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FAST RESPONSE VANES FOR SENSING FLOW PATTERNS IN HELICOPTER ROTOR ENVIRONMENT

By

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A TECHNICAL REPORT

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FAST RESPONSE VANES FOR SENSING FLOW PATTERNS IN HELICOPTER ROTOR ENVIRONMENT

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and

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SUMMARY

Wind tunnel experiments were conducted on four small-scale flow-direction vanes for the determination of aerodynamic response. The tests were further extended to include a standard sized low-inertia vane currently employed in aircraft flight testing. The four test vanes had different aspect ratios and were about 35 percent of the surface area of the standard vane. The test results indicate satisfactory damping and frequency response for all vanes tested and compare favorably with the standard design.

INTRODUCTION

The free-trailing flow-direction vanes have been in use for some time in flight tests for measurements of relative wind direction and gust effects. A design currently in use has been described by Richardson [1] and tests performed showed remarkably high damping ratio and satisfactory frequency response. While this vane with its 11.3 in^2 (0.00727 m^2) area has found wide acceptance for standard aircraft testing, it was considered rather large for flow field studies of helicopters.

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The need for smaller vanes called for an experimental study of performance under subsonic speed conditions ranging from 30 (13.4 m/s) to 135 mph (60 m/s). To determine the optimum aspect ratio, four experimental vanes, with aspect ratios 3/8, 1/2, 1 and 2, were made, similar in construction to the standard design. The first set of vanes subjected to tests were of 2 in^2 (0.00129 m^2) area and these proved insufficient to provide adequate torque for actuating the potentiometer employed in measuring attenuation. Subsequently, the area of the vanes was increased to 4 in^2 (0.00258 m^2) and this report presents the results obtained.

SYMBOLS

f_n	natural frequency of vane, Hz
t	time, seconds
t_r	response time (defined in Appendix II)
τ_r	comparative response time
ΔT	time required for the vane to move from β_o to $0.5\,\beta_o$, seconds
U	free stream velocity, mph or m/s
β_o	initial offset angle, degrees
β_1	offset angle at time $t = t_1$ degrees
ω_n	natural frequency, radians/second
ξ	damping ratio, non-dimensional

APPARATUS AND TESTS

Models

The vanes selected for testing were similar in shape and design to that extensively tested by N.R. Richardson [1]. However, while Richardson's vane had a projected area of 11.25 in^2 (0.00719 m^2) with an aspect ratio of 1/2, the four vanes under consideration in the tests described here all had a projected area of approximately 4 in^2 (0.00258 m^2) with aspect ratios 3/8, 1/2, 1 and 2, respectively, as shown in Figure 1(a), where all relevant dimensions are also noted. A comparison in size between the Richardson and test vanes appears in Figure 1(b).

The vanes were made of 0.096-in (2.438-mm) thick balsa wood and were bonded with epoxy resin to the cylindrical brass shaft of 3/16-in (4.76-mm) diameter. Half of the shaft material was cut away, leaving a flat surface where the vane was joined and the remaining half was streamlined to form a suitable rounded leading edge. Each model was statically balanced by a flat counterweight bonded to the shaft and extending on the opposite side of the vane at some distance away to minimize interference. The end of the shaft was provided with a sleeve which connected the vane shaft with the spindle of the supporting apparatus.

Apparatus

All models were tested in the 3 ft (0.914 m) x 4 ft (1.219 m) closed wind tunnel at Old Dominion University.

The apparatus supporting the models essentially consisted of a turntable, support arm, and spindle. The turntable, holding the support arm, was situated directly beneath the center of the testing section of the wind tunnel and could be turned about a vertical axis. The support arm protruded vertically into the tunnel for about 15 in (0.381 m) and then bent into a horizontal position for 12 in (0.305 m) facing the stream. All models were mounted, in turn, on top of the vertical spindle which passed through the horizontal section of the support arm and could freely rotate. Free rotation was accomplished by two antifriction bearings housed inside a sleeve, 6-in (0.152 m) long, fitted to the top of the support arm about 3 in (0.076 m) from the end facing the stream. The lower end of the spindle extended into a potentiometer (see Fig. 2).

Prior to setting the vane free to perform an oscillating motion, it was first offset and then restrained by a mechanism that could be manually triggered to release the vane at a given instant. The mechanism essentially consisted of a radial cam and a springloaded pushrod which provided a stop for a taper pin extending from the side of the spindle.

The cam profile consisted of a "slow" ramp over its circumference and a step that provided a discontinuity in the ramp. When at the maximum radius of the cam, the pushrod was positioned so as to block movement of the taper pin, thus "freezing" the spindle and model. Additional rotation of the cam allowed the pushrod to instantaneously slide into the step by the actuating spring force, thus releasing the spindle. A long thin rod extending through the tunnel wall was provided to rotate the cam.

The potentiometer relayed the angular displacement of the vane through an electrical bridge to an oscillograph, which recorded the oscillations graphically.

Procedure

In addition to the four test vanes, a Richardson vane was also tested for comparison purposes.

Prior to testing, the model vane selected was mounted into position parallel with the anticipated flow direction. The turntable was then set into zero position with the vane resting against the stop. Subsequently, air was set to motion and the potentiometer was adjusted for optimum linearity at about 7-1/2 degrees angle. The reason for choosing this angle was due to consideration of the operational initial offset angles* normally being 3, 5, and 10 degrees.

The oscillograph was subsequently adjusted for maximum deflection of the pen corresponding to 1 millivolt per millimeter. This yielded on the graph approximately 2.25 mm distance per degree of offset angle.

After these preliminary procedures the models were ready for testing. For each test run the following routine was observed:

a) the alignment of the model was checked;

b) airflow was started;

c) the pin was brought against the stop by rotating the cam into proper position;

d) the turntable was rotated to the selected offset angle with the vane being bound to follow the turning;

e) the oscillograph was started, and was immediately followed by the

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* Note: The initial offset angle is the amount of angular displacement of the vane from equilibrium prior to release. The word "initial" will be dropped from further discussions.

release of the vane; after the oscillations were recorded over a period usually lasting about 1 sec, the movement of the recorder was quickly discontinued, as the run was completed;

f) in order to reset the stop, the turntable was rotated in the opposite direction to a negative angle.

This practice was repeated three times for each of the offset angles -- 3,5, and 10 degrees.

The entire procedure was repeated with increasing air velocity of increments of 15 mph, starting with 30 mph (13.4 m/s) and ending with 135 mph (60 m/s).

The chart of the oscillograph was set for a speed of 0.125 m/s.

Test Results

Results of the tests are presented in Figures 3 to 7. More particularly, in Figure 3 the damping ratio of the various vanes is shown; in Figure 5 the natural frequency is plotted, while in Figure 7 variation of response time is presented. All variables are plotted against the air speed approaching the models, for offset angles 3, 5, and 10 degrees. Details of the calculation of damping ratio and natural frequency are shown in Appendix A.

It appears that initial offset angle affects damping and generally higher damping ratios were observed for lower offset angles. The low aspect ratio vanes produced the highest damping and comparison of damping between various vanes for the same offset angle, 5 degrees, is shown in Figure 4.

Damping also appeared to be largely independent of air speed, although small variations are noticeable. These are considered experimental errors. The higher damping ratios at lower velocities may be caused by the friction in the potentiometer which increases relative to the decreasing aerodynamic forces at lower velocities. Richardson's test vane, relatively large in size, does not show these effects. The "scale effect," that is, the difference between the half aspect ratio vanes (the Richardson and the test model) is quite marked, and gives rise to speculation because the smaller vane is expected to yield higher damping. Although the discrepancy varies somewhat, the difference rises to more than 10 percent at certain airspeeds. Also, the effect of offset angle on damping is more marked for the Richardson vane while it appears almost negligible for the AR = 1/2 test vane. The damping is surprisingly low for the AR = 2 vane, especially for the 10-degree offset angle. The best damping was attained when employing the AR = 3/8 vane.

The results on (natural)* frequency are found to be in accordance with theory and show, on the average, linear increase with airspeed for all vanes tested. In addition, the results agree with theory which is known to predict an inverse relationship between frequency and damping for models at a particular airspeed. Accordingly, the AR = 2 vane shows the highest and Richardson's test vane the lowest frequency. Effects of offset angle appear to be the smallest for the AR = 3/8 vane. A large scatter of observations, especially noticeable at higher speeds (Fig. 6), leads to questions about either the accuracy of the experiment or the accuracy of reading the results produced by the oscillograph. Furthermore, effects of vibrations of the vane shaft must be taken into consideration. This became especially noticeable with the AR = 2 vane which, at speeds exceeding 60 mph, became so excited naturally that its oscillations were visible through the access panels. Shortening the shaft stabilized but not completely eliminated the oscillations.

The combined effects of frequency and damping are shown in Figure 7 where, for 5 degrees of offset angle, response time is plotted against airspeed. Derivation of this parameter is given in Appendix B, and it is shown that response time is inversely proportional with the product of frequency and damping. Values plotted were calculated from values presented on Figures 4 and 6.

It appears from Figure 7 that response time consistently decreases with increasing airspeed except for the AR = 2 vane which has shown excessive vibration at higher speeds.

It is noted here that the results of frequency obtained in these experiments differ slightly from those obtained by Richardson and other investigators. The discrepancy is of the order of 10 percent with observations being higher at lower airspeeds and being lower over 75 mph (33.5 m/s). Repeated tests did not alter these findings.

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* The use of natural frequency rather than the damped frequency seems to find wider acceptance.

DISCUSSION OF RESULTS

The results presented in the previous section may be grouped into two categories:

1. For each of the vanes tested:

    a) Damping appears to be independent of airspeed;

    b) Frequency appears to increase with airspeed;

    c) Response time appears to decrease with airspeed.

On the other hand,

2. For a specified airspeed:

    a) Damping increases with decreasing vane aspect ratio;

    b) Frequency increases with increasing aspect ratio;

    c) Response time increases with decreasing aspect ratio.

On the basis of these findings it would be impractical to design a vane that satisfies the demand for both high damping and high frequency. The test showed that the results are contravening because the larger aspect ratio vanes have the quickest frequency responses while the smaller aspect ratio vanes have the higher damping ratio. Therefore, the optimum vane design for high frequency requires large aspect ratio, whereas for high damping low aspect ratio is needed.

In order to end this apparent confusion it is proposed to predict the suitable design for the selection of vanes on the basis of a single parameter embodying the combined effects of frequency and damping.

In Appendix B it is shown that the time required for a displaced vane to reach equilibrium is inversely proportional to the product of frequency and damping. The vane which produced the best response at lower speeds was the vane with AR = 2. In excess of about 60 mph, however, the curve shown in Figure 7 deviates from its probable course and cuts across the curves of the AR = 1 and AR = 1/2 vanes. This effect was caused by vibrations, and one may conclude that since this vane was found aerodynamically less stable than the others, its use may not be recommended until further studies are made which may include structural improvements to the shafting and variations to the vane planform without affecting the aspect ratio.

The model with the slowest response was the vane with AR = 3/8 and the Richardson. The Richardson vane may be set aside for the time being, since its size is larger than the rest of the test vanes and thus its inertia relative to the aerodynamic forces produces some differences when compared with the test vanes which were made of the same balsa wood of comparable thickness (0.096 in [2.438 mm] as against Richardson's 0.125 in [3.175 mm]).

The long and relatively slender low aspect ratio vanes have shown slow response although their damping ratio is high. The low response is due to the mass inertia of the vanes about the axis of rotation, which increases with decreasing aspect ratio. Since, however, the return moments of aerodynamic forces are favorable, their damping is high. On the other hand, the low aspect ratio vanes are susceptible to bending as well as to structural damage due to being long and slender.

CONCLUSION

Consideration of the above leads to the conclusion that while a clear cut answer for optimum vane design does not appear from the analysis of the test results, a common sense compromise may be found by excluding the high and low aspect ratio vanes for reasons stated above.

This clearly leaves the "medium" aspect ratio vane, that is the planform with aspect ratio one, or near one, as probably the best selection for vane design.

REFERENCES

1. Richardson, Norman R., "Dynamic and Static Windtunnel Tests of a Flow-Direction Vane". NASA TN D-6193, April 1971.

2. MacCready, Paul B., Jex, Henry R., "Response Characteristics and Meteorological Utilization of Propellor and Wind Sensors." J. of Appl. Meteorology, Vol. 3, p. 182, April 1964.

APPENDIX A

Damping Ratio and Natural Frequency

The damping ratios were determined using the first and second peaks of the damped oscillations read from the oscillograph. The well known equation used was:

$$\xi = \ln \frac{\beta_0}{\beta_1} \Big/ \sqrt{\pi^2 + \ln^2 \frac{\beta_0}{\beta_1}} \qquad (1)$$

The natural frequency was obtained [2], using the damping ratio, from the equation*

$$f_n = 1/[\Delta T \ (6.0 - 2.27 \ \xi)] \qquad (2)$$

where ΔT is the time required for the vane to move from its β_0 offset position to $0.5 \ \beta_0$. The quantity ΔT is obtained by dividing the measured length on the chart by the chart speed.

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* MacCready and Jex [2] use the quantity $(6.0 - 2.4 \ \xi)$ derived graphically, but mathematical derivation yields $(6.0 - 2.27 \ \xi)$.

APPENDIX B

Response Time

An important aspect in determining the applicability of a particular vane is its time response, i.e., the time required for the vane to return to some given fraction of its initial offset.

Consider the envelope created by the peaks of the "overshoots" of a damped oscillation as shown in Figure B-1.

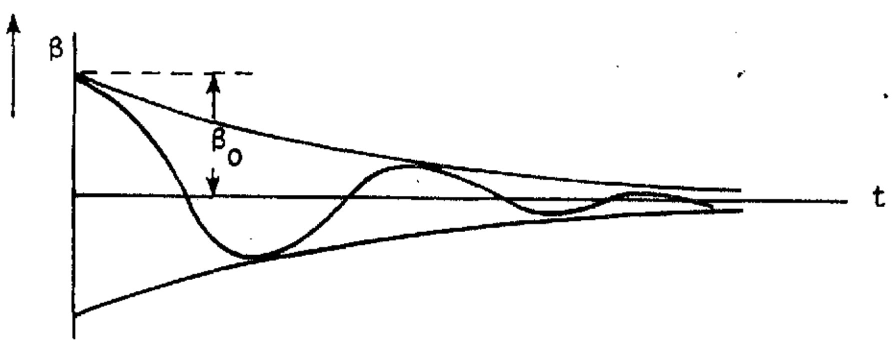


Figure B-1

For a simple, single degree of freedom damped system, the equation of the envelope is given by

$$\beta = \beta_o \exp(-\xi\omega_n t) \tag{3}$$

Solving for t and defining t_r as the response time required for β to diminish to a specified fraction of β_o, the equation becomes

$$t_r = \frac{1}{\xi\omega_n} \ln \frac{\beta_o}{\beta} = \frac{1}{2\pi f_n \xi} \ln \frac{\beta_o}{\beta} \tag{4}$$

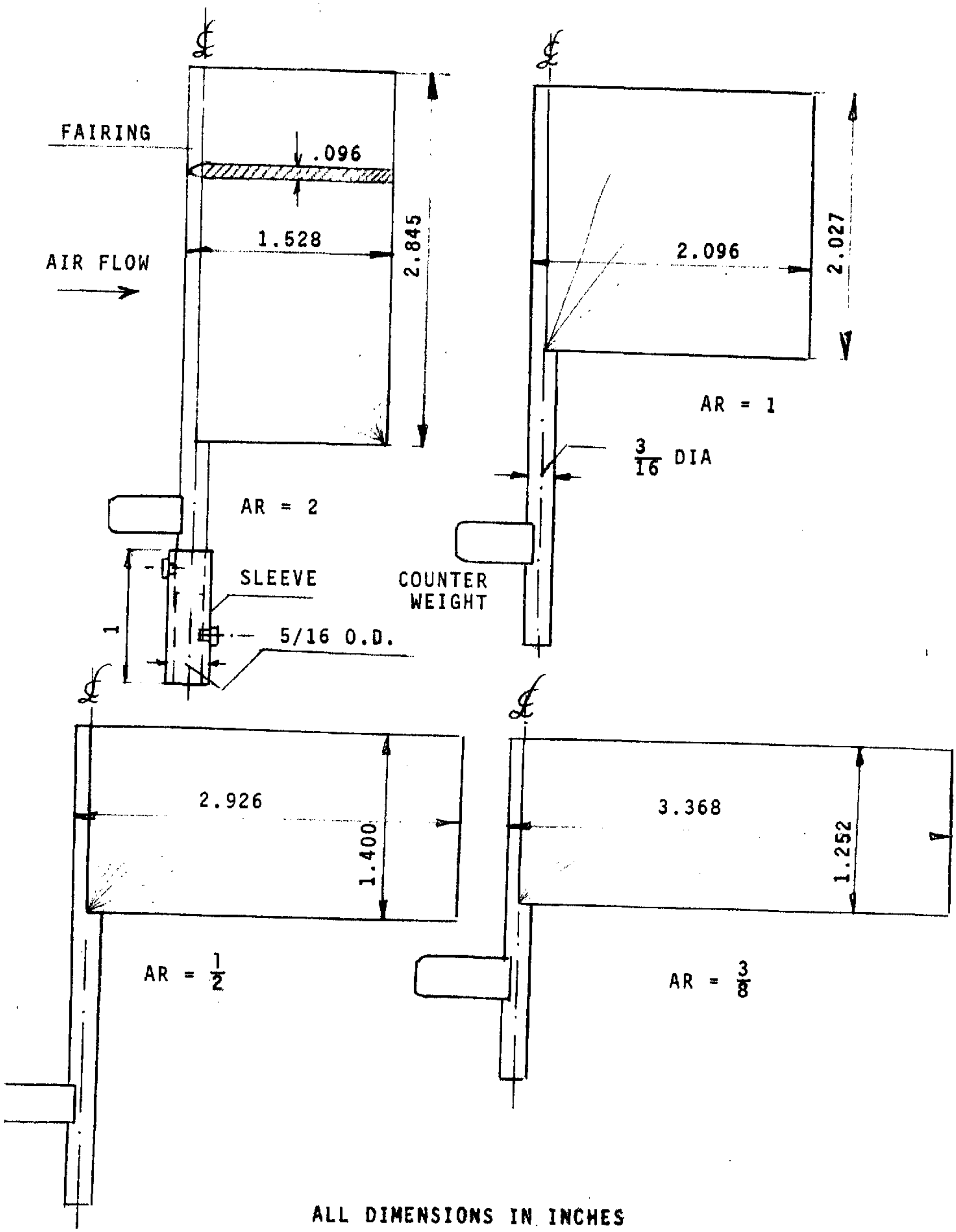
The damping ratio ξ can be read from the dynamic response curves and the natural frequency f_n can be obtained from the equations described by equations (1) and (2).

When comparing different aspect ratio vanes, the quantity $\ln \frac{\beta}{\beta_o}$ will be considered constant for all the vanes regardless of the value of β chosen.

By defining $\tau_r = \frac{2\pi t_r}{\ln \frac{\beta_o}{\beta}}$ as the "comparative response" time, equation (4) becomes

$$\tau_r = \frac{1}{\xi f_n} \tag{5}$$

It can be seen that the comparative response time, τ_r, is inversely proportiona to both damping ξ and natural frequency f_n. This comparative response time is plotted for the test vanes in Figure 7.



ALL DIMENSIONS IN INCHES

Figure 1(a) Details of Experimental Model Vanes (Actual Size)

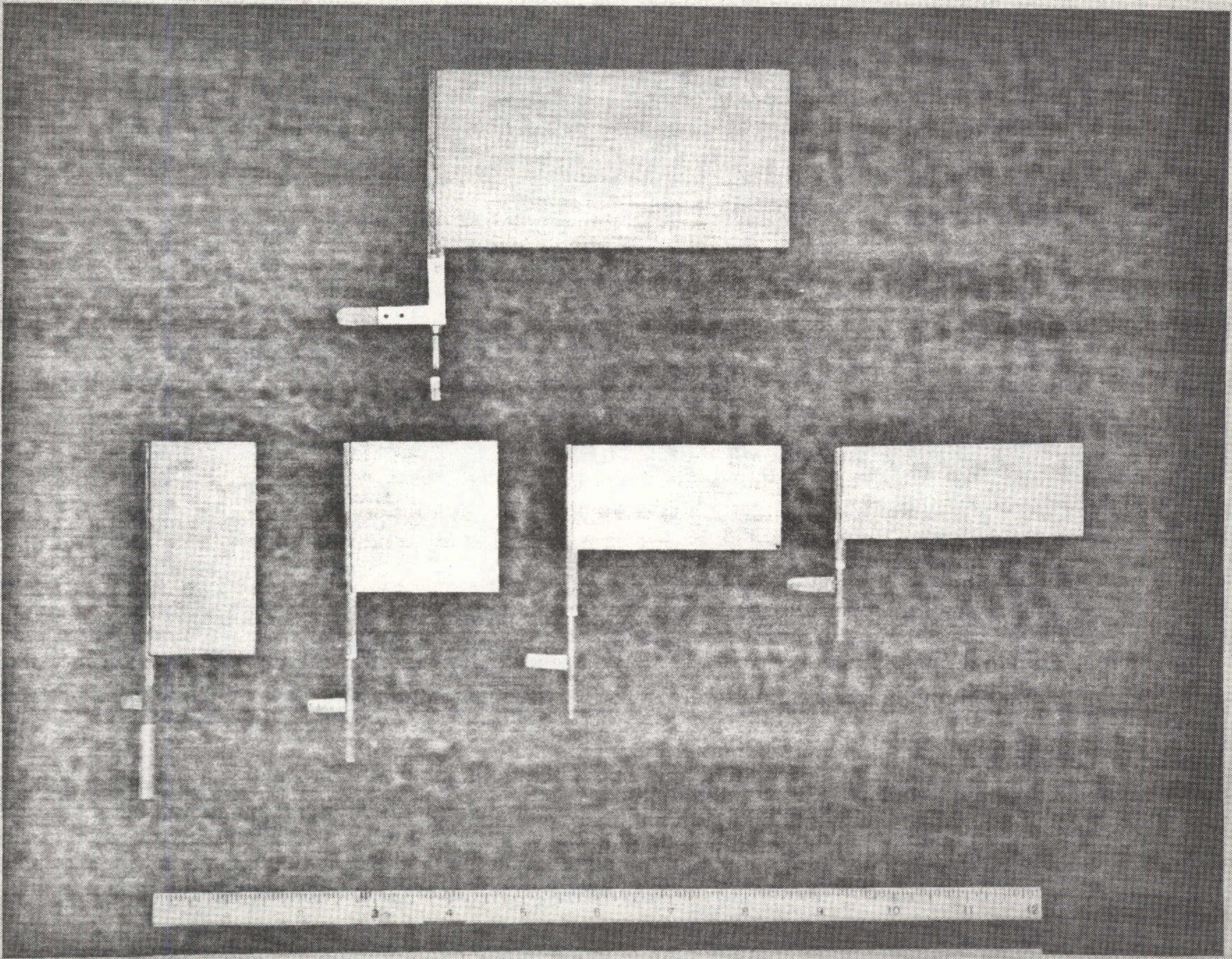


Figure 1(b) Photographic View of Experimental Vanes. (Vane on Top is the Standard Design)

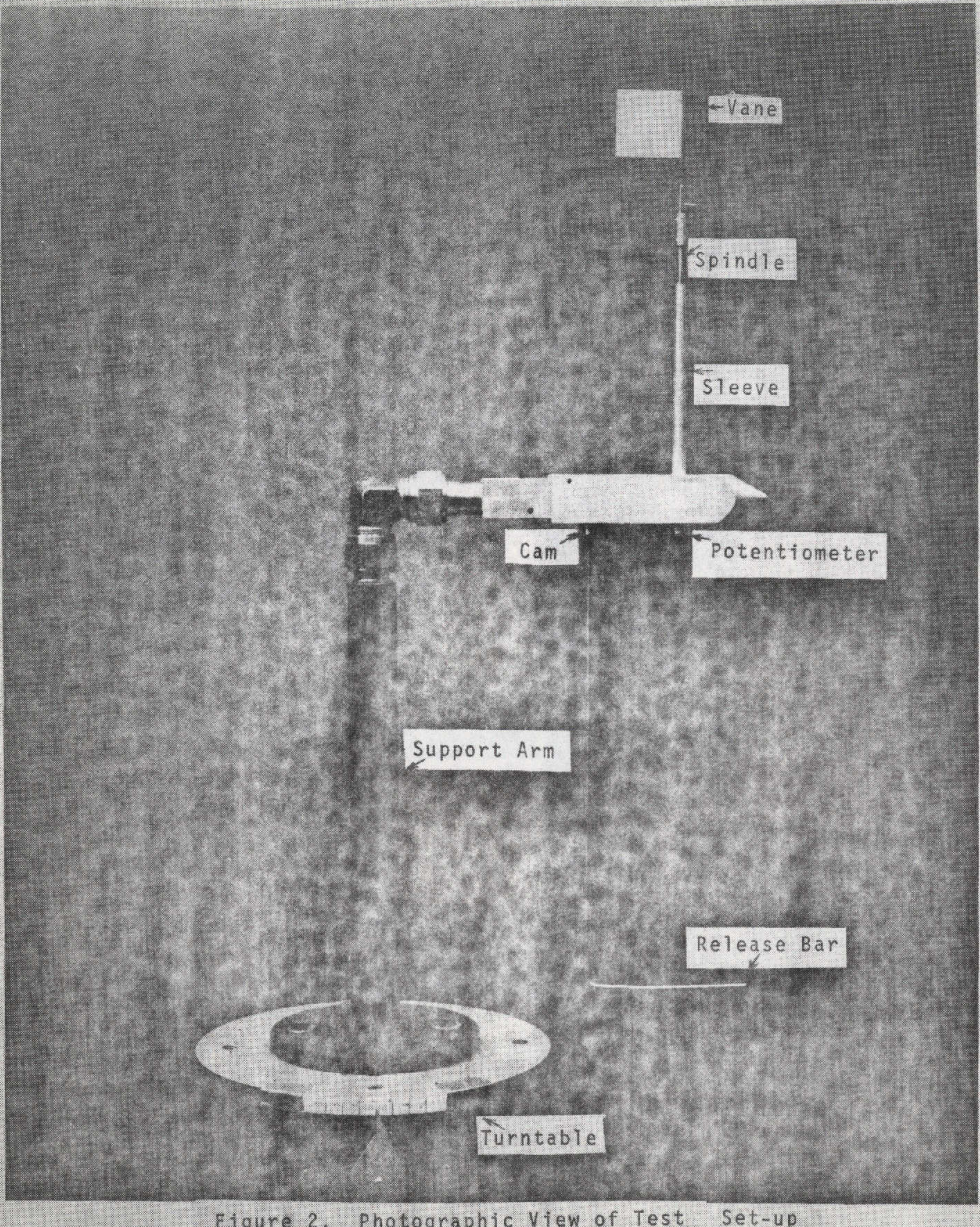
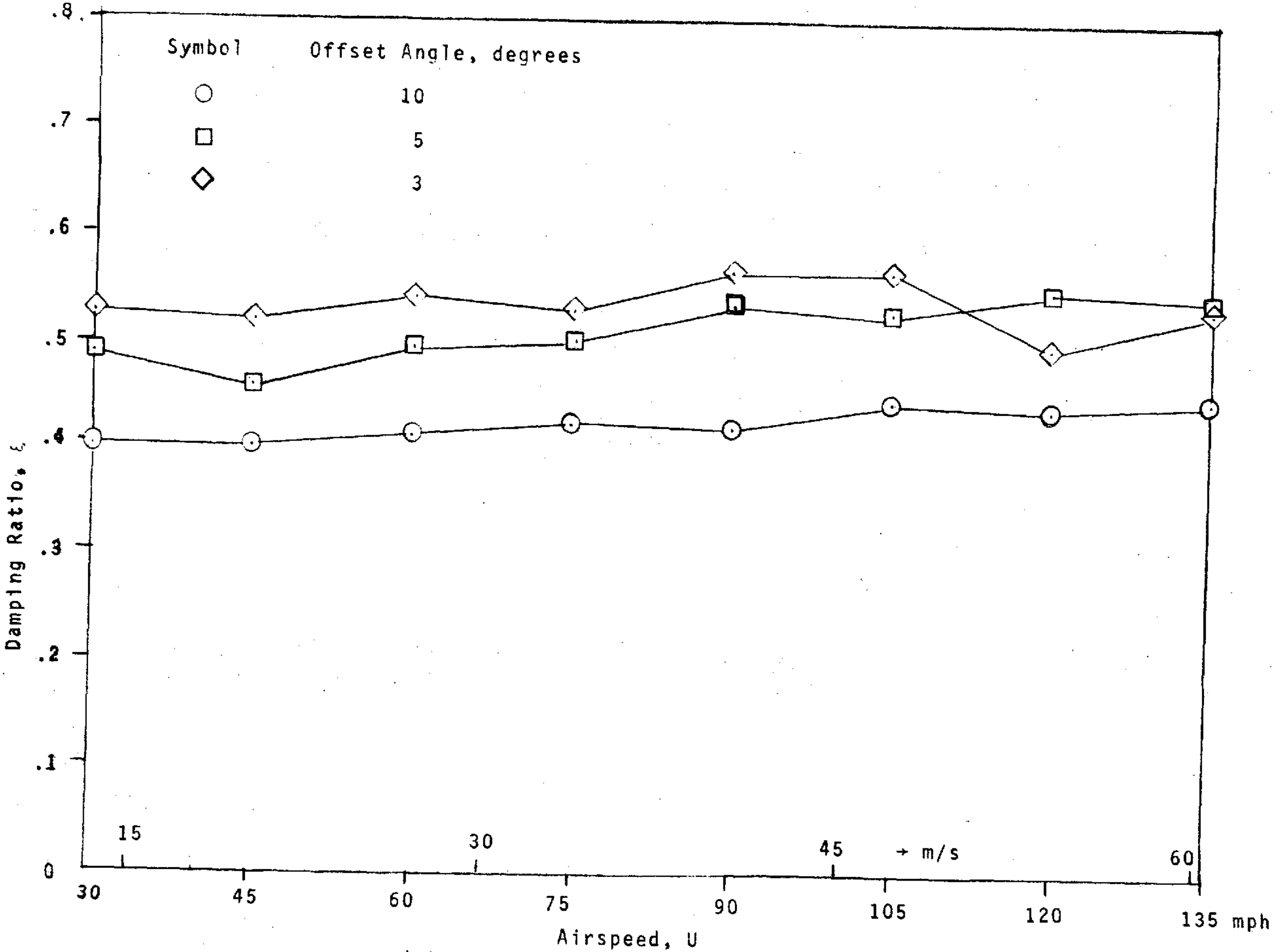
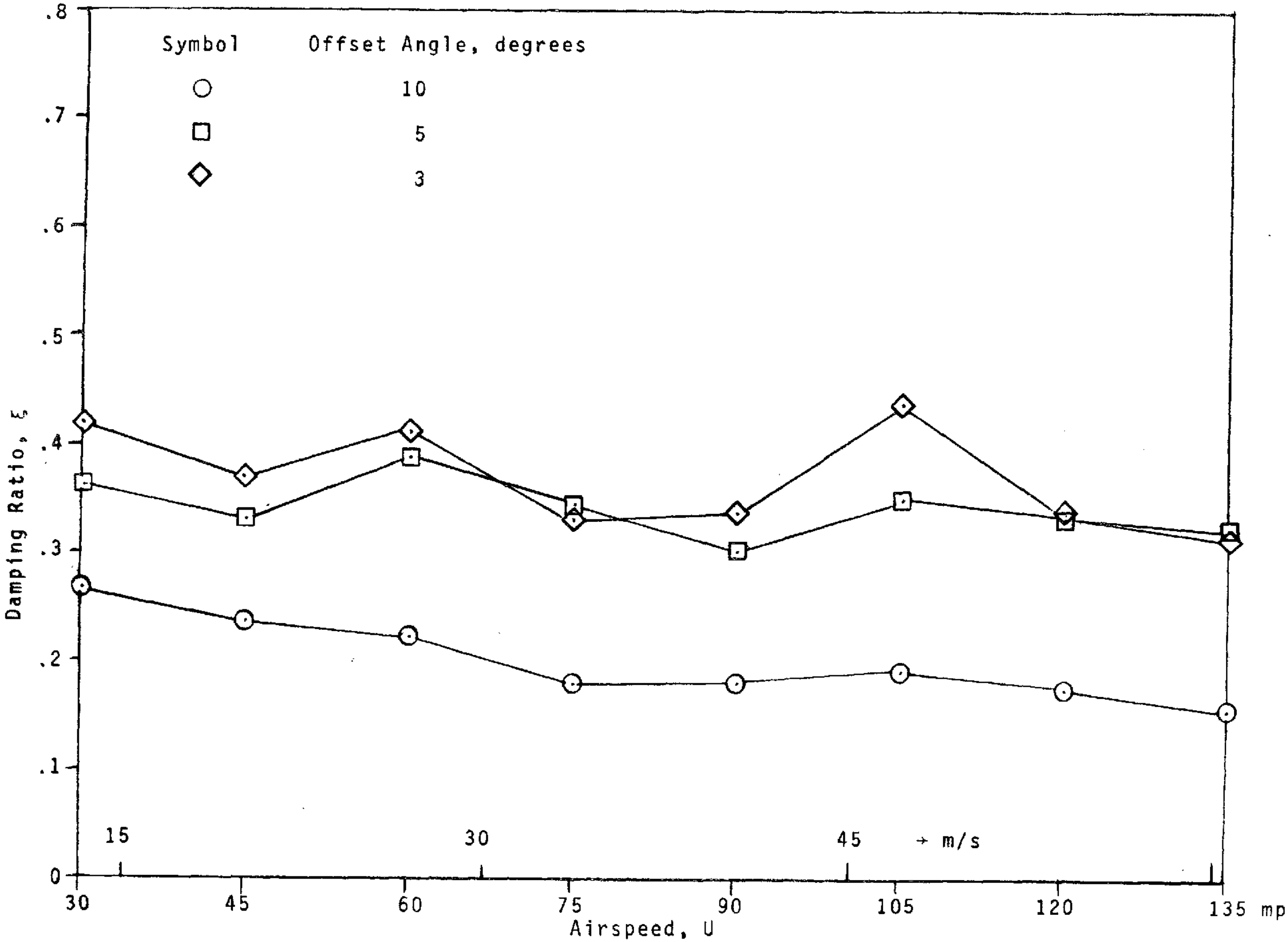


Figure 2. Photographic View of Test Set-up



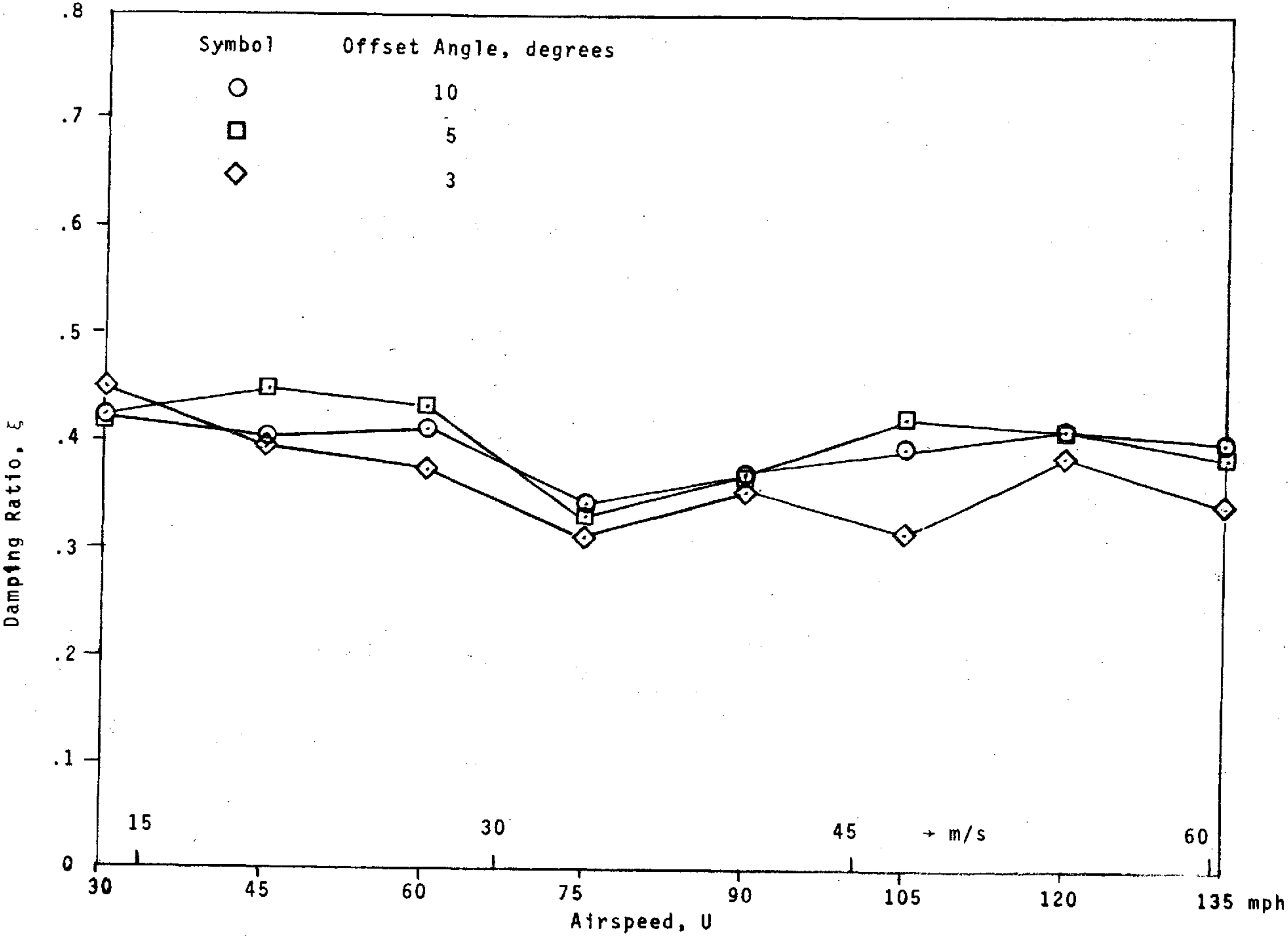
(a) Model: Richardson Vane

Figure 3. Variation of Damping Ratio with Airspeed and Offset Angle



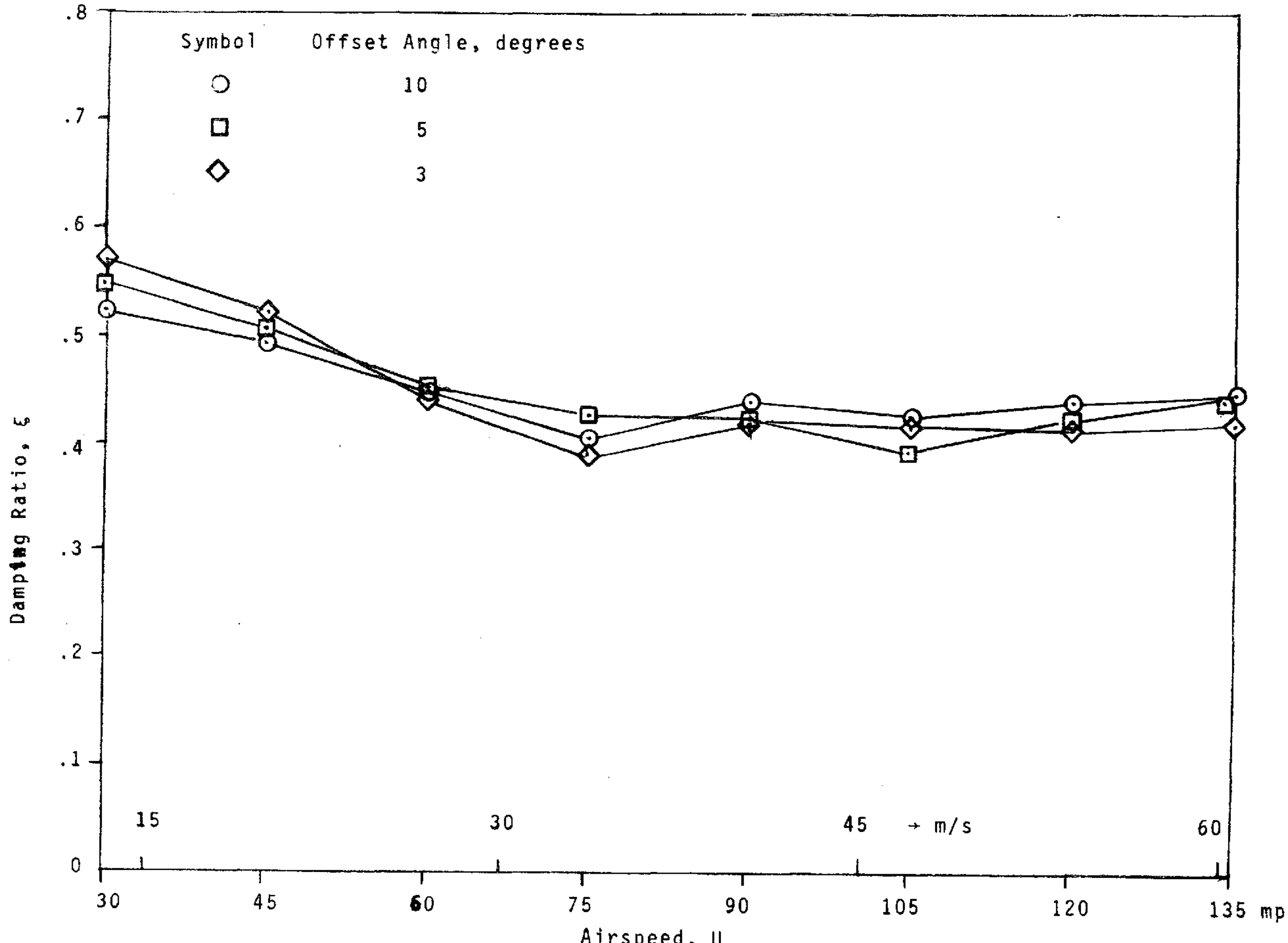
(b) Model: Aspect Ratio 2

Figure 3. - Continued



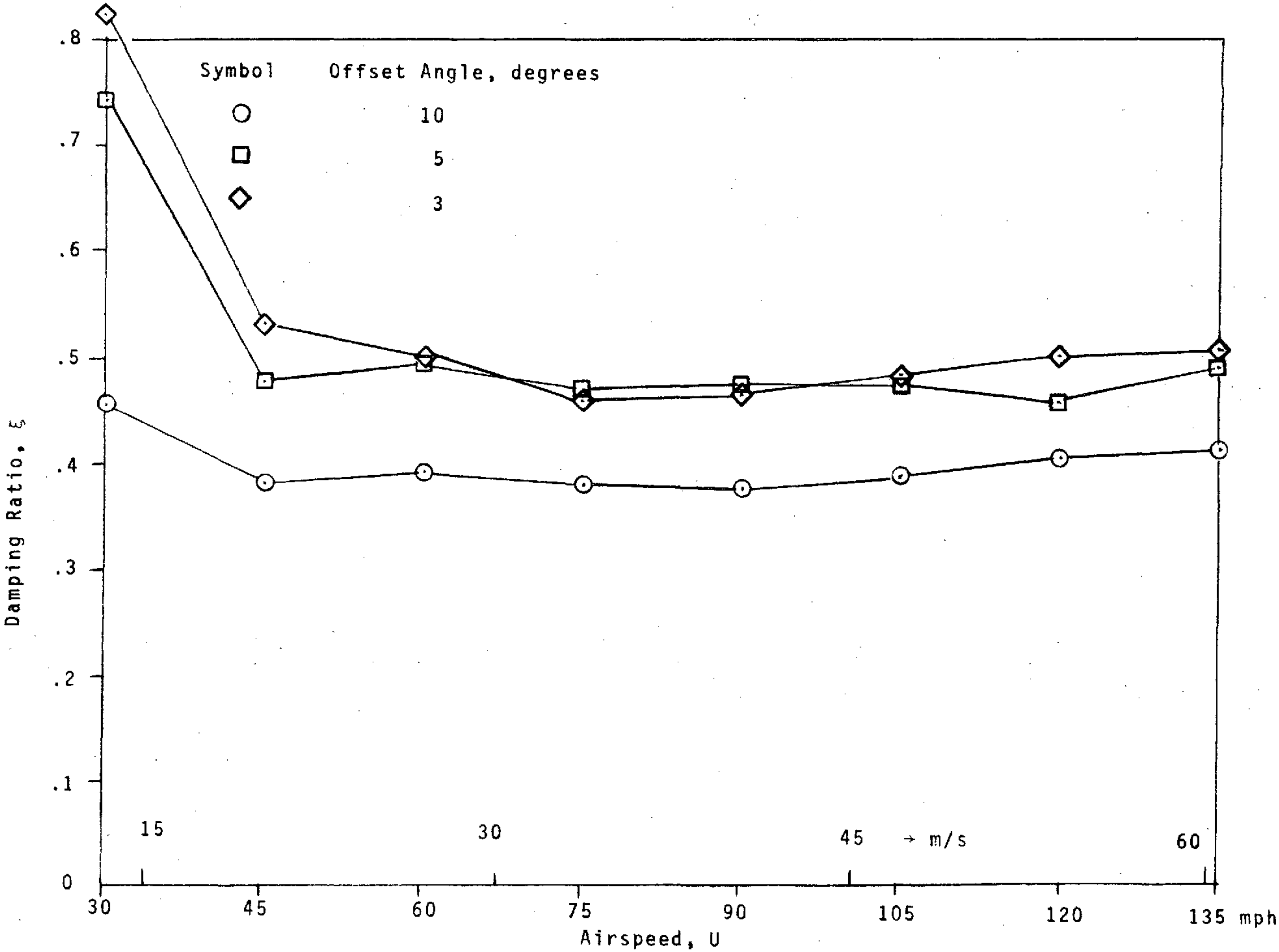
(c) Model: Aspect Ratio 1

Figure 3. - Continued



(d) Model: Aspect Ratio 1/2

Figure 3. - Continued



(e) Model: Aspect Ratio 3/8

Figure 3. - Concluded

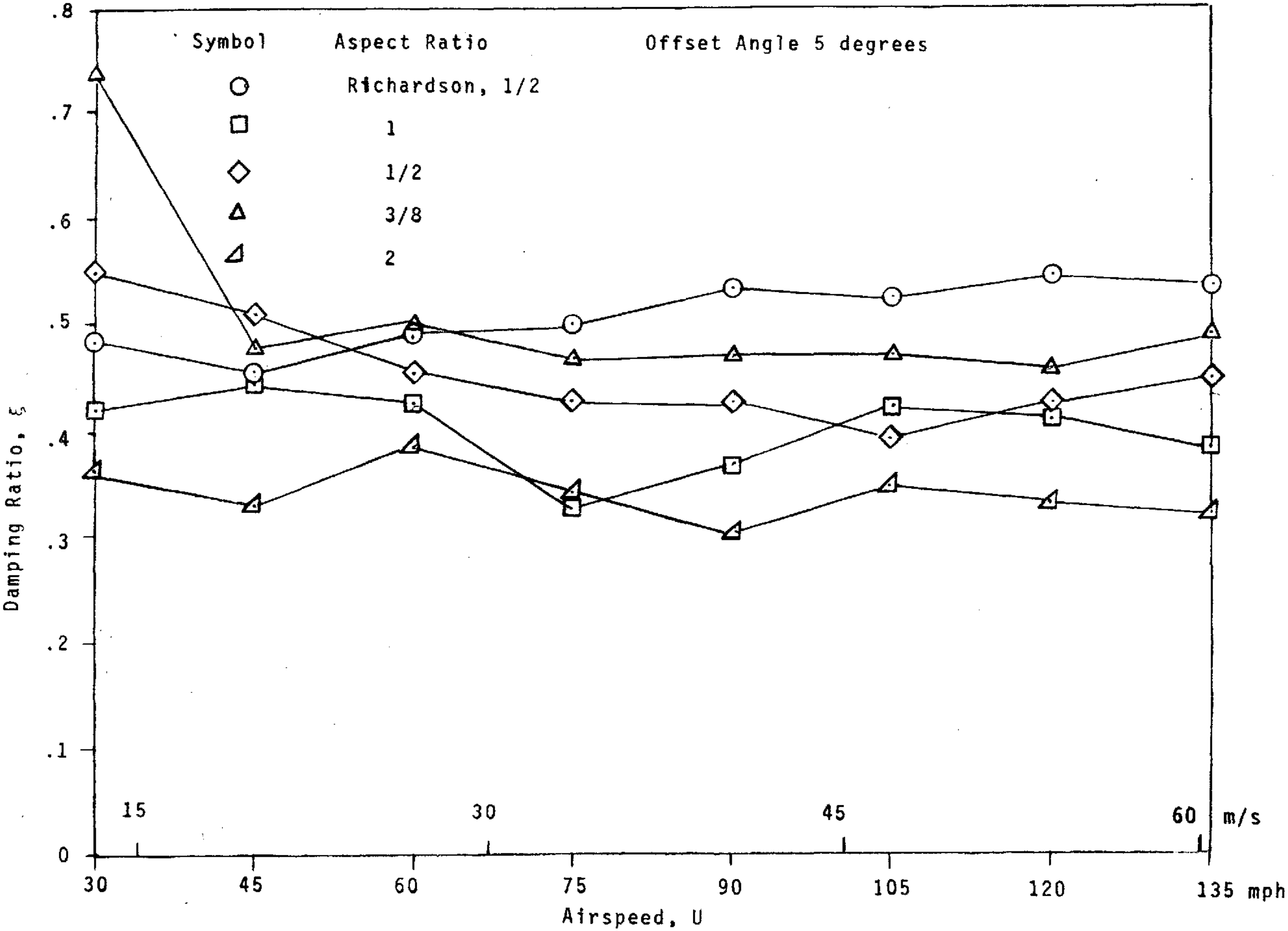
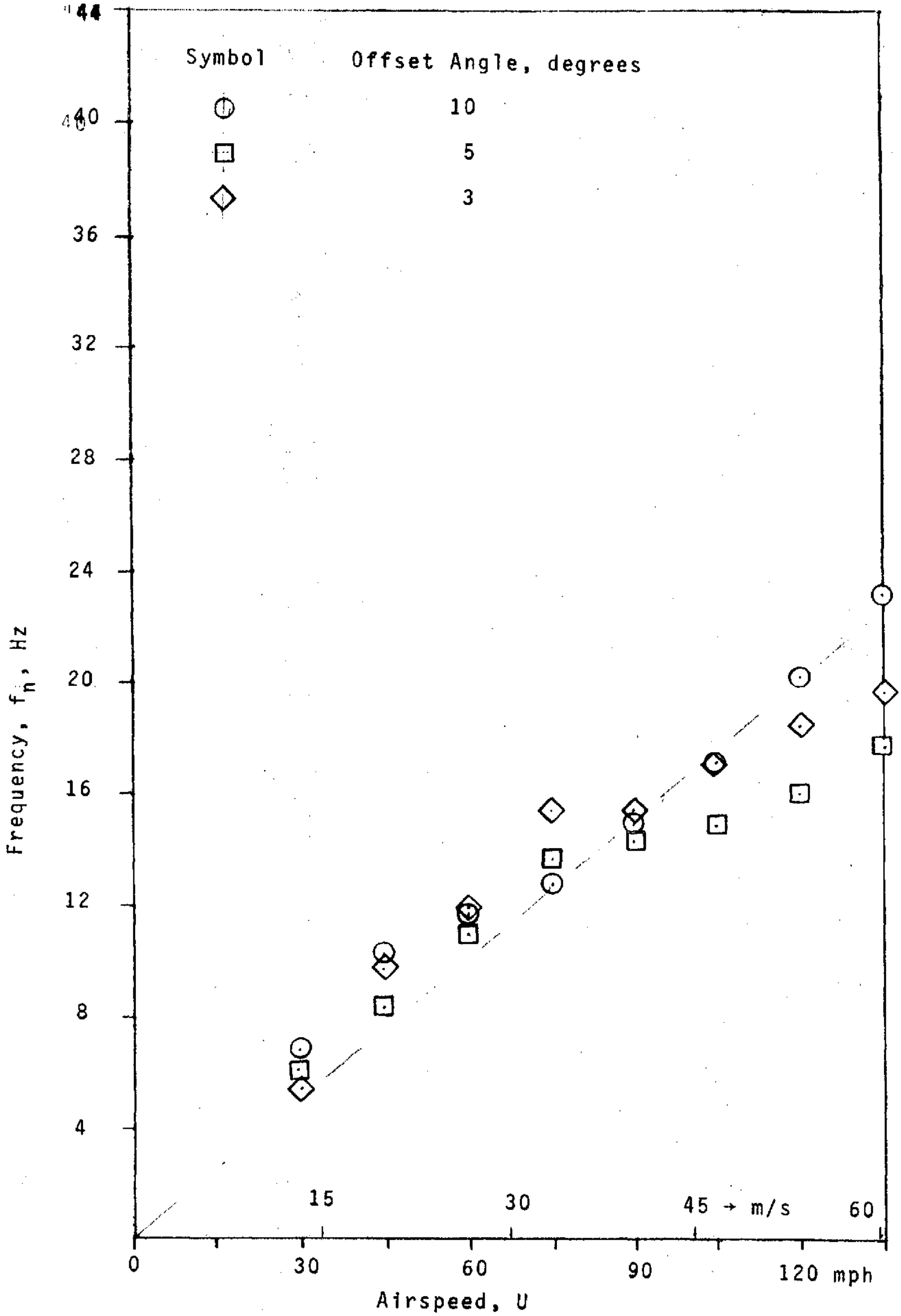
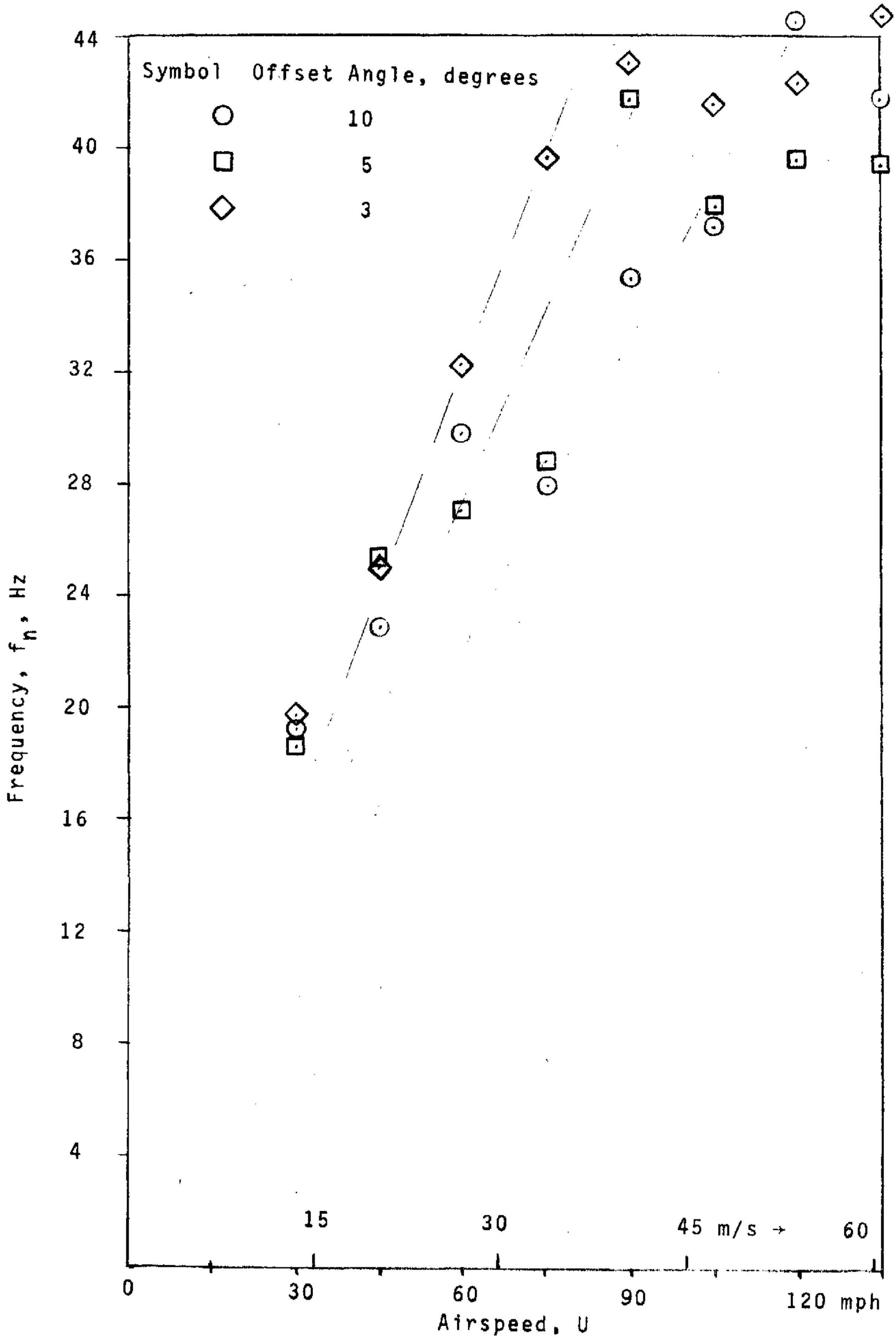


Figure 4. Comparative Representation of Damping with Airspeed for Five Vanes Tested With the Same Offset Angle



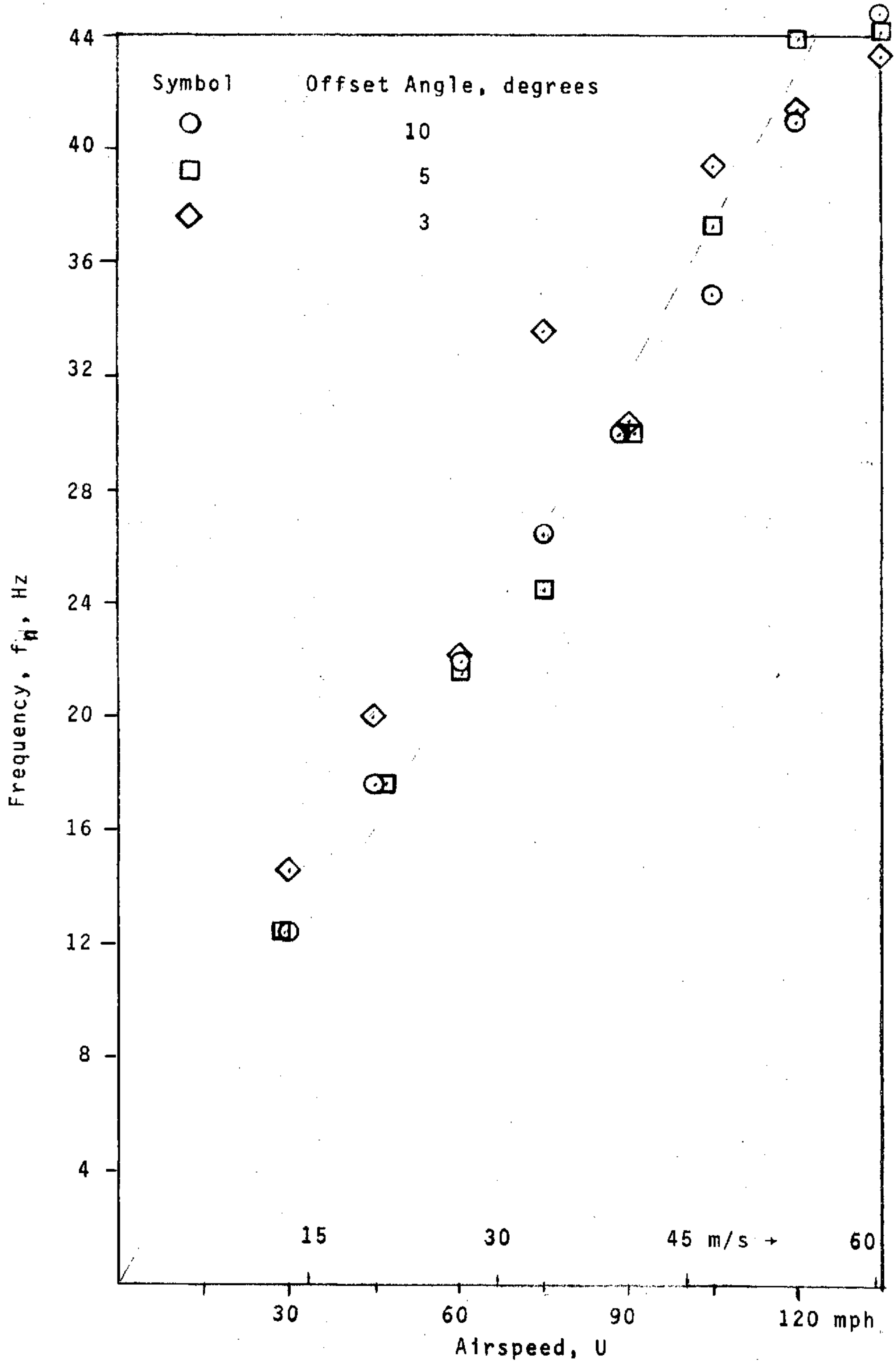
(a) Richardson Vane

Figure 5. Variation of Frequency with Airspeed and Offset Angle



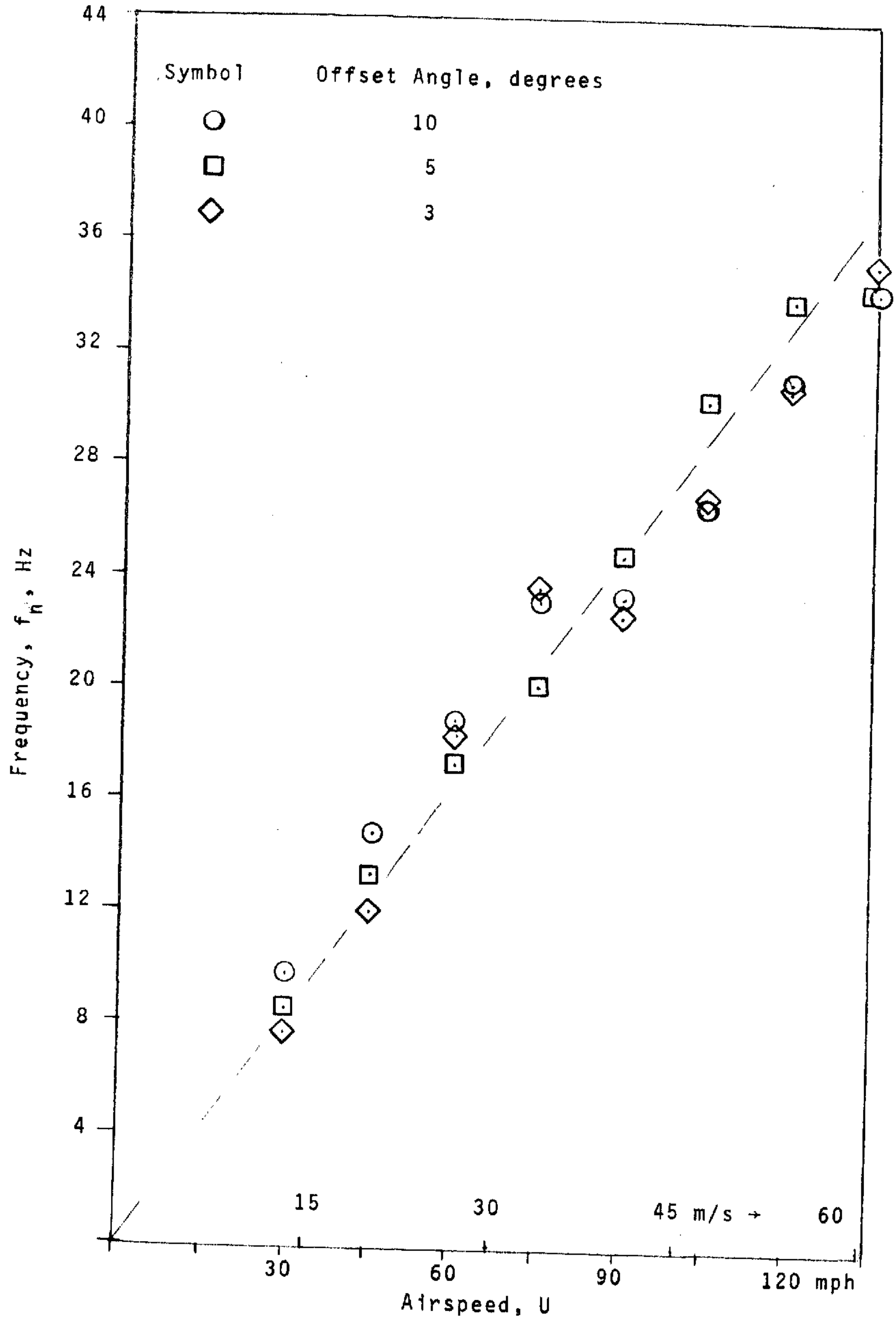
(b) Model: Aspect Ratio 2

Figure 5. - Continued



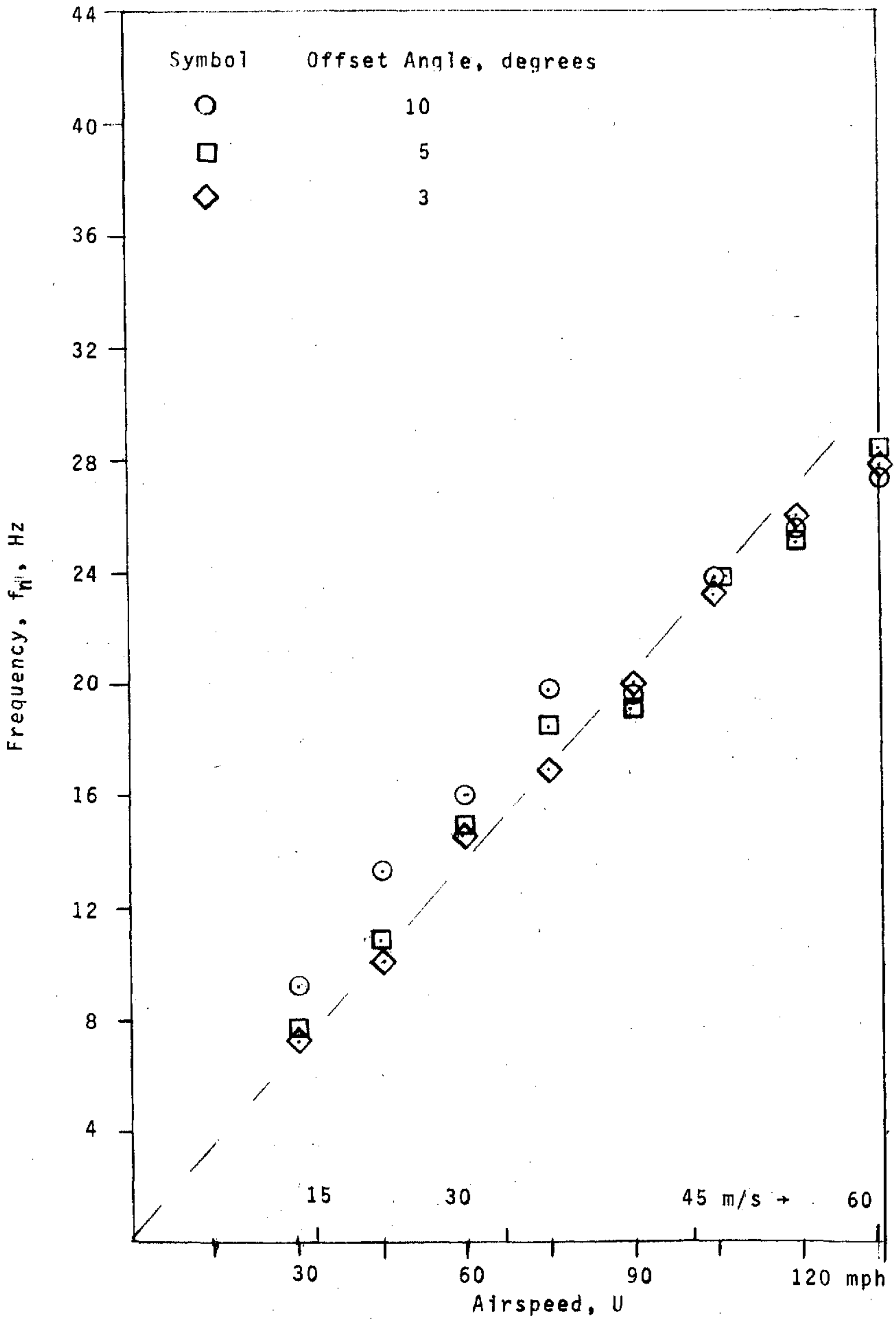
(c) Model: Aspect Ratio 1

Figure 5. - Continued



(d) Model: Aspect Ratio 1/2

Figure 5. - Continued



(e) Model: Aspect Ratio 3/8

Figure 5. - Concluded

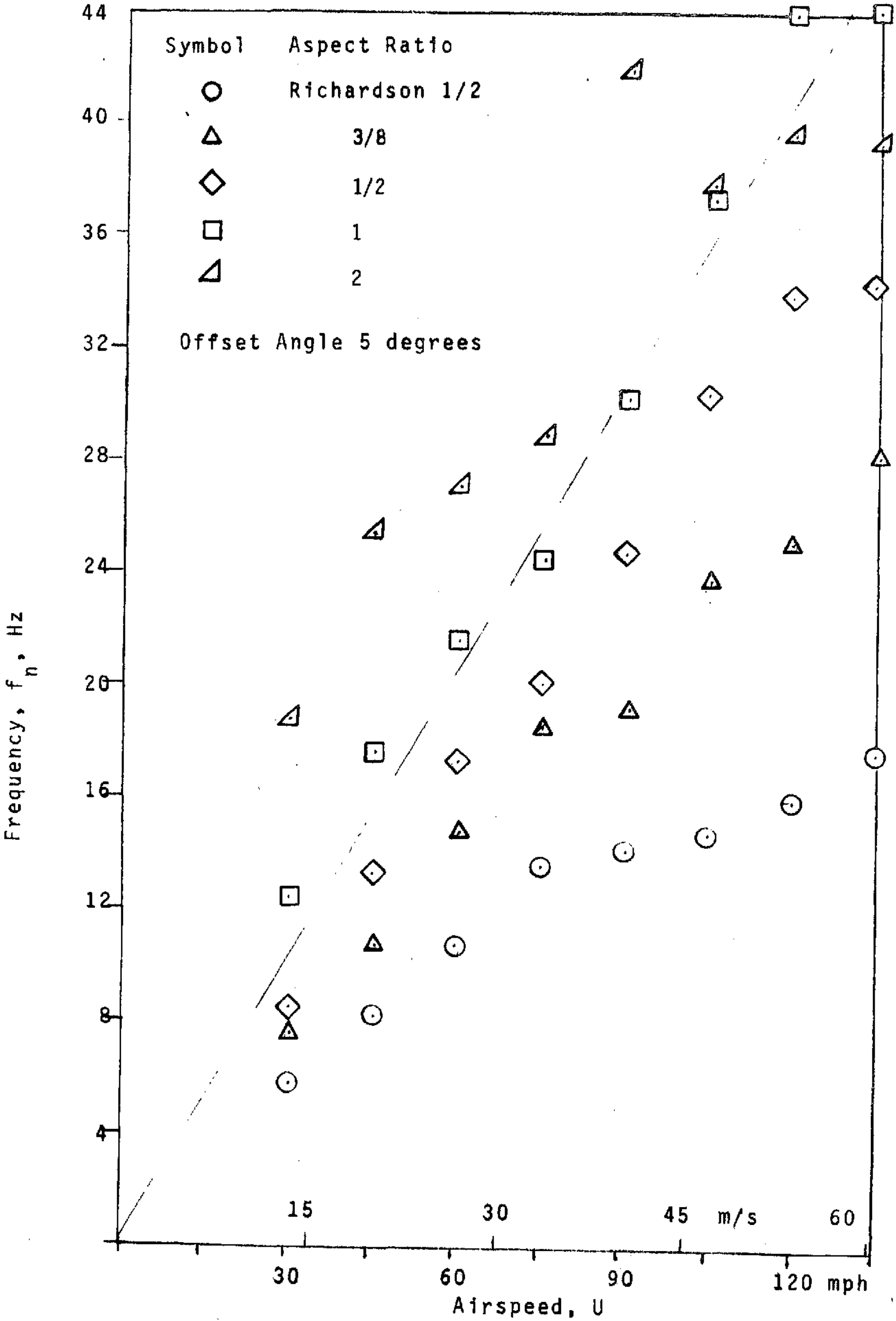


Figure 6. Comparative Representation of Frequency with Airspeed for Five Vanes Tested with the Same Offset Angle

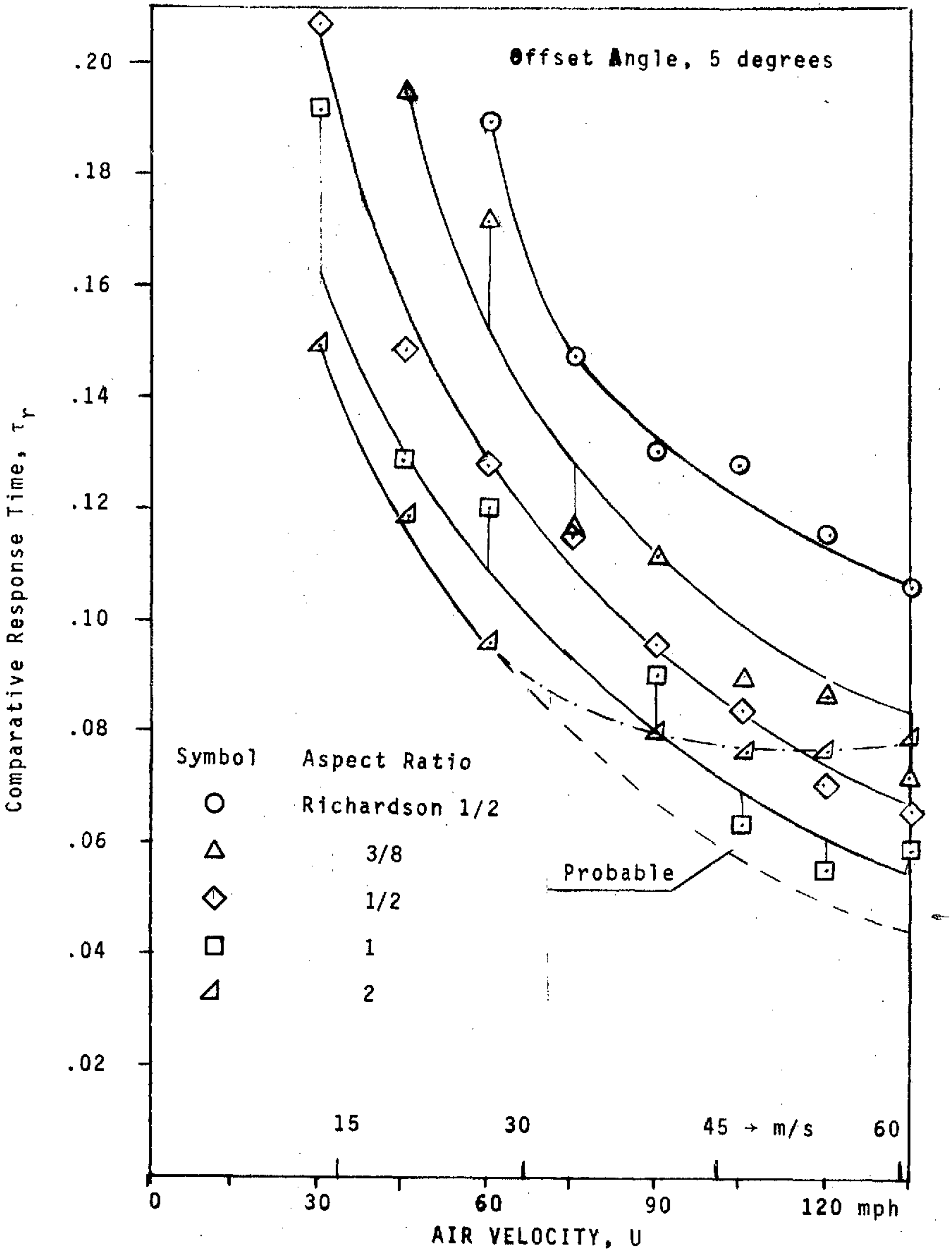


Figure 7. Variation of Response Time With Airspeed