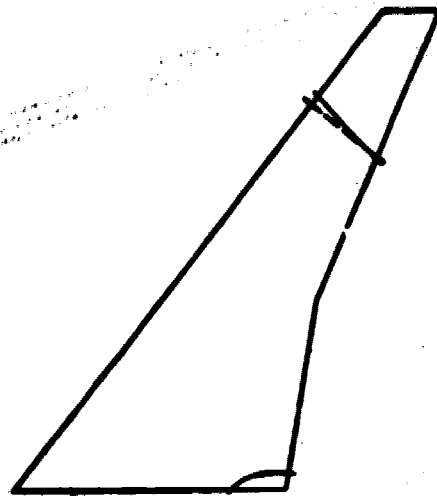
(b) Vortex diffuser details.

Figure 2.- Concluded.

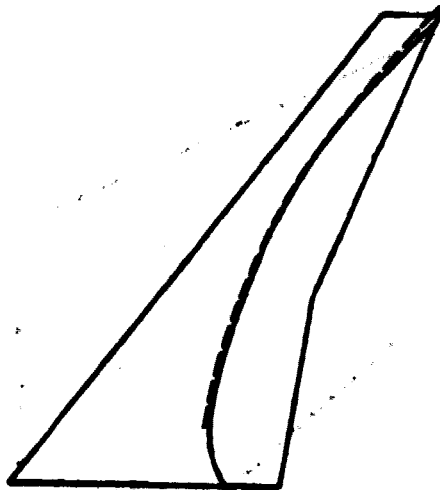
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- - - - EXPERIMENT



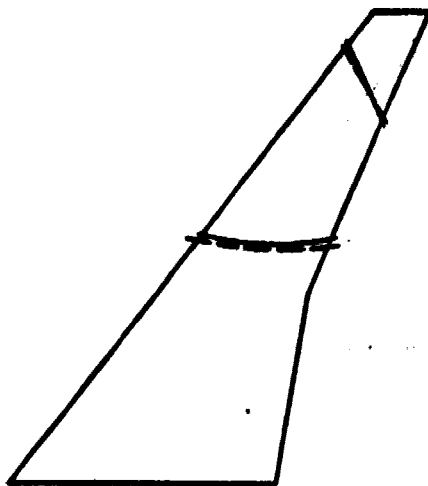
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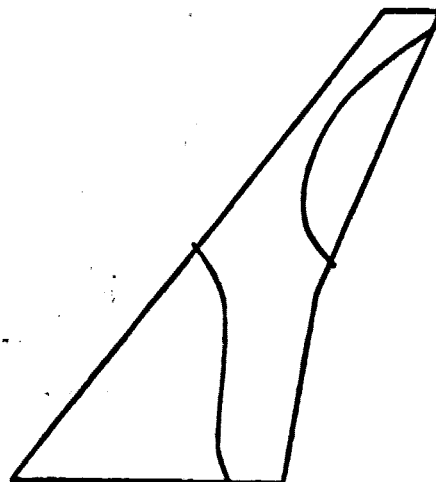
MODE 2



MODE 3



MODE 4

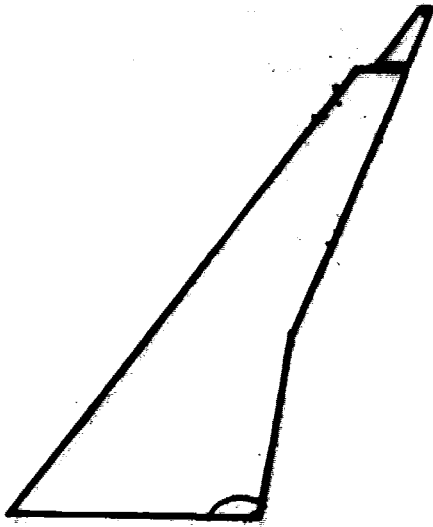


MODE 5

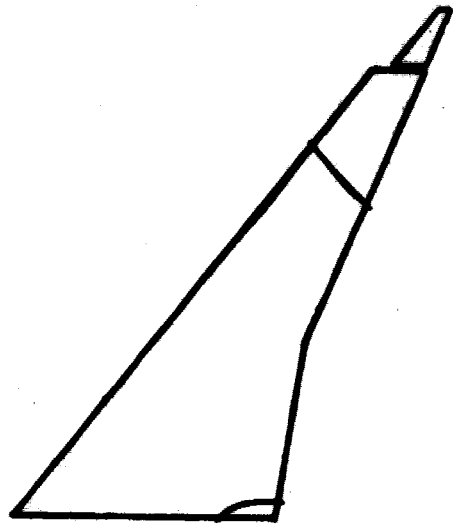
(a) Basic wing model.

Figure 3.- Calculated and measured node lines.

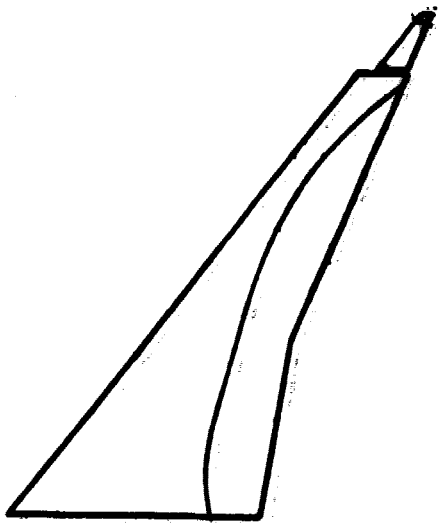
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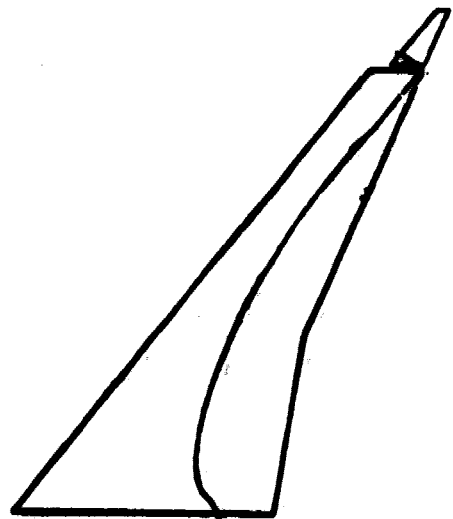
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MODE 2



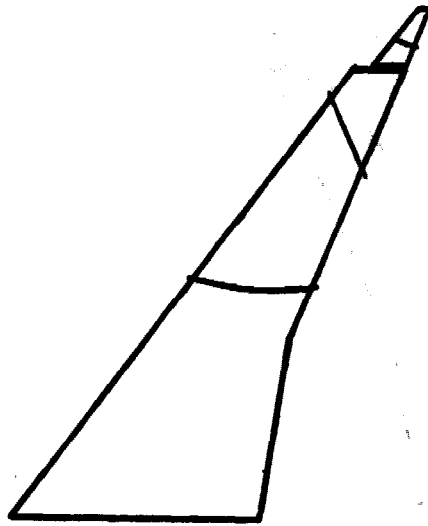
MODE 3



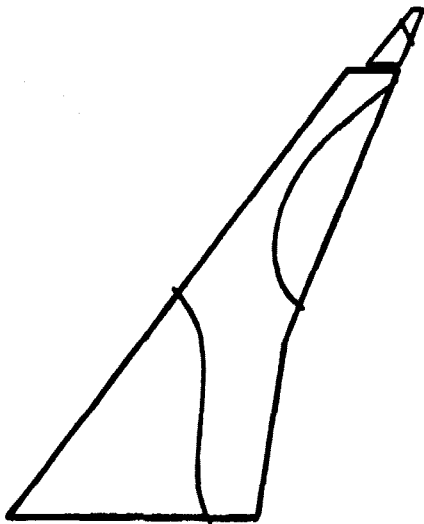
MODE 4

(b) Light vortex diffuser model.

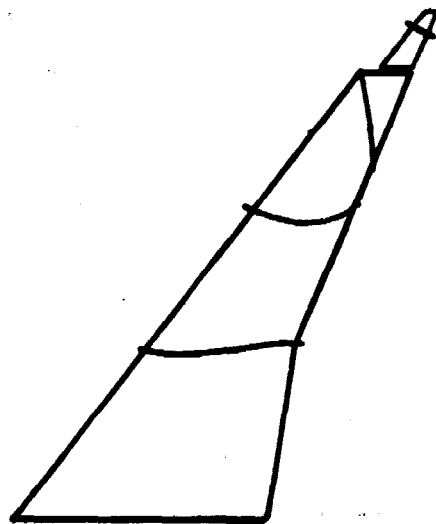
Figure 3.- Continued.



MODE 5



MODE 6

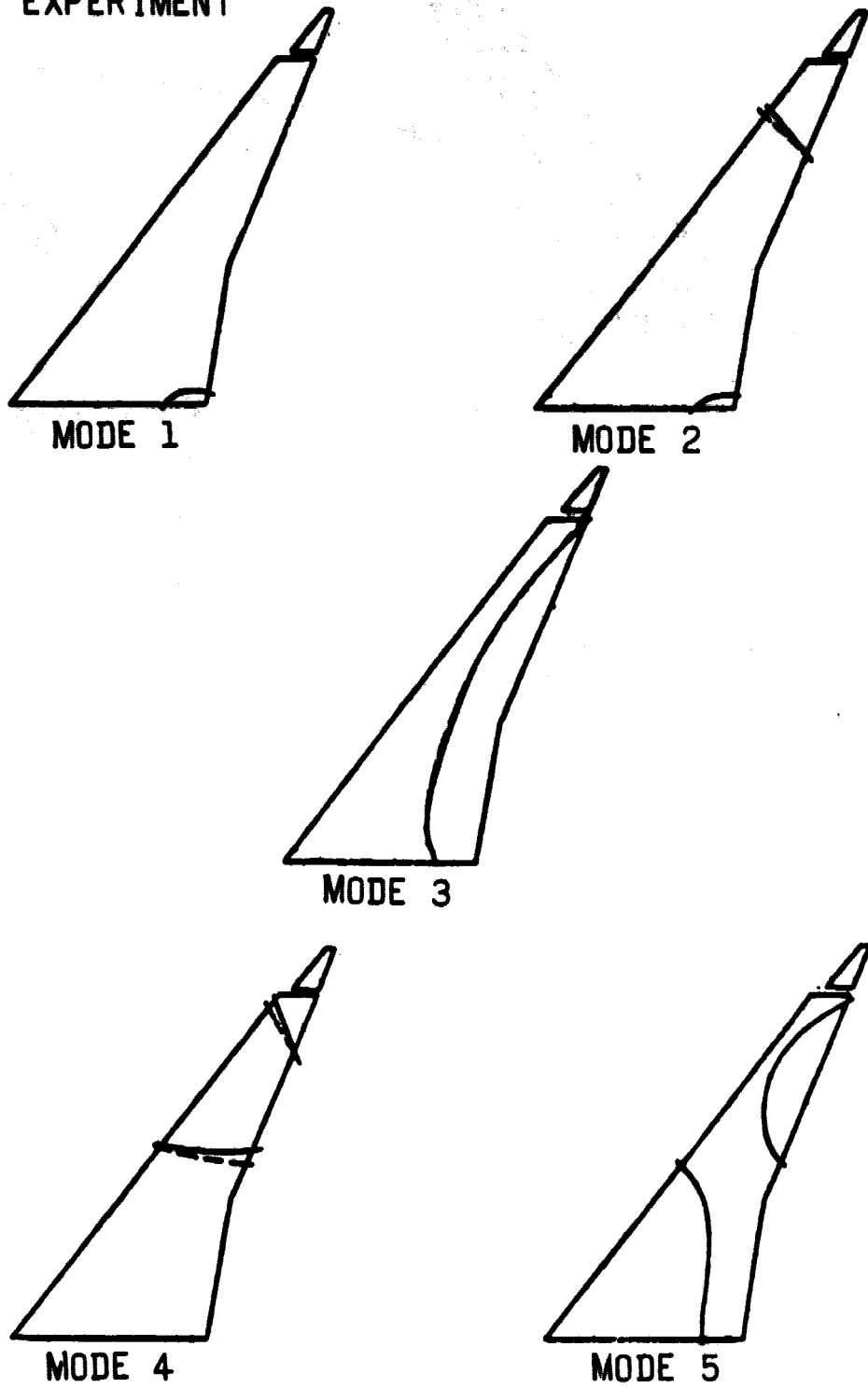


MODE 7

(b) Concluded.

Figure 3.- Continued.

———— CALCULATED
- - - - EXPERIMENT



(c) Heavy vortex diffuser model.

Figure 3.- Concluded.

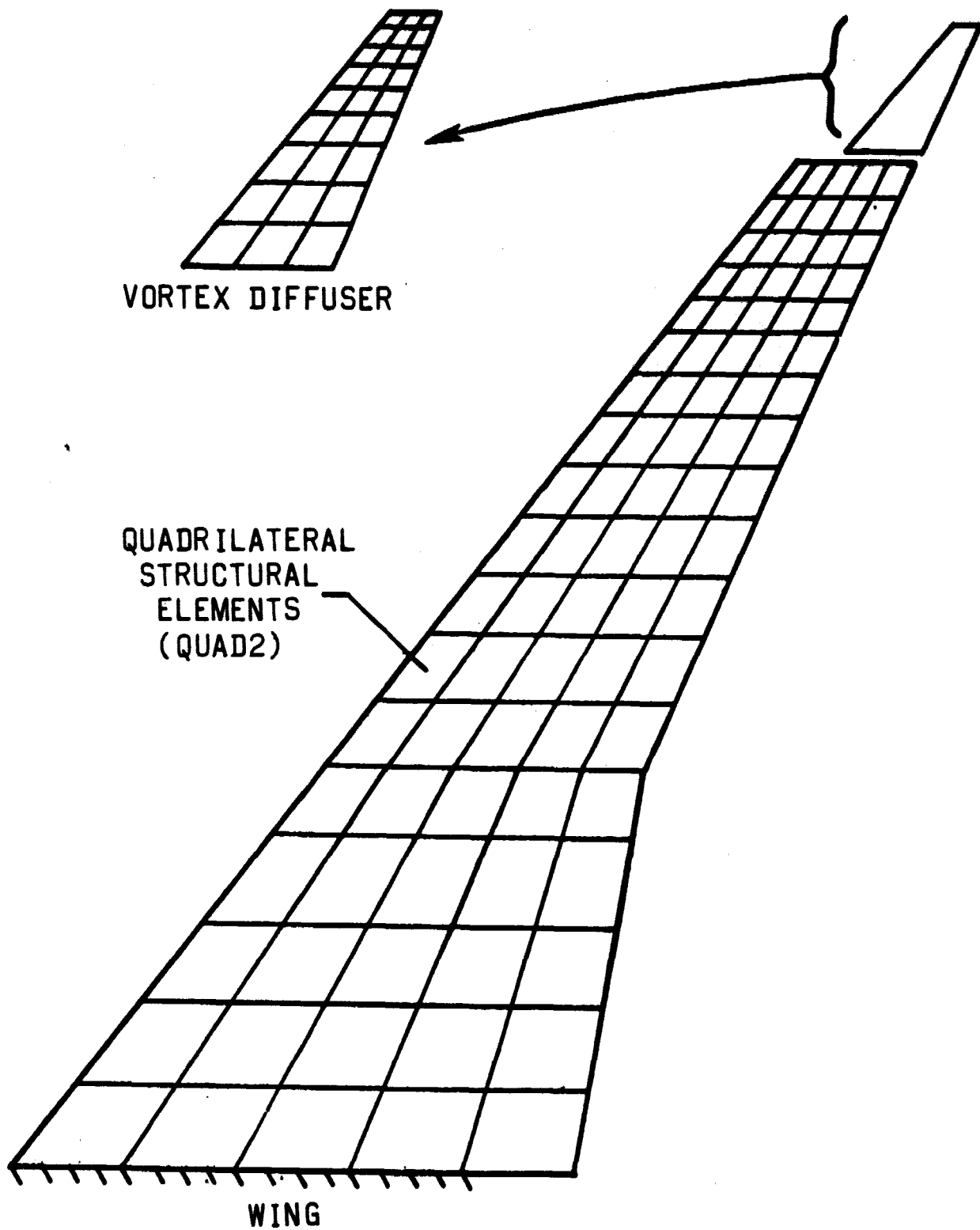


Figure 4.- NASTRAN structural model.

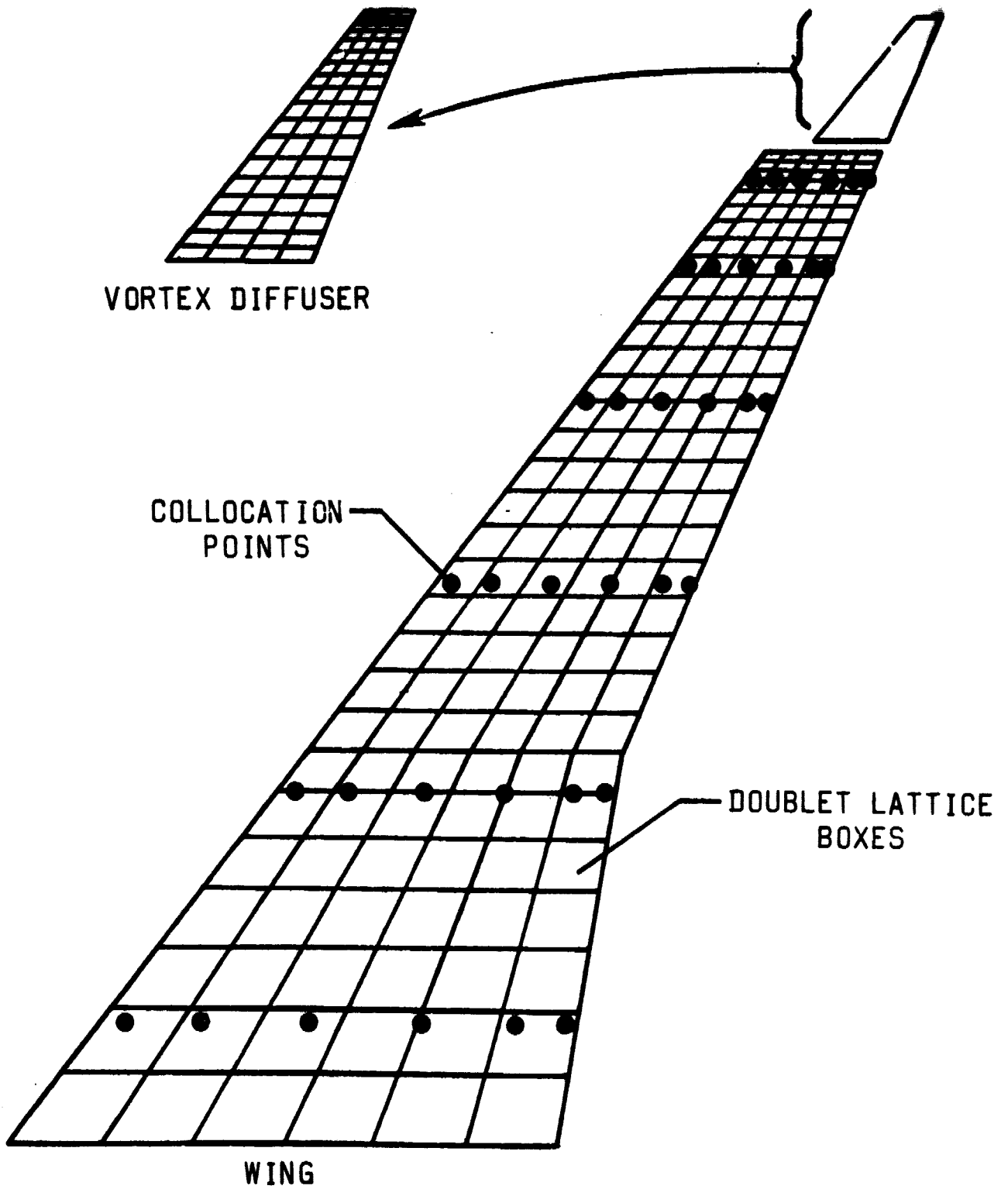
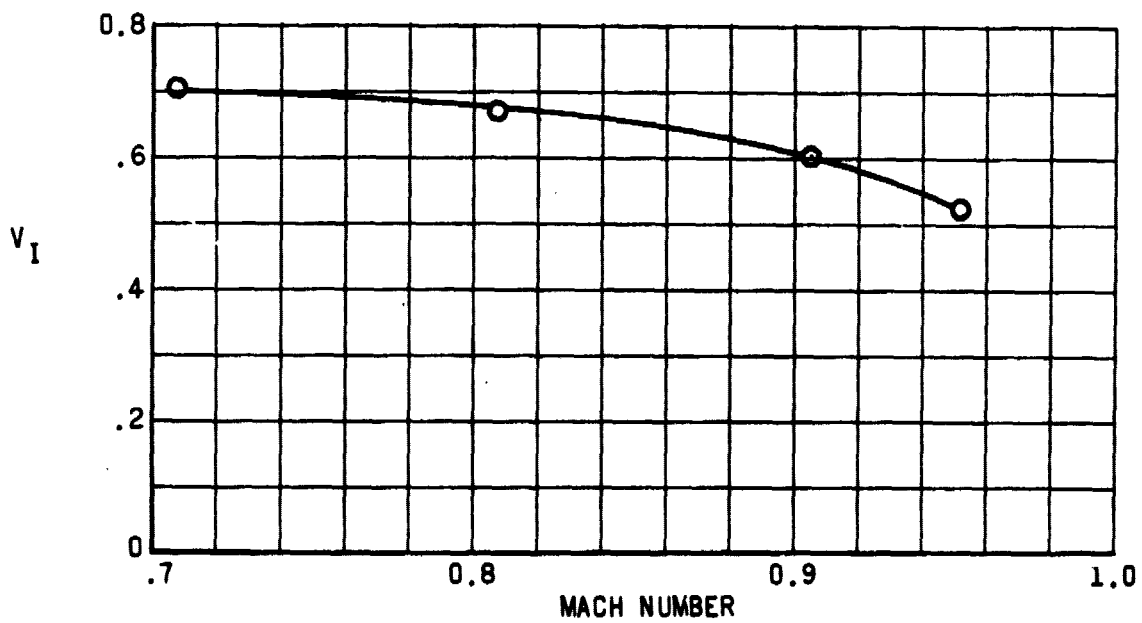
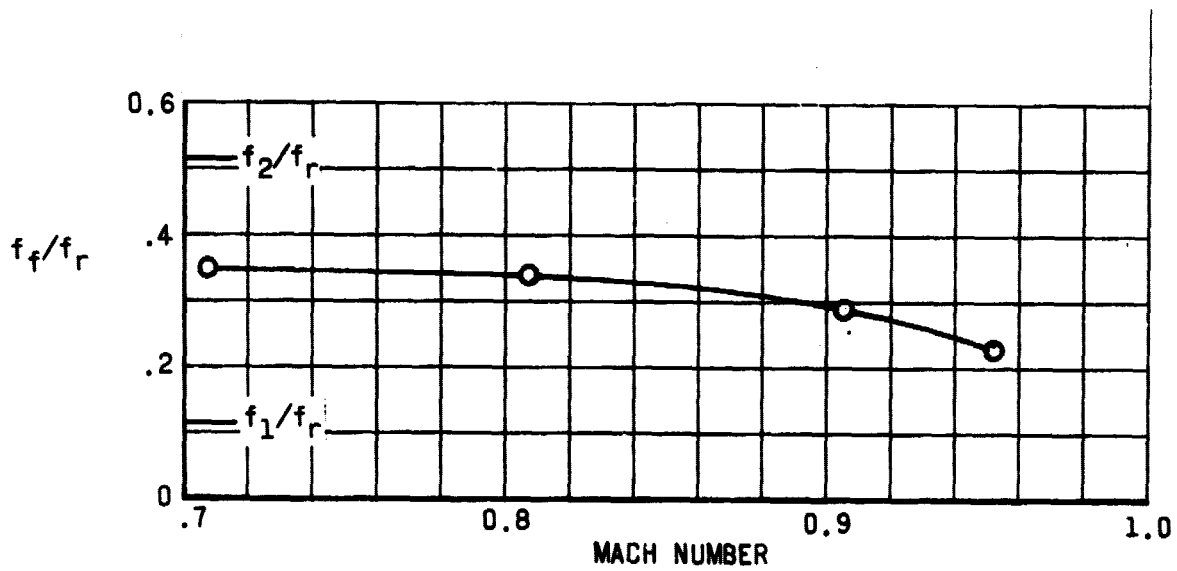
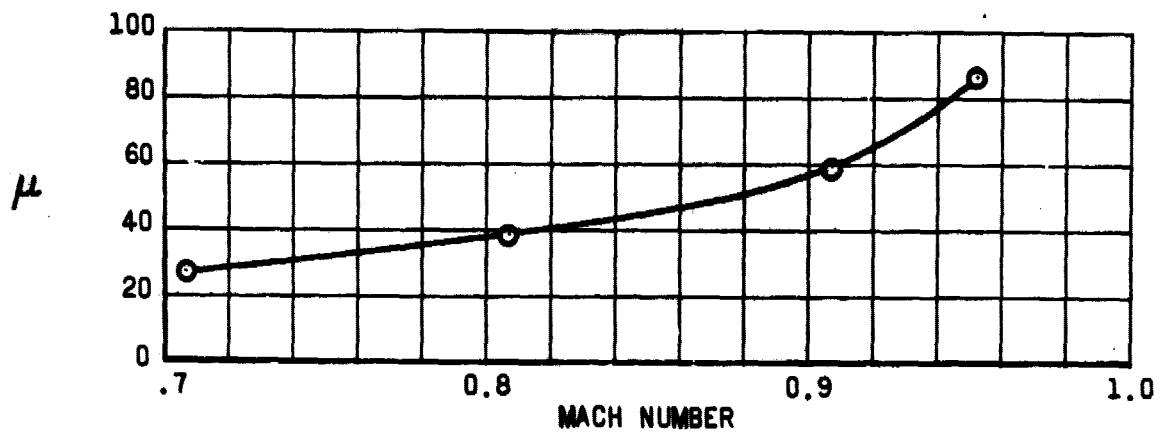
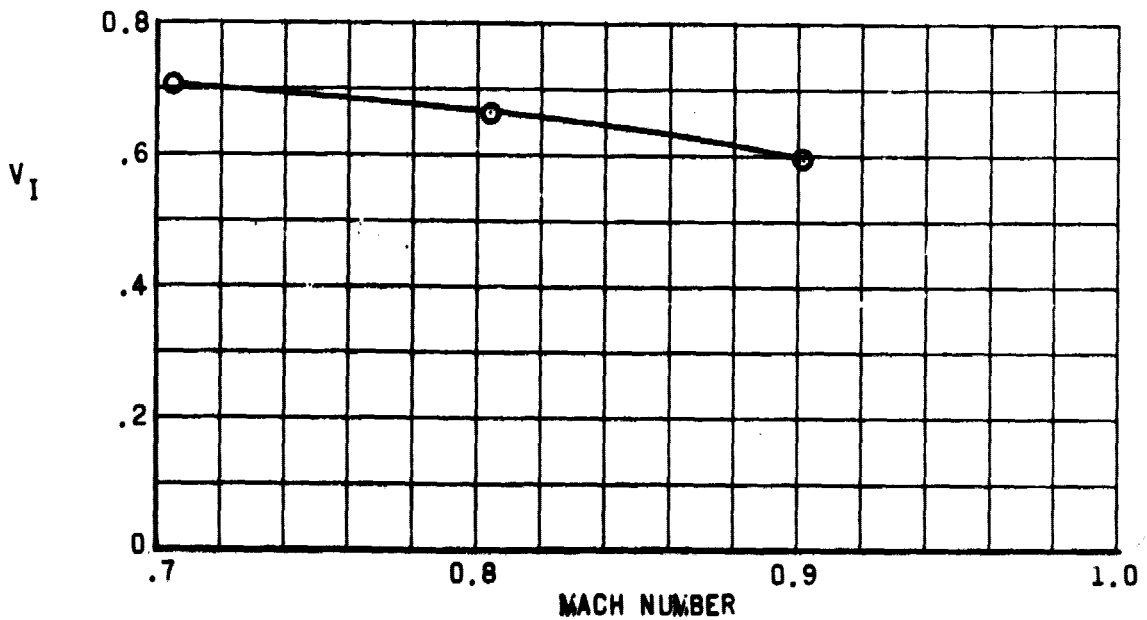
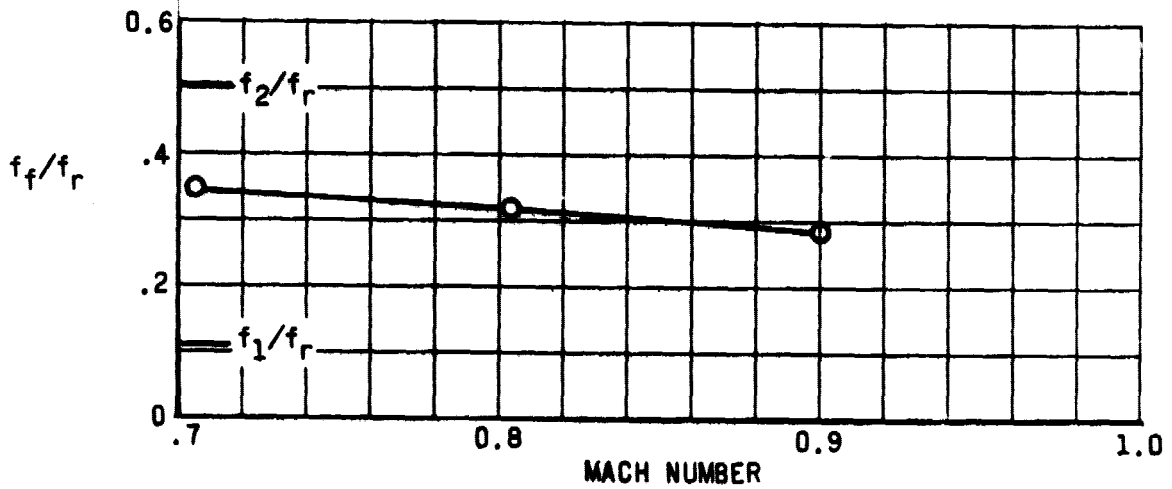
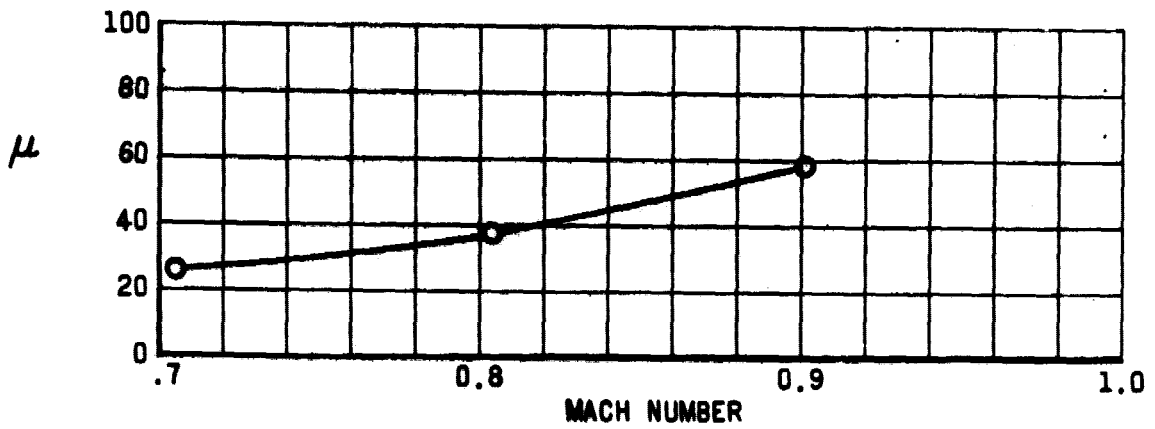


Figure 5.- Aerodynamic model.

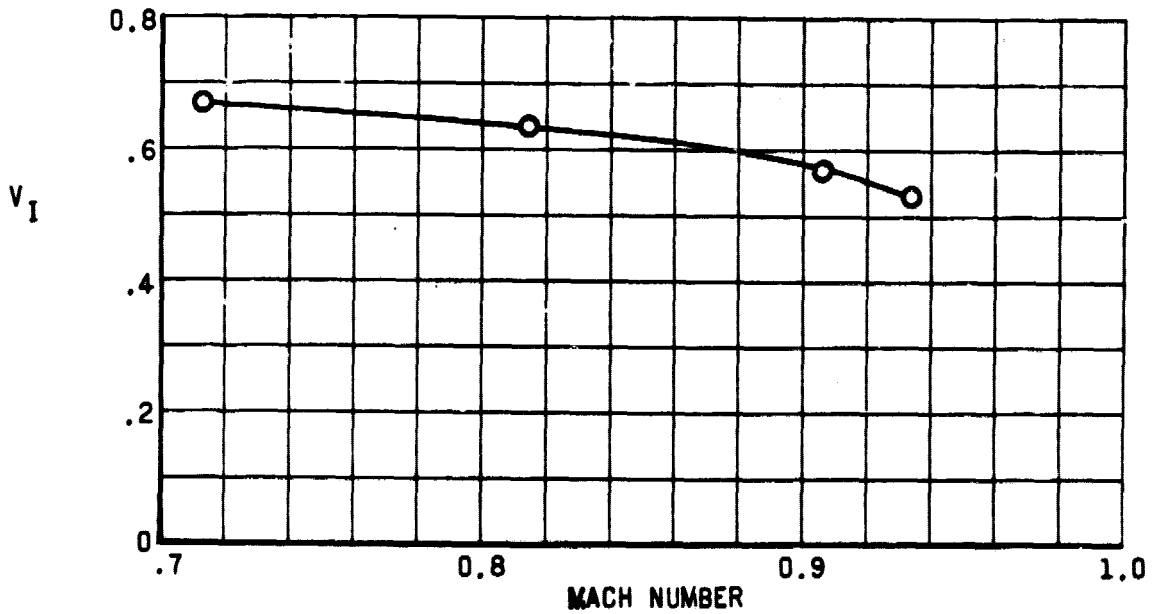
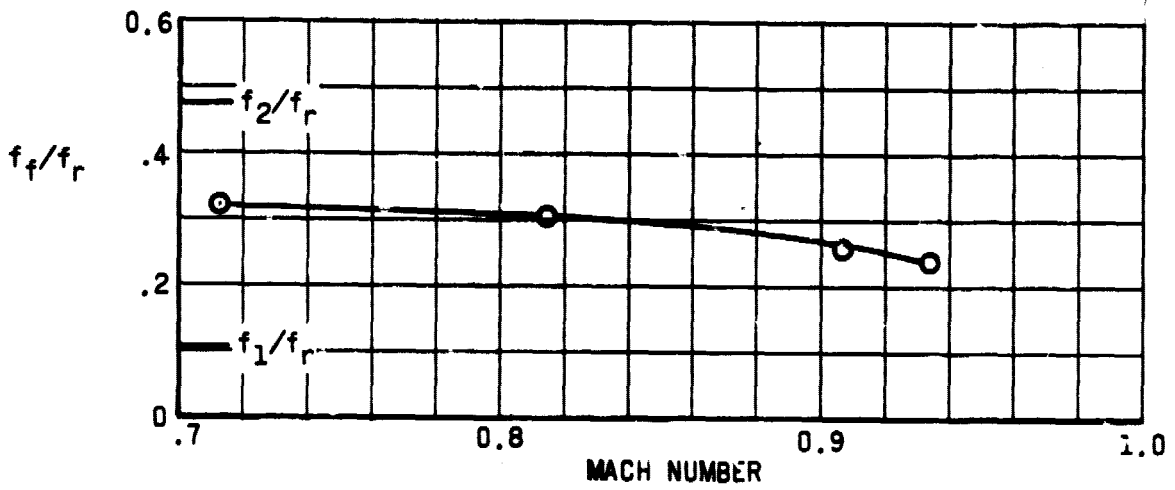
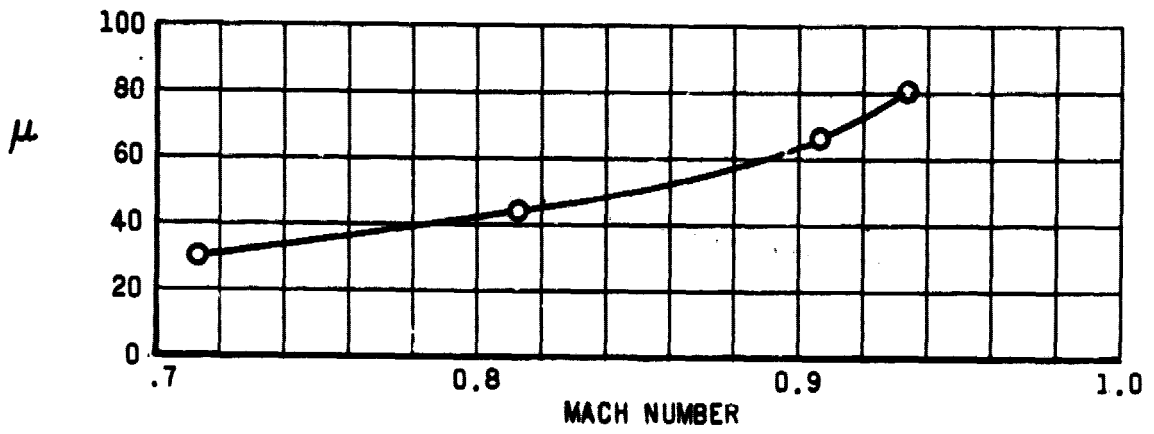


(a) Basic wing model.

Figure 6.- Experimental flutter results.



(b) Light vortex diffuser model



(c) Heavy vortex diffuser model.

Figure 6.- Concluded.

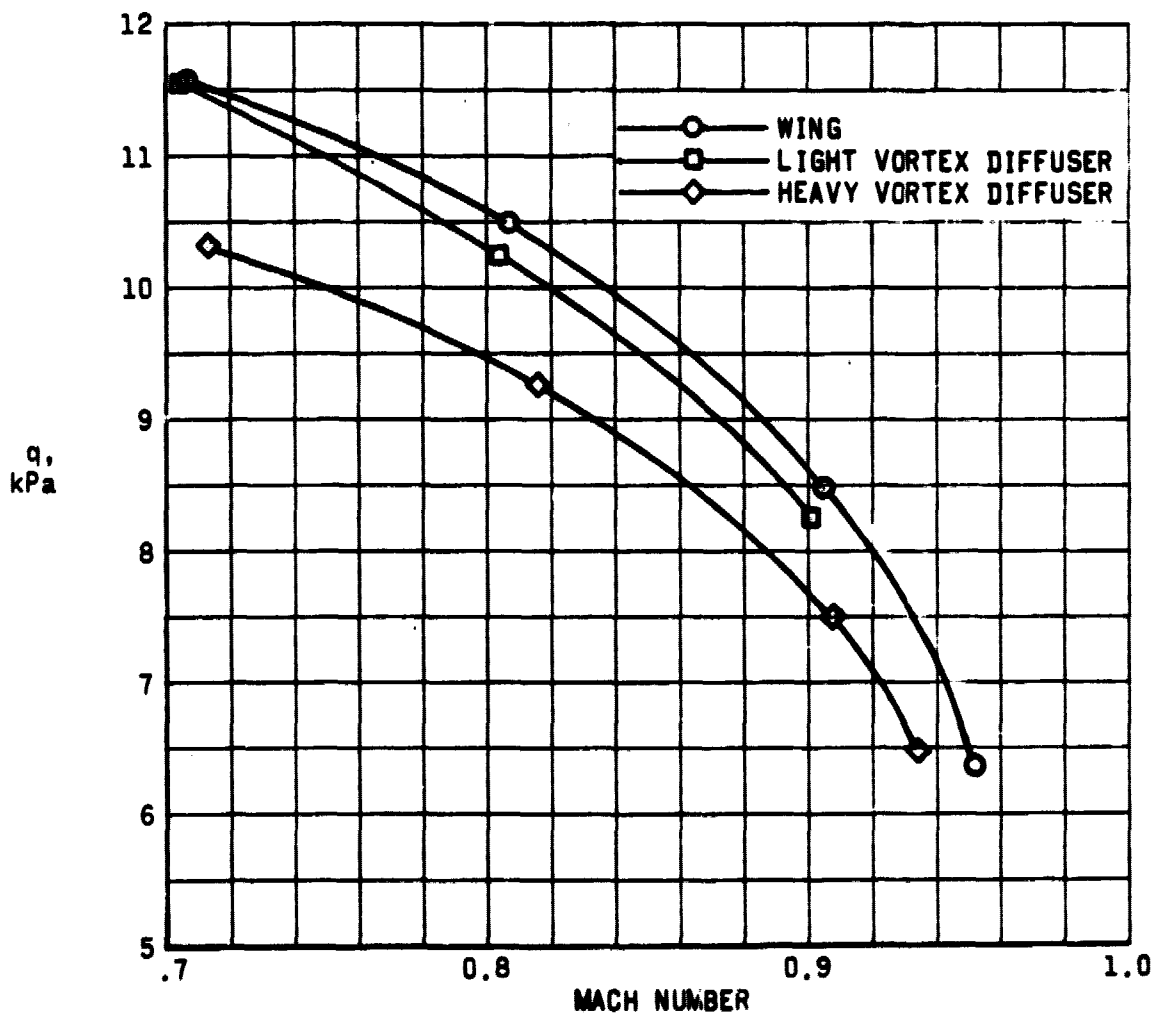
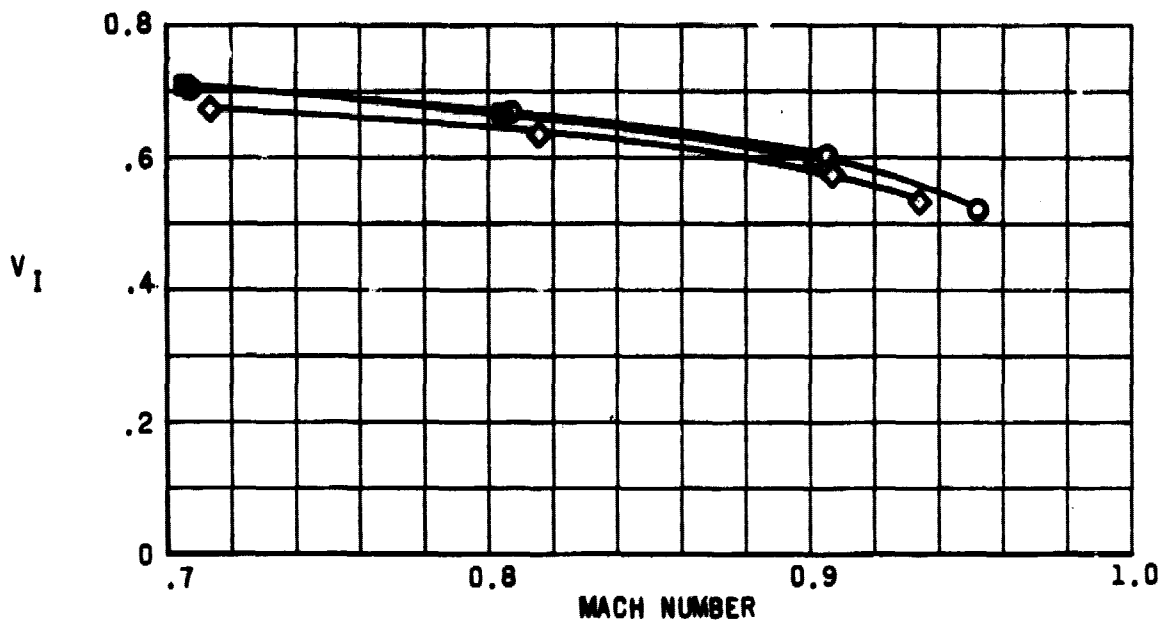


Figure 7.- Comparison of the experimental results for the three models.

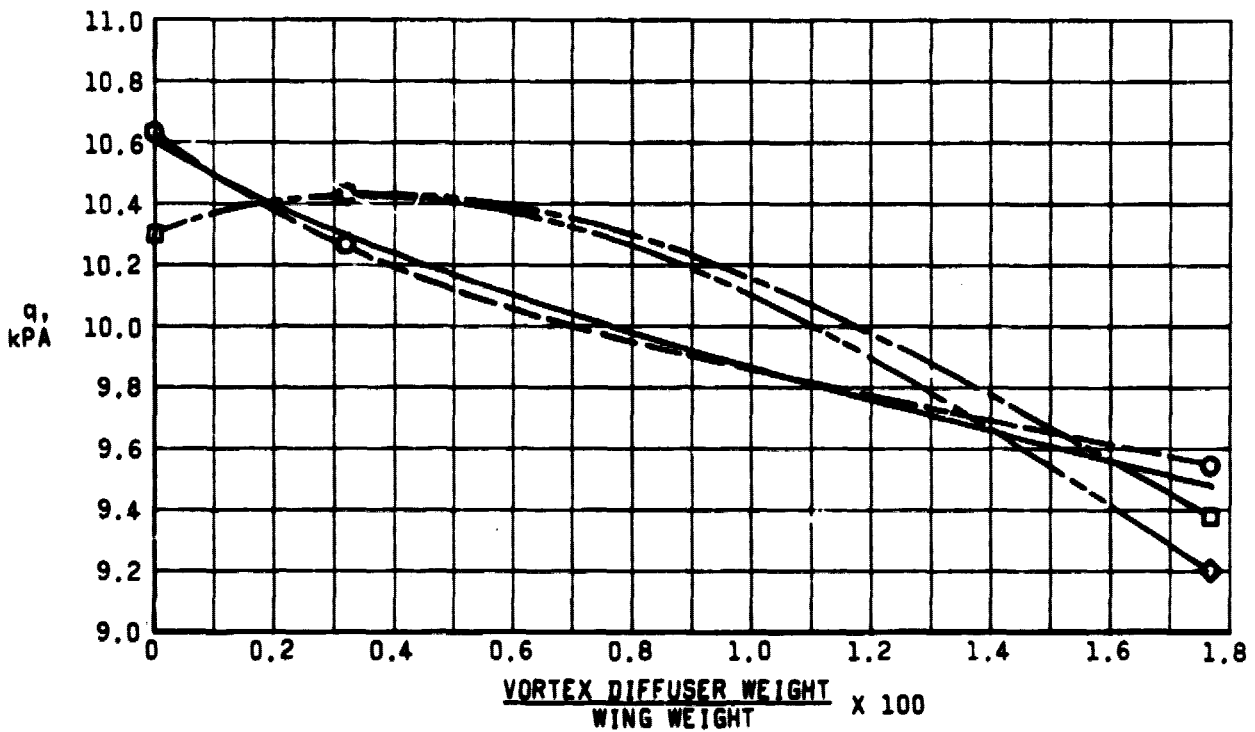
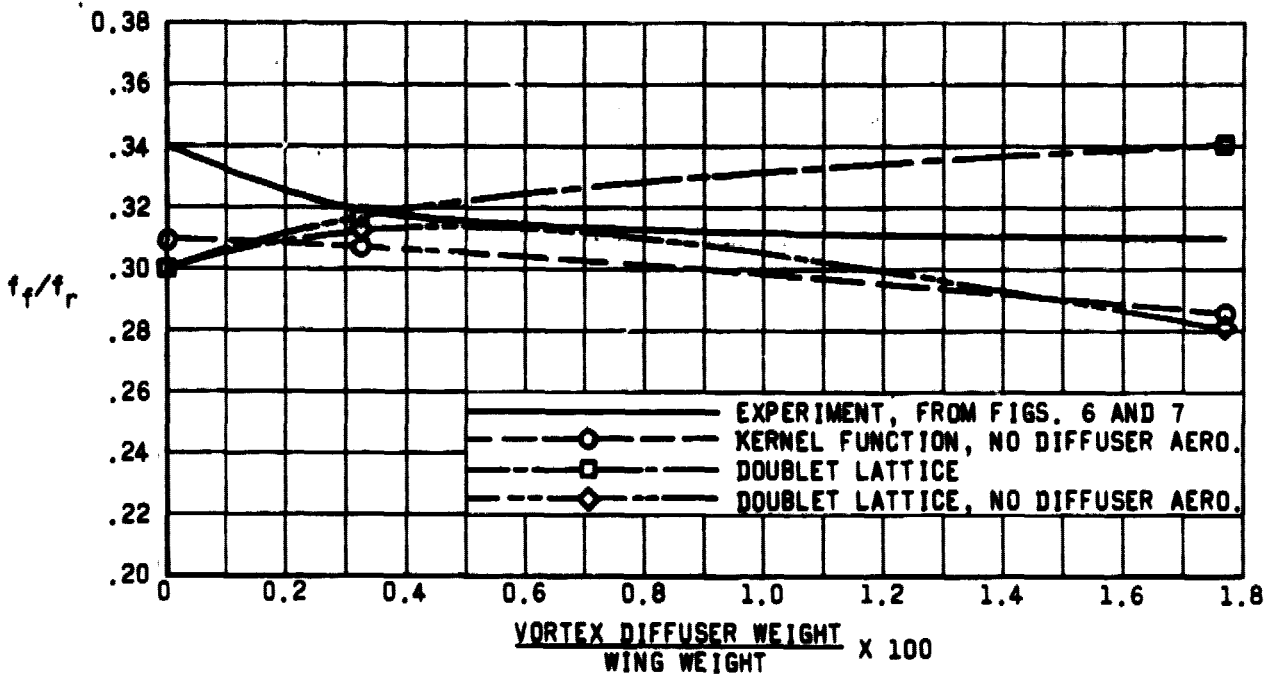


Figure 8.- Comparison of calculated and experimental flutter results.