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RSIC-644

STUDY OF TWO DIMENSIONAL PANEL FLUTTER AND PANEL DIVERGENCE IN SUBSONIC FLOW (III) -EXPERIMENTAL STUDIES OF TWO DIMENSIONAL AND THREE DIMENSIONAL PANELS IN LOW SPEED WIND TUNNEL

by

T. Ishii

Kōkū-Uchyū Gijutsu Kenkyūjō Hōkōku, No. 87, 21-40 (1965)

Translated from the Japanese

February 1967

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STUDY OF TWO DIMENSIONAL PANEL FLUTTER AND PANEL DIVERGENCE IN SUBSONIC FLOW(III) -EXPERIMENTAL STUDIES OF TWO DIMENSIONAL AND THREE DIMENSIONAL PANELS IN LOW SPEED WIND TUNNEL

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Several metal panels, 300 mm long and 70 mm wide, pin-supported at their leading and trailing edges, are placed between a pair of parallel end-plates.

These two-dimensional models are tested in a low speed wind tunnel which provides the maximum wind speed of 45 m/sec.

As has been predicted by our theory of Part I, even the thinnest steel panel with thickness ratio 1.33×10^{-4} did not flutter. The observed instability is divergence only. The measured divergence boundary agreed quite well with our theoretical results.

By taking off the end-plate and modifying the model mountings, three-dimensional panels with various aspect ratios were tested in the same wind tunnel. Our experimental study revealed that three-dimensional panels, simply supported at their leading and trailing edges with two sides free. are subjected to a series of complicated instabilities.

These instabilities may be classified into three categories depending on the aspect ratio of the panels.

Panels	Instabilities
(i) High aspect ratio panels	Divergence only.
(ii) Medium aspect ratio panels	A series of divergence shape, from a half wavelength of sine shape to S shape as the dynamic pressure is increased, followed by flutter.
(iii) Low aspect ratio panels	Soft standing oscillations followed by flutter.

The boundaries of these instabilities were experimentally determined, and the causes of these phenomena were revealed by experiment.

Introduction and the Purpose

The primary purpose of this study is to experimentally verify the validity of results reached by the analysis in Part I and Part II of this report concerning the aerodynamic elastic stability of the two-dimensional panel in subsonic flow.

This experiment was restricted to a region considered to be uncompressed air flow in a low velocity wind tunnel, with velocity of 0 to

45 m/sec. This is because the analytical methods used in treating the compressed flow in Part II are the same as that used in Part I, except for the procedure to obtain generalized aerodynamics, so that the results of the analysis relating to the uncompressed air flow region are proven indirectly. The fact that the numerical integration for obtaining the generalized aerodynamics of the compressed flow has a demonstrable appropriate value is evident. This can be seen either from the behavior shown in Figures 2 to 13 of Part II or Figure 18 of Part II which points out that the limit of the divergence is continuously connected when the axial force coefficient s = 0.

From these viewpoints, utilizing a wind tunnel of wind speed of 0 to 45 m/sec, we carried out the experiments on a two-dimensional panel, focused on the following three points:

(1) To verify whether flutter takes place, utilizing the thinnest panel which is obtainable.

(2) To compare the experimental divergence velocity (or dynamic pressure) with the theoretical value.

(3) To verify if the two-dimensional panel produces a self-excited oscillation, under what circumstances this oscillation occurs.

In the first half of this report, the results of the experiments were called "Two-Dimensional Panel Experiment".

The second half of this report deals with the "Three-Dimensional Panel Experiment" not directly related to the assumptions contained in the theoretical analysis. This was undertaken to supplement the above, because of the considerations to be related below.

While it is clear that the conclusions reached will not fit quantitatively with the conclusions related to the finite span two-dimensional panel, can they qualitatively provide the same conclusions? Such a question will naturally arise. This is because we know, although not precisely, from observing such phenomena as a flag or a streamer which reacts to wind by flapping, that the three-dimensional membrane is dynamically unstable in an air current. From this analogy, if we assume that there are elements causing a basically different type of aero-dynamic elastic instability phenomenon between two- and three-dimensional panels, the question is what are these elements. We thought it necessary to clarify this experimentally, so we added the "Three-Dimensional Panel Experiment".

Two-Dimensional Panel Experiment (Experimental Facility)

(a) Model

The five panels used in the experiment were aluminum and steel panels, 68 mm wide and approximately 300 mm long, having the characteristics shown in Table I.

Table I

Material	Length (b) (mm)	Thickness (h) (mm)	Thickness Ratio (h/b)
Steel	300	0.04	0.133×10^{-3}
Steel	300	0.1	0.333×10^{-3}
Steel	299	0.12	0.401×10^{-3}
Steel	300	0.2	0.667×10^{-3}
Aluminum	301	0.17	0.564×10^{-3}

All these model panels were, as shown in Figure 1, held between two 650- by 400-mm end-plates mounted parallel to each other and separated by a 70-mm space. In order that the end-plates do not restrict the displacement of the panel, they were set up with a gap of one mm between the two ends of the panel and the end-plates. To have the same conditions as in the assumptions of the theoretical analysis, the leading and trailing edges of the panels were set up with about 0.3 mm of space, in such a way that the bakelite plates are in the same plane. Thin cellophane sheets were used to cover the panel edges in order to restrict the air flow through this space, so arranged that the cellophane did not restrict the movement of the panels.

A perforated brass plate was placed below the panel in order to reproduce the conditions in the theoretical suppositions which called for a zero differential in pressure between the top and the bottom of the panel, before bringing about the aerodynamic elastic instability phenomenon.

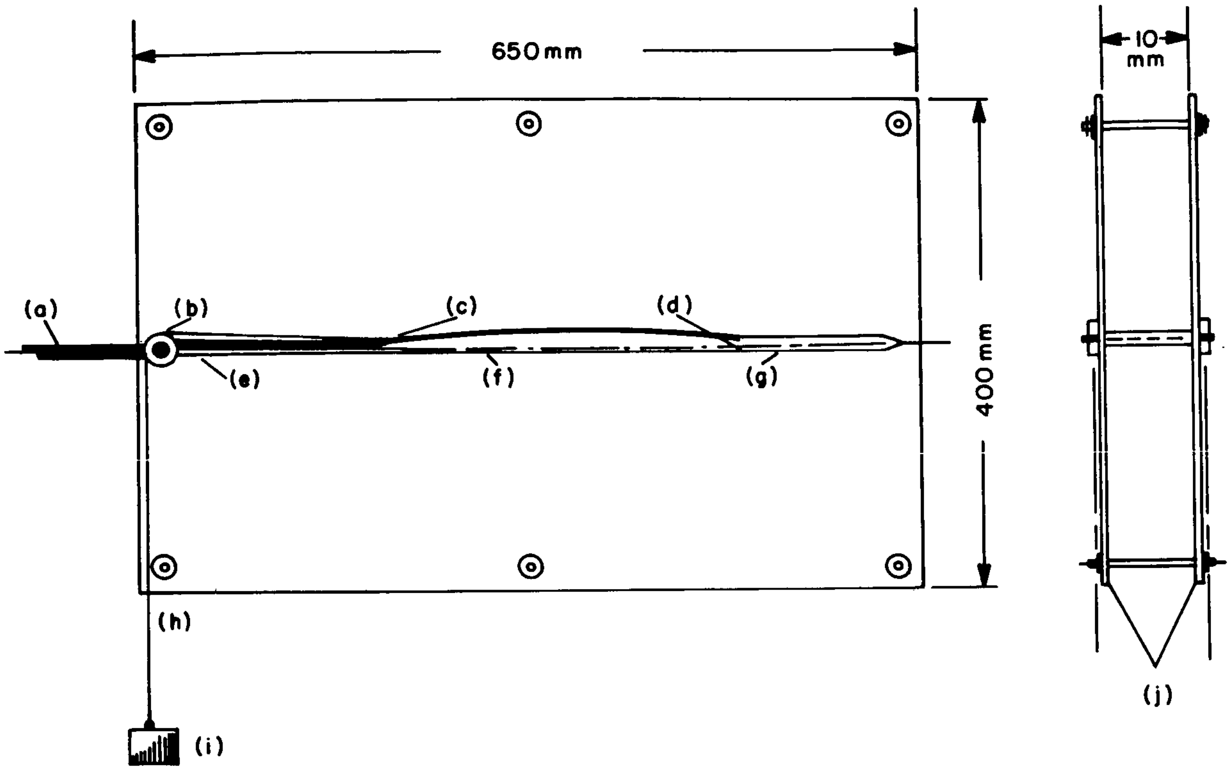


Figure 1.

a--Brass Plate; b--Pulley; c--Slit; d--Panel Model (length: 300 mm); e--Bakelite Plate; f--Perforated Plate; g--Bakelite Plate (thickness: 10 mm); h--Wire; i--Weight; j--End-Plates.

The holes of this perforated plate were drilled at the intersecting points of the 5-mm spaced rectangular lattice. If the opening ratio is too large, the air on the bottom of the panel will no longer be the static atmosphere which is the theoretical assumption. On the other hand, if the opening ratio is too small, even for a small displacement of the panel, the pressure on the bottom of the panel will change, and it becomes non-uniform.

Therefore, supposing that the allowable error for the uniformity of the pressure at 25 m/sec wind speed is 1/20 mm in the alcohol column, we carried out many experiments by varying the diameter of the holes and finally decided on 2.5 mm as a necessary minimum diameter (opening ratio approximately 19.6 percent).

1.5-mm diameter steel pins were attached to the leading and trailing edges of the panel by araldite or aron-alpha (acrylic rapid-dry binder). In the parallel end-plates, slits 2 mm wide and approximately

20 mm long were made at the position corresponding to the leading edge of the panel and in the direction of the air flow. The steel pins at the leading and trailing edges of the panel were inserted into these slits and holes.

In order to provide a tension to the panel, a wire was put on two ends of the steel pins at the trailing edge (Figure 1), and a weight was hung on the other end of the wire which exerted a force via a pulley.

One reason that we put a slit support in the trailing edge is that, by allowing a larger divergence amplitude, we can make this phenomenon more marked and so increase the accuracy of measuring the velocity of the divergence threshold. The second reason is, even if the panel model was not cut precisely in a rectangular shape, if the error is very minor, that it has the advantage of having an uniform surface stress through the entire surface.

The entire model was hung in the wind tunnel measurement box by means of piano wires.

(b) <u>Wind Tunnel</u>

We used the low speed wind tunnel of our Department of Measurement and Calculation for this purpose.

The wind tunnel is a single loop flow system with a cross section of 500 by 500 mm in the measurement box which is open to the atmosphere.

(c) <u>Experimental Results: I</u>

Under the same conditions as in the theoretical analysis, we increased the weight which applies tension to the panel, by steps of 100 g, and the wind speed was varied between zero and 45 m/sec which is maximum for our wind tunnel. The phenomena occurring within this range were measured. The result was that we verified that flutter did not occur in any panel. The validity of the conclusion of Part I was proven, relating to this point. (The minimum thickness of the steel plate which we could obtain was 0.04 mm.)

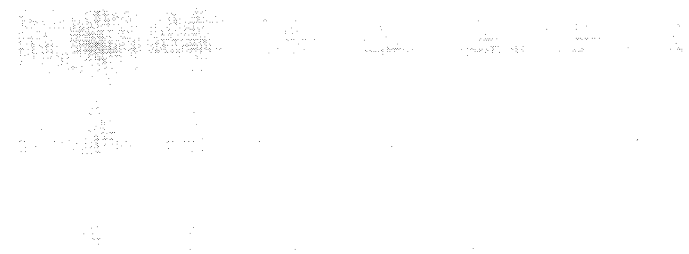


Figure 2. Divergence Two-Dimensional Panel

(d) Experimental Results: II

At first, we tried the following two methods to measure the threshold dynamic pressure of divergence. The methods were: (a) by increasing the wind speed we measured the starting point of the divergence, (b) by decreasing the wind speed we measured the stopping point of the divergence. By comparing the data from these two methods, it was found that for small values of tension, the results of method (a) are greater than the other, but by increasing the tension, the difference between these two values decreased. An example of this can be seen in Figure 4. Furthermore, as the dynamic pressure of the starting point of divergence was less susceptible to repetition in comparison to the dynamic pressure of the finishing point, we decided to utilize the latter value as experimental data.

In the theoretical analysis, the threshold dynamic pressure of the divergence was obtained by neglecting the influence of the gravity on the panel. But in the thick panel experiment, we found that we could not neglect the influence of the gravity in the case of small tension, so we determined the data, eliminating the influence of gravity, by the method referred to in Appendix A.

The threshold dynamic pressure of divergence determined as related above was plotted in Figures 3 to 7. The theoretical values for each panel were plotted by solid lines, and were in rather good agreement.

While the differences between the theoretical and experimental values were small, to ascertain the possible causes of this difference, the following three cases are mentioned:

(i) The shape of the divergence is not an exact sine wave. Since the thinner the plate, the maximum displacement point tends to be further back, we think that this is caused by air resistance.

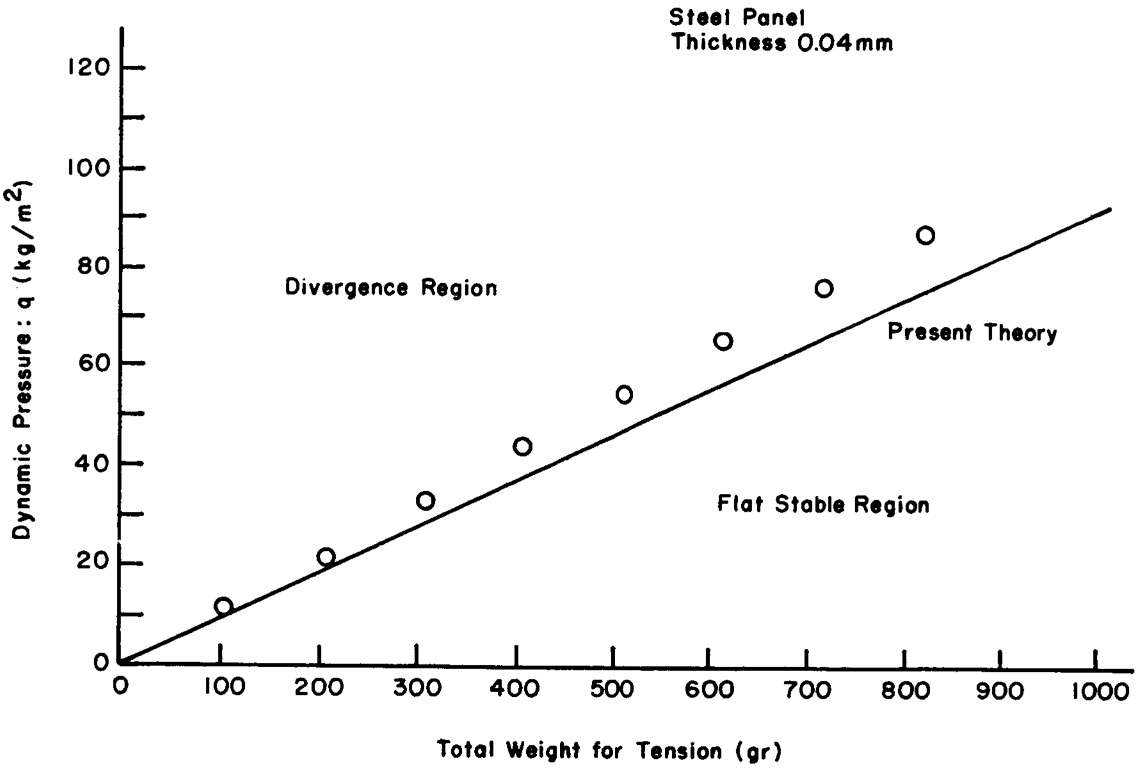


Figure 3.

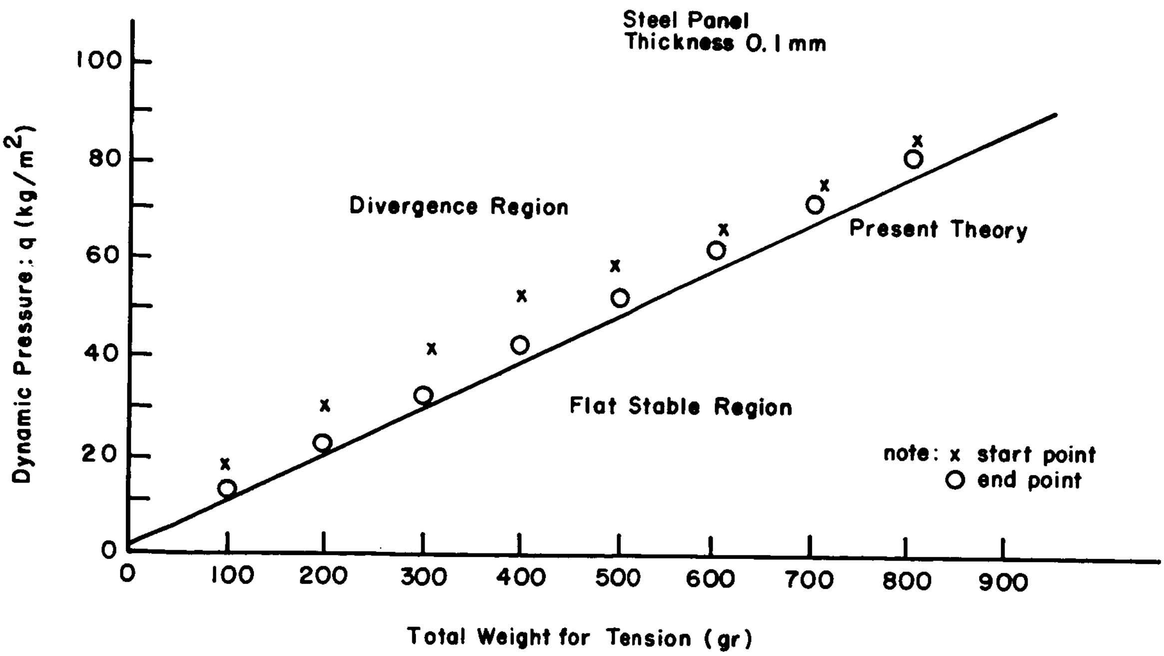


Figure 4.

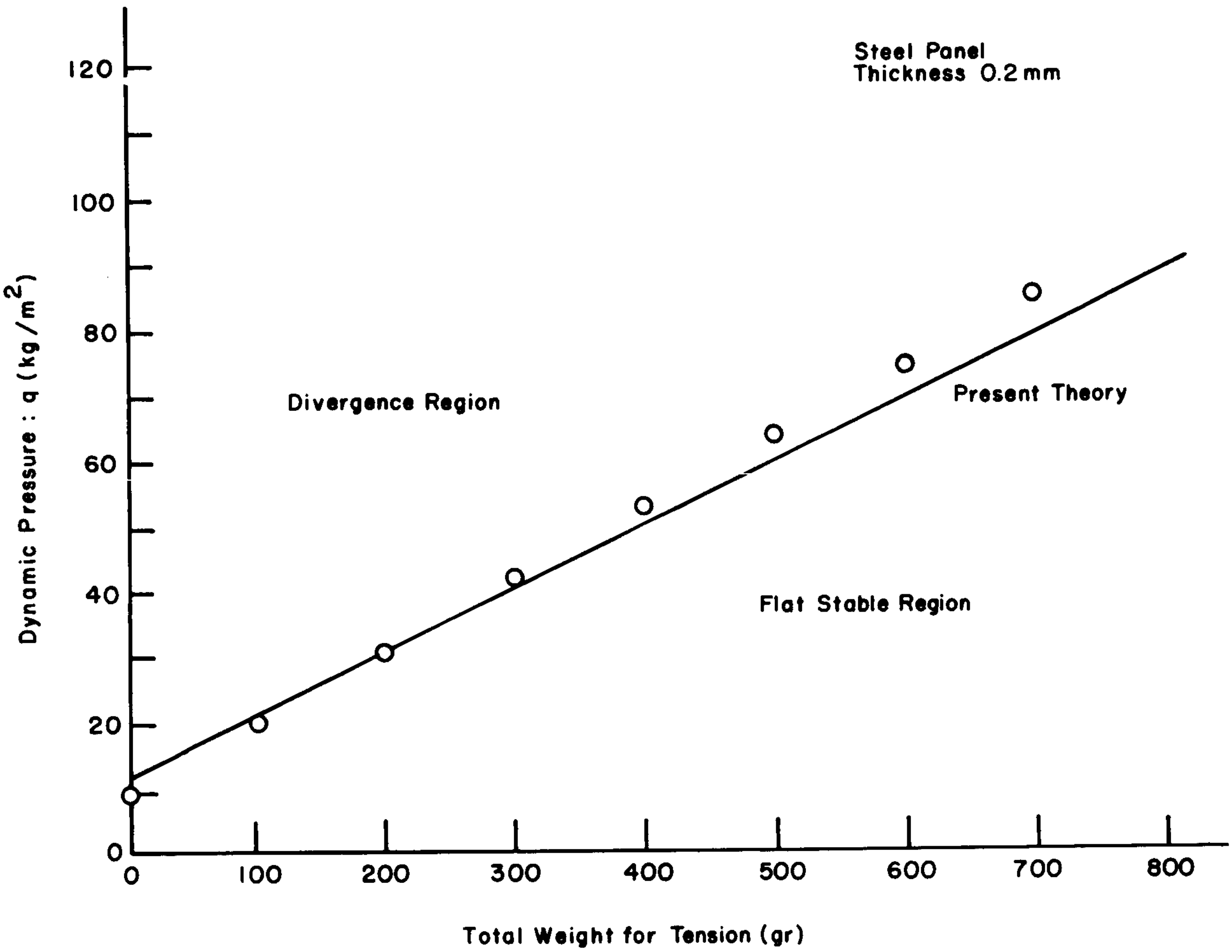


Figure 5.

(ii) Because of the 1 mm wide space which was put in the left and right boards of the panel in order to avoid restricting free movement of the panel, the distribution of the pressure in the direction of span is not completely two dimensional. Due to this slot, the difference in pressure of the divergence is decreased. This might be one of the reasons why the measured values of the threshold divergence dynamic pressure were larger than the theoretical values.

(iii) The flow direction in the tunnel changes according to the change in wind speed. When we set up the model in the wind tunnel, we checked that the model is parallel to the flow at a specific speed (about 25 m/sec). In the case of other speeds, a disalignment of about ± 1 degree from the air flow is believed to have taken place.

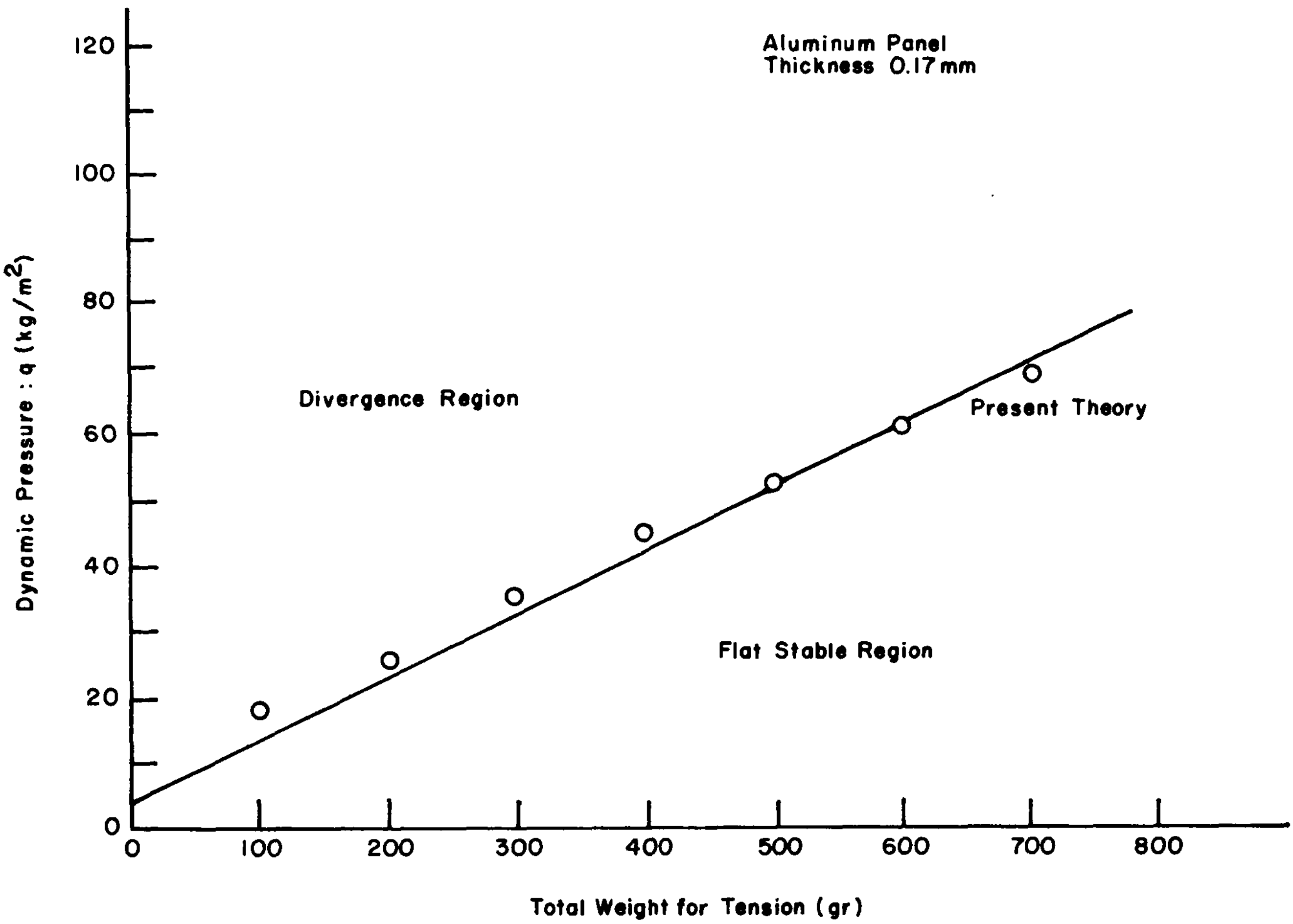


Figure 6.

In order to verify the influences stated in (i) and (ii), 11 static pressure holes were made in the half-chord of the 0.2 mm thick steel plate, and we measured the pressure distribution of the divergence.

The comparison of the experimental and the theoretical values are plotted in Figure 8.

(e) Experimental Results: III

We discovered experimentally that when we increase the pressure on the rear half of the panel in the wind tunnel, the panel produces a self oscillation of traveling wave type under very limited conditions of pressure distribution. A high-speed film (64 frames/sec) has shown that this oscillation is rather far from harmonic oscillation. In such a case with an increasing pressure gradient in the flow, it is notable that the two-dimensional panel produces flutter. The stroboscopic picture of this oscillation and its pressure distribution are shown in Figures 9 and 10.

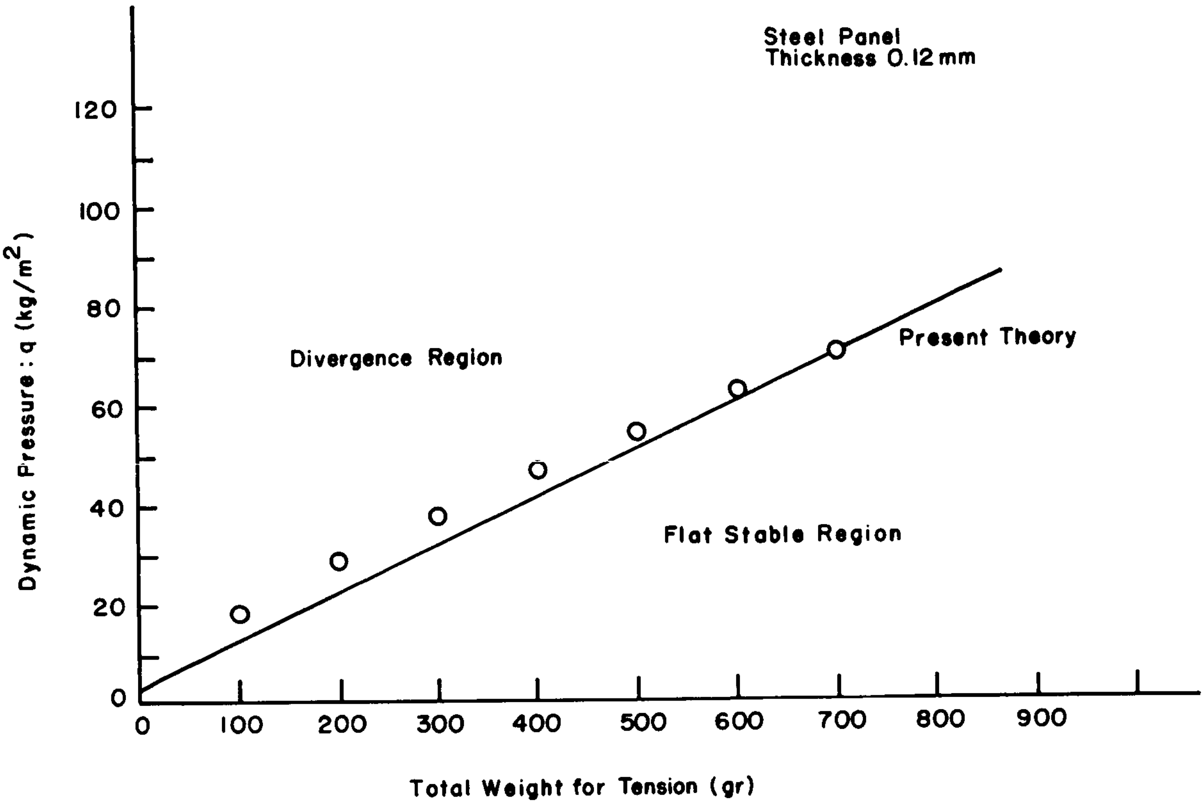


Figure 7.

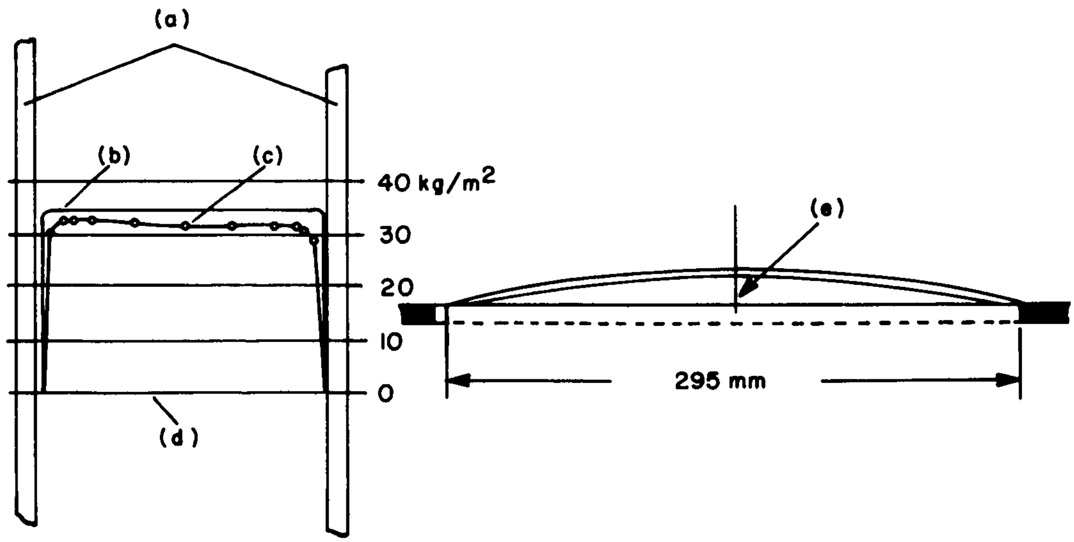


Figure 8.

a--End-Plates; b--Theoretical Values; c--Measured Values; d--Panel; e--22 mm (measured).

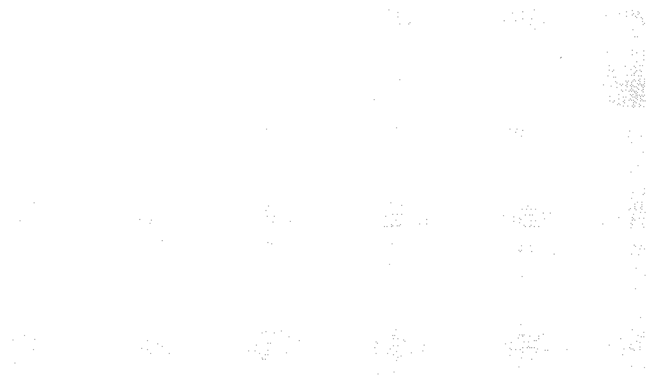


Figure 9. Flutter Stroboscope Picture in a Flow with Pressure Gradient

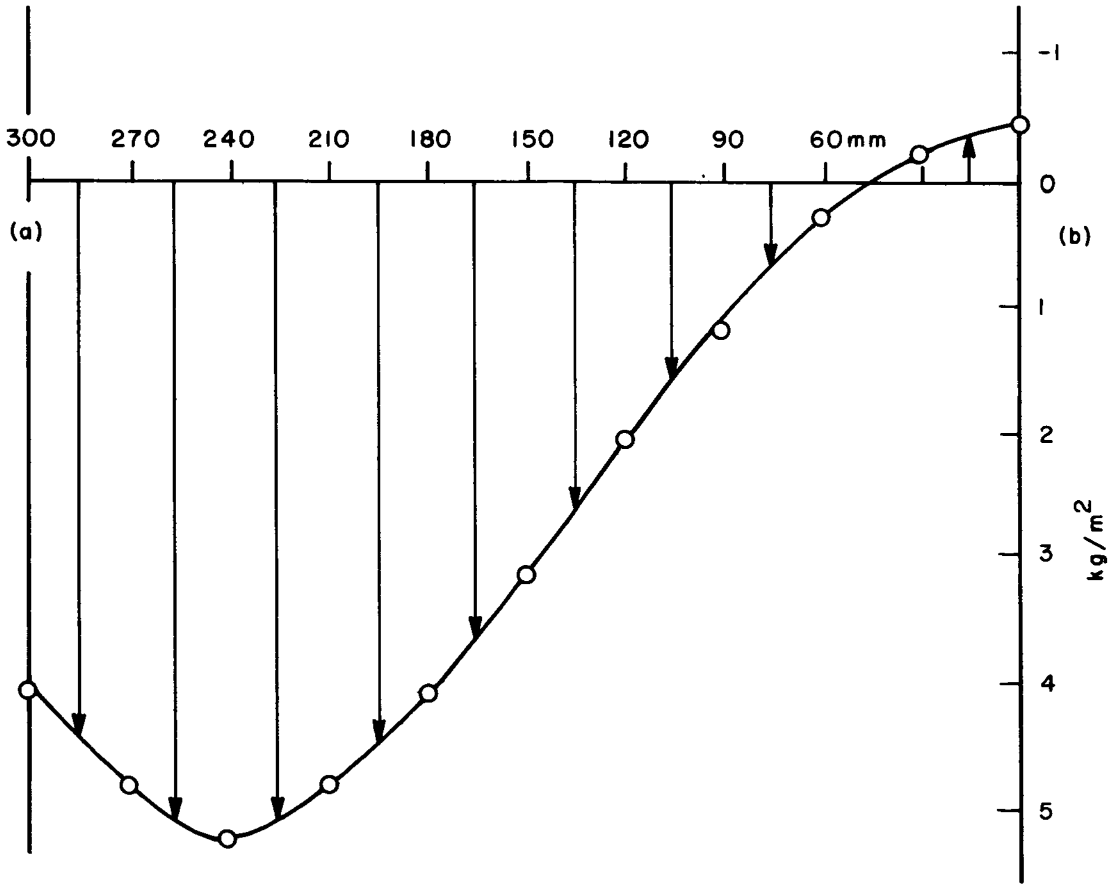


Figure 10.

a--Leading Edge; b--Trailing Edge

Three-Dimensional Panel Experiment

(a) Model

As shown in Figure 11, we passed a 1.2-mm outer stainless steel tube through the leading edge of the panel and attached it to the panel with an adhesive. A piano wire was passed through this stainless steel tube and strung perpendicular to the air flow of the wind tunnel. The trailing edge of the panel was, as in the case of two-dimensional panel, rolled on the 1.5 mm diameter steel pin, and affixed with an adhesive. This steel pin was inserted into the 30-mm long slit supported in the air flow. The two extremes of the trailing edge steel pin were tied to a string which, passing over a pulley, ends in a weight which gives the necessary tension.

Table II.

	Material	Width (mm)	Length (mm)	Thickness (mm)	Aspect Ratio
Medium Aspect Ratio	Steel	68	299	0.04	0.227
	Aluminum	68	300	0.12	0.227
	Aluminum	68	379	0.17	0.179
Small Aspect Ratio	Aluminum	68	449	0.12	0.151
Large Aspect Ratio	Steel	170	298	0.04	0.570

An adjusting device was set up so that the space between the two trailing edge slits as well as the position of the leading edge piano wire could be changed to accommodate panels with any desired aspect ratios.

The aspect ratio of the panels used first in the experiment was, as in the model of the two-dimensional experiment, 68 mm wide and 300 mm long, in order to get a direct comparison with the two-dimensional experiment. However, as we discovered experimentally that the phenomenon of three-dimensional dynamic elastic instability was greatly governed by the aspect ratio, and as we followed the method of pursuing and explaining these phenomena experimentally, the aspect ratios of the tested panels were chosen by deductive reasoning from the results of the preceding experiment. Therefore, in order to be precise, a classification of results is shown in Table II.

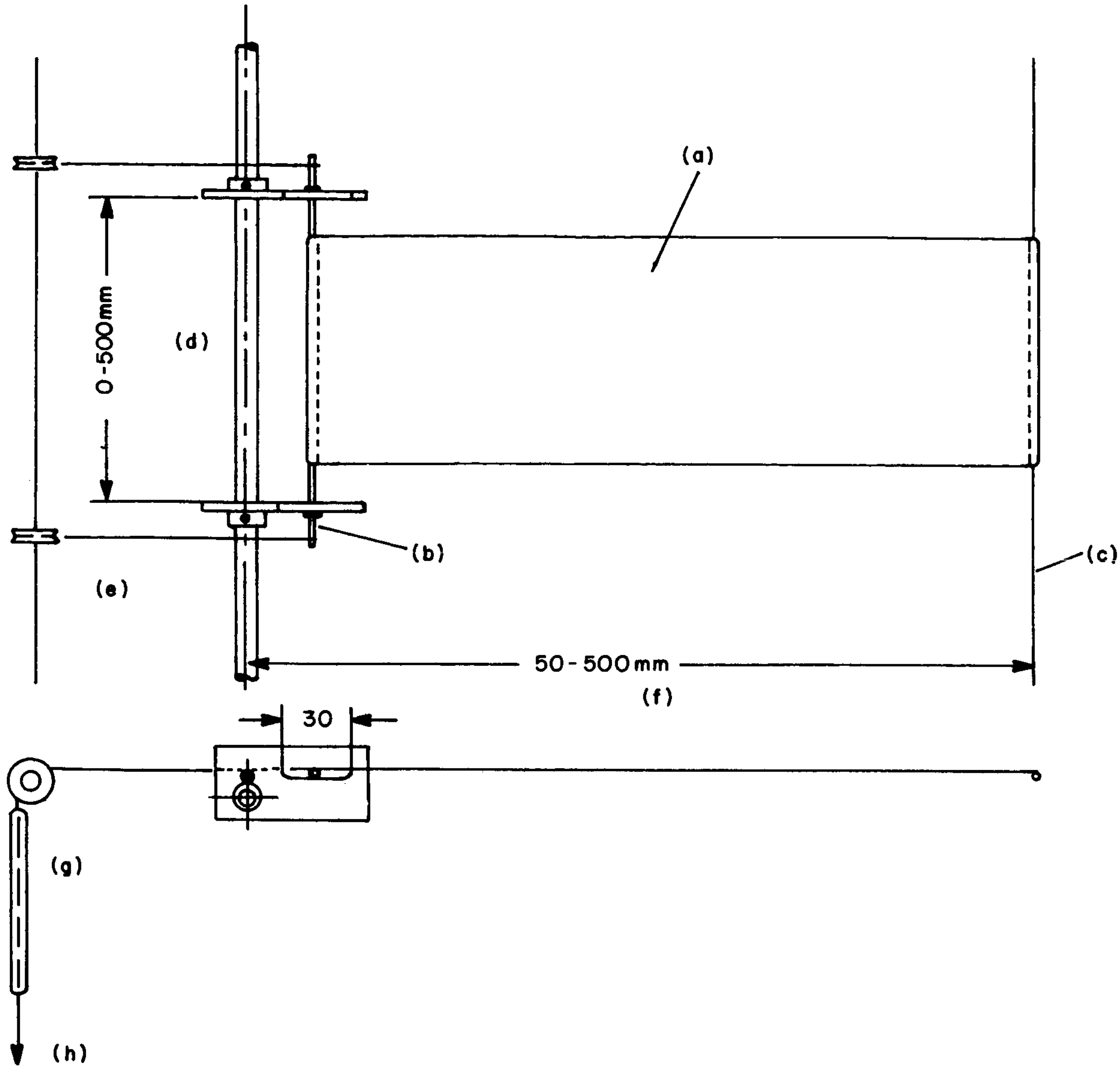


Figure 11.

a--Panel; b--1.5 mm Diameter Steel Pin; c--0.8 mm Diameter Piano Wire; d--0-500 mm (Variable); e--String; f--50-500 mm (Variable); g-- Wind Shielding Pipe; h--Weight

Figure 12. Three-Dimensional Model and Support Equipment

Experimental Results

(a) Medium Aspect Ratio Panel

The results of experiments on the medium aspect ratio panel are shown in Figures 13 through 15. If we gradually increase the air flow dynamic pressure, first of all a sine wave shape divergence occurs. This divergence phenomenon, unlike the case for two-dimensional panel, occurs not with an abrupt increase in the amplitude but instead starts at a low speed and with a small amplitude. The likely reason for this is that the pressure difference between the upper and lower surface is relieved by going around the two ends of the panel. Actually, if we introduce a probe consisting of a thin piano wire with a silk thread attached to its end near the panel ends, we see that the flow is oriented in a direction which supports the above statement.

If we further increase the dynamic pressure, as the divergence oscillation becomes greater overall (Figures 16 and 17), the difference in pressure increases particularly in the trailing edge, and the maximum amplitude of oscillation moves to the rear. To observe the flow in this condition, threads were attached to the surface of the panel and photographs were taken. They are shown in Figures 18a and b. Figure 19 shows the flow lines in the vicinity of the panel, drawn by supplementing the data obtained by observing the flow with thread probes.

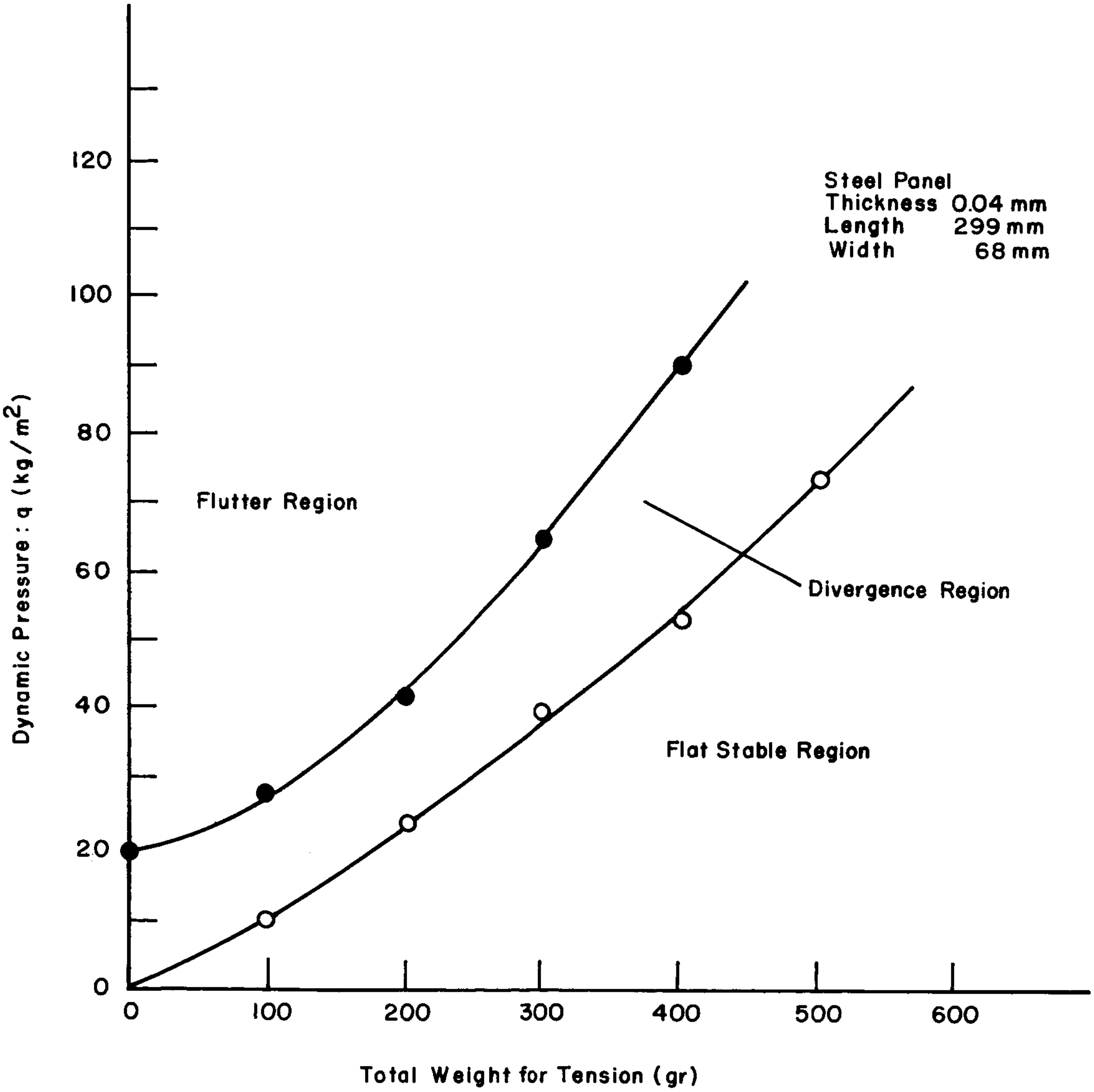
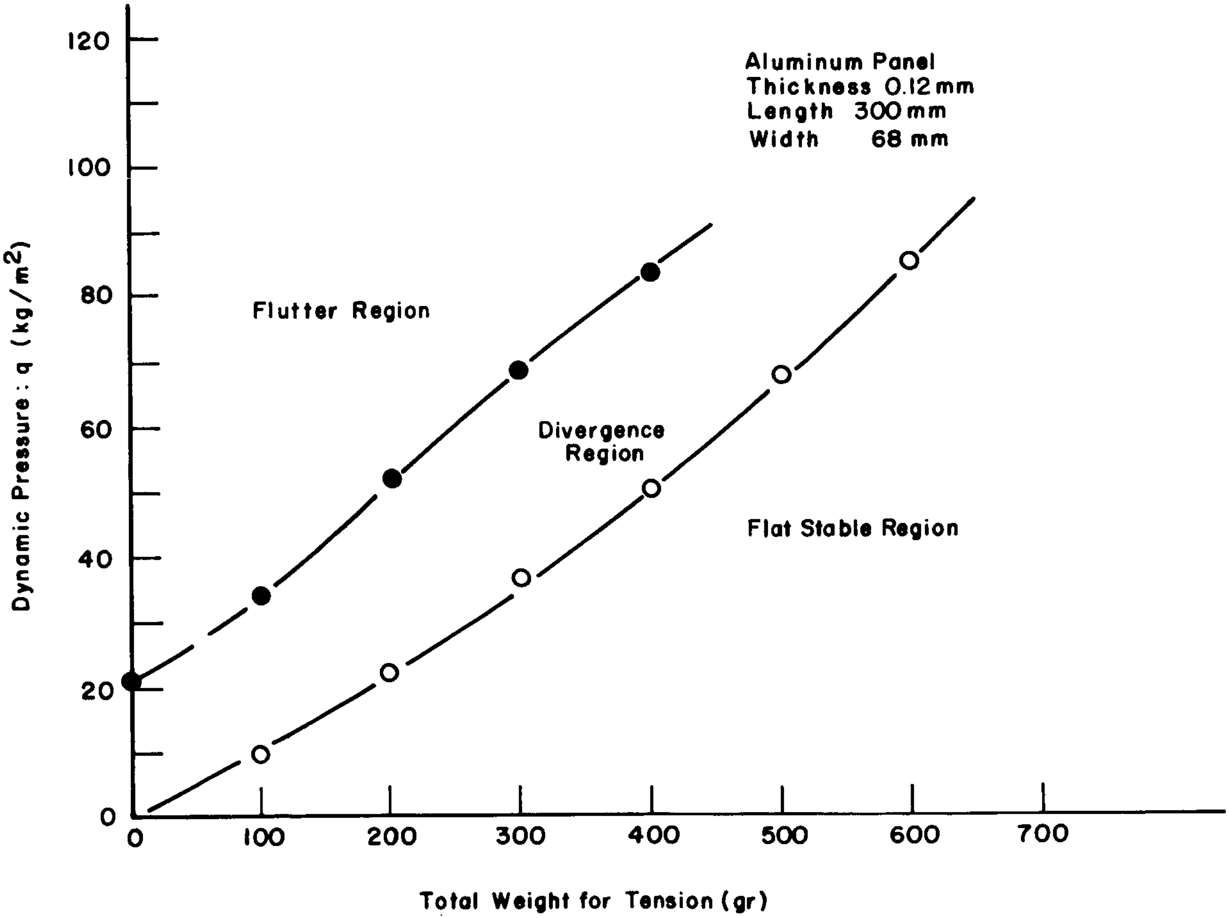

Steel Panel
Thickness 0.04 mm
Length 299 mm
Width 68 mm
Flutter Region
Divergence Region
Flat Stable Region
Dynamic Pressure : q (kg/m²)
Total Weight for Tension (gr)
0
20
40
60
80
100
120
0
100
200
300
400
500
600

Figure 13



120
100
80
60
40
20
0
Dynamic Pressure: q (kg/m^2)
Aluminum Panel
Thickness 0.12 mm
Length 300 mm
Width 68 mm
Flutter Region
Divergence Region
Flat Stable Region
0
100
200
300
400
500
600
700
Total Weight for Tension (gr)

Figure 14

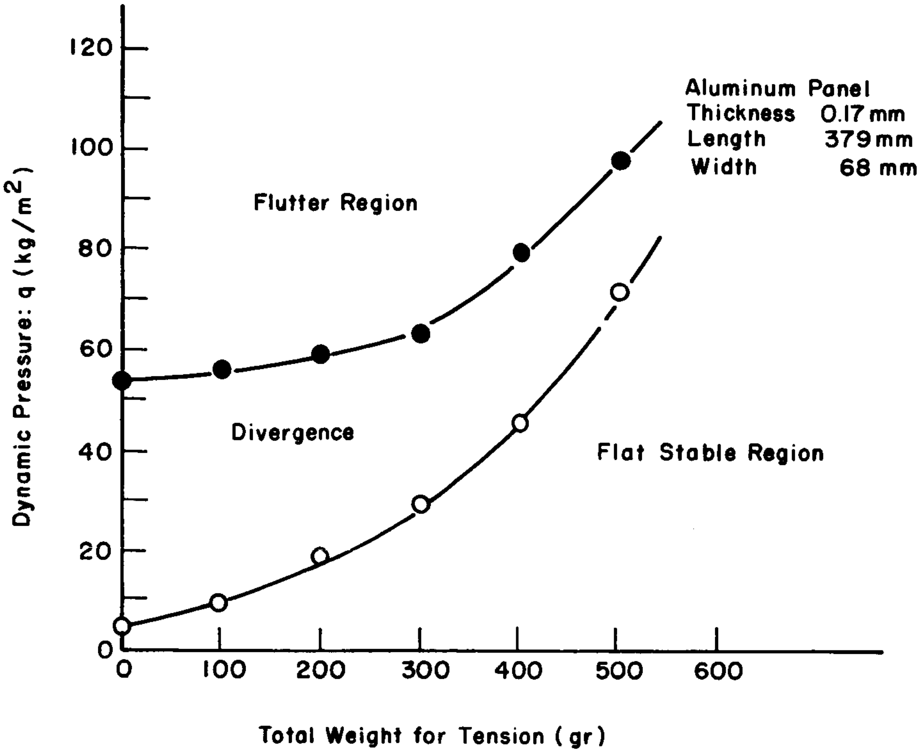


Figure 15

Figure 16. An Example of Continuous Photographs of the Shape of the Divergence Which Changes with the Dynamic Pressure

If we increase the dynamic pressure further, the part near the front edge is raised and the panel becomes S-shaped. This is probably due to the increase of the stagnation point pressure in the bottom of the panel near the leading edge and also due to the decrease in pressure of the eddy domain on the top of the panel. The panel in this condition is statically very unstable. In particular, there is an unstable up-down movement near the middle part of the panel-chord. By merely introducing a rod of about 2-cm diameter into the flow, about 20 cm from either the bottom or the top of the panel to apply a variation in the pressure, by only this fact the panel jumps abruptly to the lower pressure side, and again forms an S-shape but inverted from the former S-shape. This jumping is a phenomenon similar to the Durchschlag of the buckling plate.

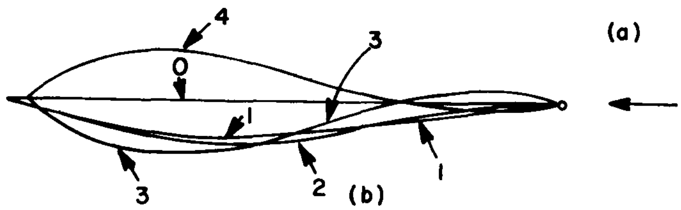


Figure 17.

a--Air Flow; b--The figures represent the order of increasing dynamic pressure. From 3 to 4 there is an abrupt jump and after that it enters into flutter.

If we further increase the dynamic pressure of the air flow, the panel first jumps to the other side and immediately goes into flutter. From high speed photographs (64 frames/sec), it becomes clear that this oscillation is not a harmonic oscillation but an oscillation which stops momentarily at the top and bottom maximum amplitude points.

If we apply dynamic pressure well above the threshold flutter dynamic pressure, a stress wave appears in the flutter oscillation wave.

The panel flutter phenomenon in this (a) group is due to the three-dimensionality of the flow, so that it is a phenomenon which never occurs in the two-dimensional panel. It is hoped that analytical research on this phenomenon will be done in the future.

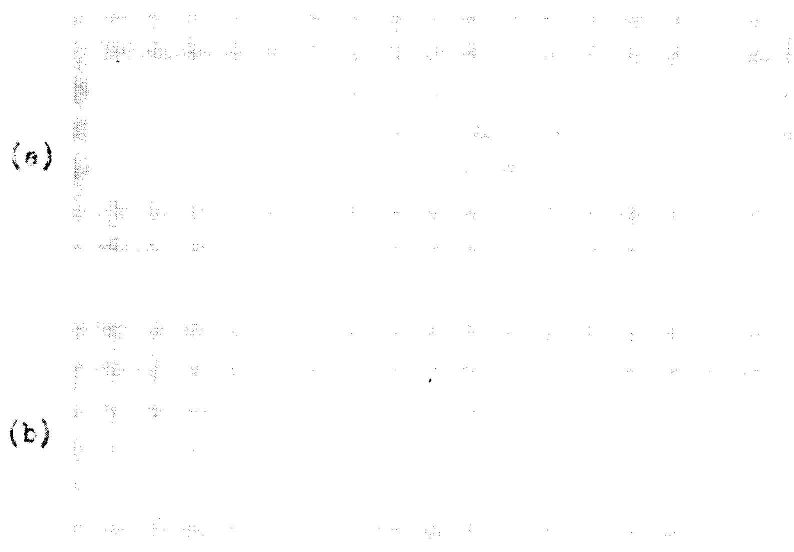


Figure 18. Photographs of the Flow on the Panel Surface in Divergence (on the Approximate order of 2-3 in Figure 17)

a--Upper Surface; b--Lower Surface

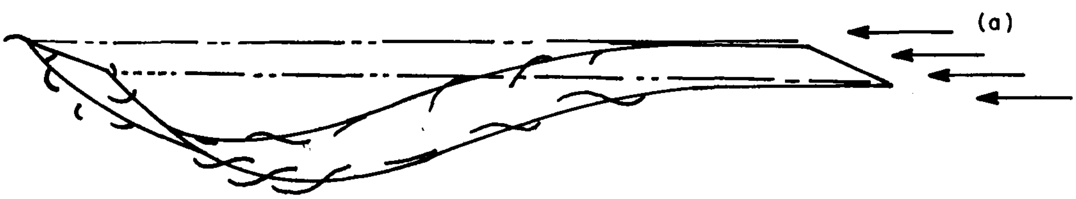


Figure 19.

a--Air Flow

(b) Small Aspect Ratio Panel

When we emphasize three dimensionality by taking a small aspect rate for the panel, the likelihood that the action of relieving the pressure of the divergence would be strengthened and the divergence phenomenon would be weakened can be readily surmised if we assume that the interpretation of the experimental results on (a) group panels is correct. The experimental results were plotted in Figure 20.

The divergence was virtually unnoted, but instead an oscillation close to a standing pressure wave with uniform amplitude appeared. Let us call this soft oscillation. This soft oscillation is a wave which produces 3 or 4 wave lengths on the total panel-chord and advances very slowly in the direction of the flow. But if we compare it with the flutter wave which comes after that, it is almost a standing wave.

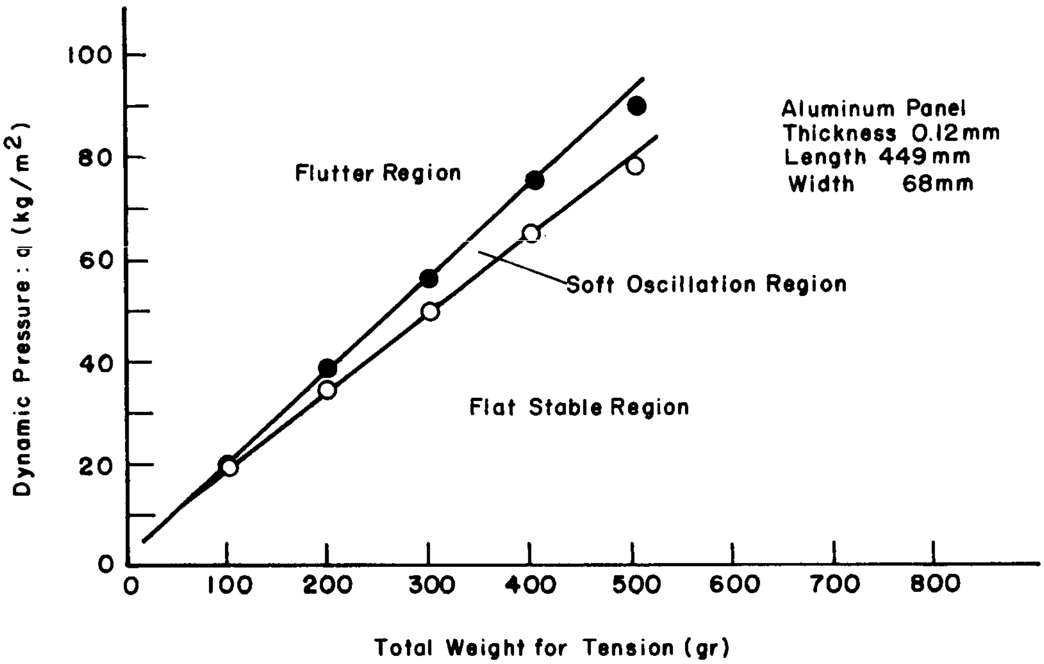


Figure 20.

Moreover, over the whole chord the maximum amplitude of any one of the waves is almost always constant.

If we apply an external disturbance to this soft oscillation wave to locally produce a large amplitude, eliminating this external disturbance will reduce the oscillation which comes back to a constant amplitude. Conversely, if we artificially stop this soft oscillation, and then release the panel, the oscillation then increases coming back to the same constant amplitude. This suggests a limit cycle for non-linear oscillation.

If we further increase the dynamic pressure of the flow, the panels enter into flutter from their trailing edge. It is interesting that on the tension versus dynamic pressure diagram, the tension threshold curve of the soft oscillation and the threshold curve of the flutter are represented by straight lines.

(c) Large Aspect Ratio Panel

The above mentioned flutter phenomenon in both (a) and (b) groups has been inferred as being caused by three dimensionality in the flow which effects relieving of the pressure. To prove experimentally the validity of this inference, a large aspect ratio panel was tested. It was considered that in the large aspect ratio panel the influence of the flow having a pressure relieving effect is limited to the vicinity of two ends of the panel, and that the great part of the central part of the panel is covered by the two-dimensional flow. Therefore, we inferred that the dynamic elastic instability phenomenon in the large aspect ratio panel is also similar to the same phenomenon in the case of the two-dimensional panel. This experiment was carried out on this basis.

The experimental results are plotted in Figure 21.

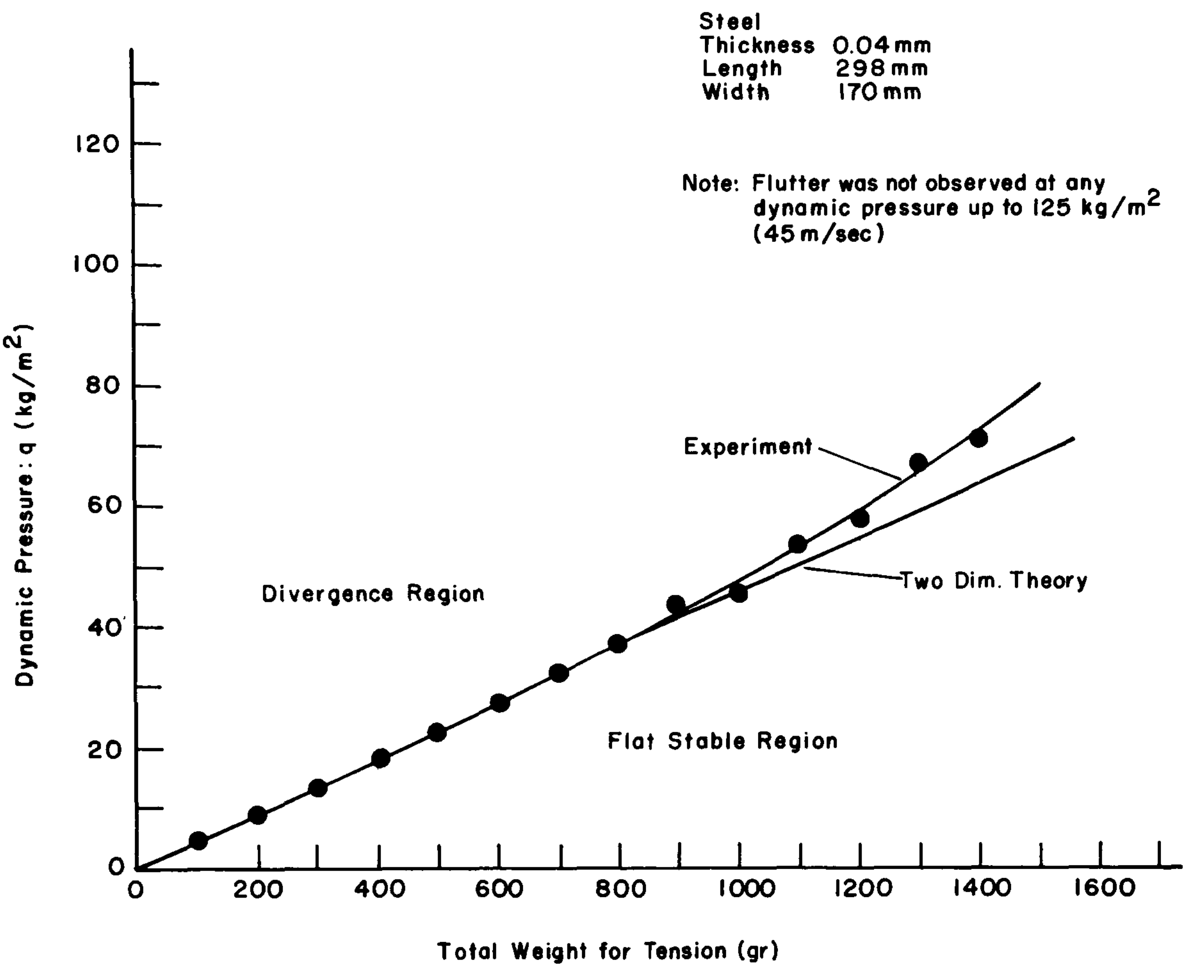


Figure 21.

As shown in the figure, only divergence was produced and flutter was not observed in the range although the maximum speed of 45 m/sec (dynamic pressure 125 kg/m^2) was produced by the wind tunnel. The threshold values of the divergence according to the theory of the two-dimensional panel were also plotted for comparison.

Conclusion

(1) The correctness of the theoretical conclusion in Part I that a two-dimensional panel exposed to an uniform flow will not produce flutter at low Mach numbers, and, with respect to aerodynamic elastic instability, will only produce divergence, was proven for Mach numbers M = 0 through 0.132.

The divergence threshold obtained theoretically in Part I is also numerically correct.

(2) If there is a pressure gradient in the main flow in the direction of the increasing pressure at the rear half of the panel, and, in addition, if this was a case within a very limited form of the pressure distribution, the panel loses its static equilibrium, produces an oscillation, and begins to flutter.

(3) The aerodynamic elastic instability phenomenon in the three-dimensional panel produces different phenomenon depending on the aspect ratio. The cause for this lies not in the inherent elasticity of the panel, but in the three-dimensional flow of the fluid. That is to say the cause lies in the flow which originates in the process of relieving the difference in pressure between the top and the bottom surfaces of the panel, which accompanies the divergence.

(4) In the small aspect ratio panel which is strongly three dimensional, there exists instability in the form of soft oscillation which is a stable oscillation close to a standing wave, and flutter which moves in the direction of the flow and whose oscillation is amplified in the direction of the flow.

(5) In the large aspect ratio panel in which three dimensionality is weak, divergence only is produced and flutter does not occur.

(6) In the medium aspect ratio panel which comes in between the cases (4) and (5), divergence occurs first, but as the dynamic pressure increases, the form of divergence becomes S-shaped finally losing static equilibrium and suddenly entering flutter.

Postscript

In the preparation and the measurement of this experiment we were assisted by Mr. Mitsunori Yanagisawa, Mr. Isao Uchida, and Mr. Yoshihiro Harada, from the First Department of Aerodynamics. We offer our thanks to Mr. Higuchi, head of this Research Lab's Measurement Department, and Mr. Tabata, chief of the laboratory, for their ready consent to the lengthy use of the wind tunnel.

Moreover, we give thanks to Prof. Kuichiro Washizu from Aeronautics Department, School of Engineering, Tokyo University, and his discussion group for their participation in the many discussion sessions involving this research.

Appendix A

CONSIDERATIONS ON THE INFLUENCE OF GRAVITY ON DIVERGENCE OSCILLATIONS

If the gravitational potential, i.e., the positional potential

$$\int_0^b \rho_p h G Z_p(x) dx, \text{ G being the unity of gravity}$$

is introduced into (II) of Part I, and we solve, mainly, the case of the stable flow, the amplitude of the panel oscillation is easily obtained as follows. (In this case also, as the first mode prevails, we are going to take only A_1.)

$$A_1 = \frac{4\alpha X}{\pi^5} \frac{-(81+9s)X - R_{33}^R + R_{13}^R}{\left\{(1+s)X + R_{11}^R\right\}\left\{(81+9s)X + R_{33}^R\right\} + \left(R_{13}^R\right)^2}$$

where

$$\alpha \equiv \frac{b^3 \rho_3 h}{D} \quad .$$

Here also, if we numerically consider $R_{33}^R >> R_{13}^R$, we obtain

$$A_1 = -\frac{4\alpha X}{\pi^5 \left\{(1+s)X + R_{11}^R\right\}}$$

$$= -\frac{4\alpha}{\pi^5 \left\{(1+s)\frac{R_{11}^R}{X}\right\}} \quad .$$

Now, if we substitute

$$\left(R_{11}^R\right)_{k=0} = -2.42472$$

$$1/X = \frac{2}{\pi^4} \frac{\frac{1}{2}\rho_a U^2 b^3}{D}$$

we obtain, finally a relation between the oscillation amplitude and dynamic pressure as

$$A_1 = \frac{4a}{\pi^5} \frac{1}{(1 + x) - 2.42472 \frac{2}{\pi^4} \frac{b^3}{D}\left(\frac{1}{2} \rho_a U^2\right)} .$$

If we plot the variation in the amplitude of oscillation A_1 relative to the dynamic pressure $1/2\rho_a U^2$, we obtain the curve in Figure A1.

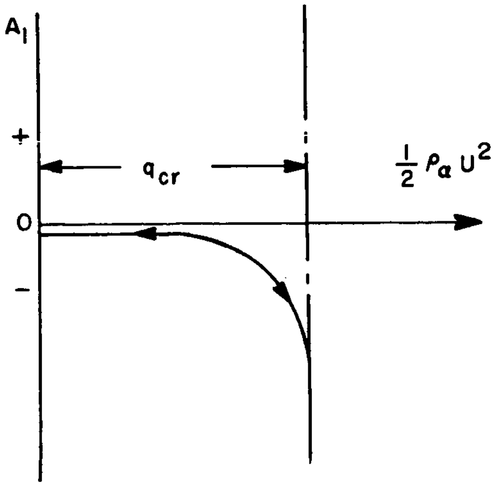


Figure A1

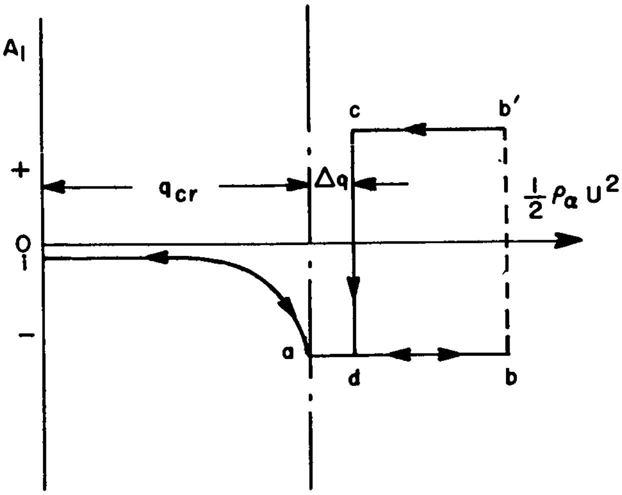


Figure A2

The dynamic pressure q_{cr} at which the amplitude A_1 diverges infinitely agrees with divergence threshold speed in the case when the influence of gravity is neglected, but it does not diverge abruptly as in theoretical values (Figure A2, dashed curve). Instead, it gradually diverges hyperbolically. Therefore, in order to read q_{cr} experimentally with high precision, we need to give it a consideration more compatible with reality.

In the panel model utilized in our experiment, the trailing edge is bound in a slit with a finite length; therefore, A_1 cannot increase indefinitely, even after divergence, and it becomes a constant (Figure A2: line ab). In the case of dynamic pressure above the divergence threshold, let us consider a case when the panel changes somehow to the positive side of the oscillation (b→b'). If we decrease the uniform flow pressure from this situation, the amplitude of the panel changes through the curve b'cd. That is to say, when the divergence comes back to the initial position from the situation in which it is lifted against gravity, the amplitude decreases to negative (in this direction) at the dynamic pressure point $q_{cr} + \Delta q$, after which it passes through the curve dai.

Δq is the increase in dynamic pressure threshold which is caused by the gravitational influence on the panel.

In order to measure experimentally the theoretical value of q_{cr}, which was calculated by neglecting the influence of the gravity, as we can see from the above considerations, let us first make the panel diverge to the lower side by applying sufficiently large dynamic pressure. Then, by decreasing the dynamic pressure gradually, we should read the dynamic pressure at the exact moment when the amplitude of the panel passes through point a of the figure.

The arrows in the figures point to the direction in which the phenomenon proceeds.

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13. ABSTRACT

Several metal panels, 300 mm long and 70 mm wide, pin-supported at their leading and trailing edges, are placed between a pair of parallel end-plates.

These two-dimensional models are tested in a low speed wind tunnel which provides the maximum wind speed of 45 m/sec.

As has been predicted by our theory of Part I, even the thinnest steel panel with thickness ratio 1.33×10^{-4} did not flutter. The observed instability is divergence only. The measured divergence boundary agreed quite well with our theoretical results.

By taking off the end-plate and modifying the model mountings, three dimensional panels with various aspect ratios were tested in the same wind tunnel. Our experimental study revealed that three-dimensional panels, simply supported at their leading and trailing edges with two sides free, are subjected to a series of complicated instabilities.

These instabilities may be classified into three-categories depending on the aspect ratio of the panels.

(Continued on Page 31)

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
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Two-dimensional panel						
Three-dimensional panel						
Subsonic flow						
Flutter						
Divergence velocity						

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13. Abstract (Concluded)

Panels	Instabilities
(i) High aspect ratio panels	Divergence only.
(ii) Medium aspect ratio panels	A series of divergence shape, from a half wavelength of sine shape to S-shape as the dynamic pressure is increased, followed by flutter.
(iii) Low aspect ratio panels	Soft standing oscillations followed by flutter.

The boundaries of these instabilities were experimentally determined. The causes of these phenomena were revealed by experiment.