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Aerodynamic Properties of Some Umbrella-type Canopies

by

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Umbrella-type canopies, which consist of a roof supported on a single central column, are an attractive solution to the problem of providing shelter with maximum access. They can be used for garages, sports stadiums and display pavilions. The design of such structures for static wind loads presents no particular problems, provided that the loads can be reliably predicted. In practice it has been found, however, that aerodynamically excited oscillations may arise at relatively low speeds and give rise to problems with an otherwise satisfactory design.

Scale model wind-tunnel tests of two actual canopy designs are described here. Static wind forces as well as dynamic behaviour were studied. The dynamic behaviour of an idealised flat-plate canopy was also studied. The oscillations measured were of two types; "random" in amplitude, but of a fixed frequency equal to that of free oscillations of a canopy, with peak amplitudes increasing more or less as the square if wind speed, and "resonant", where the amplitudes, still at fixed frequency, were more constant with time, but occurred over only a relatively narrow range of wind speeds.

Some tests of structural damping of the full scale canopies were performed. The effect on damping of filling a hollow steel central column with loose stones was studied. A promising increase in damping was noted, but no attempt was made to study optimum proportions.

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Notation

A = amplitude of oscillation, deflection
B = overall dimensions of a canopy side
C_D, C_L = force coefficients
C_T, C_m = torsion, moment coefficients
I = mass moment of inertia
N = oscillation frequency
q = dynamic pressure
S = scale ratio
V = wind speed
α = wind incidence angle
δ = logarithmic decrement
= $\frac{1}{n} \ln A_1/A_{n+1}$ where 1 and n refer to the 1st and nth oscillation amplitude.
ρ = air density
Θ = wind azimuth angle
suffixes m and f for model and full scale

Introduction

The tests described here were undertaken to study the aerodynamic forces on two configurations of umbrella-type canopies. One had been erected and had experienced noticeable oscillations in moderate winds. The other was in the process of erection.

Original designs were based on static loads presented in standard codes (1). One aspect of the wind-tunnel tests was to confirm these.

Since it had become evident that aerodynamically excited oscillations could present problems a major part of the wind-tunnel testing was on aeroelastically scaled models.

The scale models and tests performed

The full scale canopies were square in plan and were supported on single central columns. The roofs were of conventional steel sheeting on relatively light steel frames, supported on the central steel columns. Elastic properties could be controlled to some extent by selecting the rigidity of the columns at the design stage or by subsequent re-inforcement. The principal proportions of the canopies are shown on the insets in figures 1 and 2. The overall sizes, B, of both canopy roofs were of the order of 10m square. A model linear scale of S=1/32 was selected. The model canopies were made of balsa wood and were effectively rigid members. The mass of each canopy was scaled by adding discrete masses to give a model mass proportional to S^3. The masses were distributed correctly to maintain scaled mass moment of inertia I as well. The model central column was a specially constructed hollow brass tube, square in cross section, which served in turn as a scale model column for all the canopies tested. All flexibility was concentrated in this column. It was designed to give model oscillation frequencies in bending of about 5Hz, which resulted in conveniently scaled test wind speeds.

The scale of wind speeds was determined by the equality of Strouhal numbers (2) model and full scale, that is, $(NB/V)_m = (NB/V)_f$. Full scale frequencies were about 1Hz.

With model masses scaled as above model oscillation amplitude A would also be in scale provided, principally, that logarithmic damping values δ were the same as full scale. More generally, amplitudes could be rendered non-dimensional for the main variables involved by means of the grouping $(A\delta I/\rho B^6)$ or $(A\sqrt{\delta I}/\rho B^6)$. The former is more correct for resonant-type oscillations and the latter for random-type ones (3).

For the dynamic tests the central column was equipped with strain gauges at its base, that is, equivalent to ground level full scale. Strains were calibrated in terms of deflections A at the edge of a canopy caused by point loads applied there.
Static tests: Mean wind loads were measured by mounting the canopies directly on a three-component mechanical balance in a closed-jet test section of area $0.45m^2$. The flexible column was replaced by a rigid connection for these tests. The blockage ratio, that is, model frontal to tunnel area, was about 2.5%. Corrections for blockage effects were ignored. The measured

forces and moments are shown as coefficients in Figures 1 and 2. The coefficients are: C_D= drag/qB^2; C_L = lift/qB^2;C_m= moment/qB^3. Where q is the free stream dynamic pressure $\frac{1}{2}\rho V^2$. The moment was referred to the tunnel floor height which would be ground level full scale. Drag and lift were resolved along, and at right angles to, the upstream wind. Values of the coefficients that would be used, based on the British Code CP3, Chapter V, Wind Loading (1), are indicated.

Torsional moments around the central column were also measured for the canopy in Figure 1. This was done by means of a strain-gauged torsional element added to the support. Torsion was expressed as a coefficient, C_T= torsion/qB^3.

Dynamic tests: The models were tested in a closed-jet test section of about 3,0m^2 area. The flexible column was mounted on a rigid base on the tunnel floor and the effect of wind incidence was achieved by tilting the base. Strain gauge signals were recorded on a strip chart. As a preliminary to testing, the natural oscillation frequencies and logarithmic decrements of the models were measured by observing freely decaying oscillations in still air. Care had to be taken to excite initial oscillations in a pure mode to avoid problems of beats between modes with similar frequencies, for example, bending across and along the wind axis. The presence of beats makes it difficult to measure the damping precisely.

Measurements consisted of noting oscillation amplitude on the strip chart as a function of wind speed. The peak oscillation amplitude over a period of about one minute was noted in each case. Most testing was done with wind having a nominally flat profile and low turbulence, about 3%. A series of tests was also run with wind speed graded proportional to $(\text{height})^{1/6}$ and longitudinal turbulence level about 11% at the mean height of the canopy. This was achieved by adding roughness elements upstream on the tunnel floor.

The results of the tests are presented in Figures 3,4 and 5.

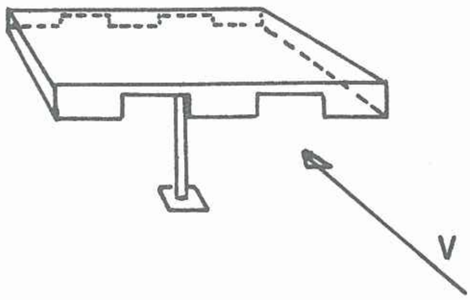
Discussion of results

Static loads: the force coefficient values from the code are clearly unable to show the detailed variation of loads with both wind direction and incidence. Generally, for the -10° roof, Figure 1, the code figures are conservative and would result in a quite adequate design. For the 20° roof, Figure 2, the code figures are less satisfactory. Lift is of the right order, but in the wrong direction, and moments are too low. A noteworthy feature of the test results is the increase in lift and moment with incidence. Winds at incidence could arise for canopies on sloping ground or near the edge of a change in ground profile. In one series of tests, for which specific results are not presented here, the canopy of Figure 1 was tested with similar canopies adjacent to it, making up a continuous roof. Loads were found to be less than for the isolated case, even for a canopy at the most exposed positions at the corners.

Torsion loads are not mentioned in the code. They are, however, relatively small. It is interesting to note that for the canopy tested the torsion was in a direction tending to line it up with a side square-on to the wind.

Dynamic effects: It is clear that both canopies were markedly prone to aerodynamically excited oscillations. All measured oscillations were at the natural frequencies of the canopies. Two types of response were present. At all wind speeds the canopies oscillated with more or less random amplitudes, about equally as strong across as along the wind, and with a small amount of torsional oscillation as well. The amplitudes increased more or less proportional to $(\text{wind speed})^2$. These oscillations were caused by a wide spectrum of excitation frequencies in the turbulent wakes of the sharp edged bluff shapes. At any wind speed there would be some component of the wake fluctuations able to transfer energy to the fixed frequency structure. The energy transferred would increase with $(\text{wind speed})^2$.

Over a narrow range of wind speeds the oscillation became much more constant in amplitude and were largely only in bending along the wind direction, that is, around an axis at right angles to the wind. These oscillations, which resembled resonant oscillations, were caused by equality of the frequencies of predominant vortices shed by the canopies and the natural oscillations. Resonant oscillations were virtually absent for the plain flate plate. The addition of lips around the edges, however, resulted in a strong resonant region. The resonant oscillations were sensitive to small structural changes. Interrupting the regularity of fore and aft edges by means of 'castellations', as sketched below, markedly reduced the severity of resonant oscillations, although it had little effect on the random oscillations.



Resonant oscillations were much weaker for wind angles other than 0°. For winds at 45° the random oscillations were also much weaker.

An increase of turbulence to 11% disrupted the resonant oscillations but increased the strength of the random oscillations. At the height of the canopies a turbulence intensity of about 20% could be expected in a typical urban environment(4). Random oscillations could then be as severe as the resonant ones.

An increase in column stiffness would be advantageous if it shifted the resonant portion out of the range of practical speeds and would in any event reduce the amplitudes of the random portions. An increase in damping would be advantageous in both cases. The random portion is, however, dependent more on the square root of the logarithmic decrement. For this reason two types of non-dimensional scales for amplitude have been used in the figures.

Measurements of structural damping

Some measurements of structural damping were taken on the full scale canopies. This was done simply by applying manual forces in resonance to a point on the roof structures to excite suitable oscillations of about 30mm amplitude. Decaying free oscillations were then recorded by means of a pen attached to the structure and writing on a sheet of paper drawn across steadily by hand.

The structure of Figure 2 gave the results shown in Figure 6. This structure was complete with roof.

The structure of Figure 4 was tested without roof sheeting added. It proved difficult to obtain pure free oscillations in a desired mode as the torsional and orthogonal bending modes were coupled and oscillations would soon 'beat' between them. Average values of the ratio of two successive amplitudes, A_n/A_{n+1} were 1.18 for torsion and 1.10 for bending. Torsion damping did not show the rapid rise with amplitude present for the completed canopy. Friction at roof sheeting joints probably accounted for this. The damping of the partially completed canopy structure was higher than would be expected for an all-welded steel frame. It is possible that incomplete grouting of the base plate caused this.

The central columns were hollow steel squares and the suggestion was made that filling them with loose stones might increase their damping. This was checked by pouring loose concrete stone of about 20mm size down the central column of the partially completed canopy. The results are tabulated below as mean values of A_n/A_{n+1}.

Mode		Amount of stone
Torsion	Bending	
1.18	1.10	empty
1.22	1.14	2m from base
1.28	1.14	full(6m±)

The stone clearly increased the damping for oscillation amplitudes in a practical range. No attempt was made to find optimum values for stone size and other properties.

Conclusions

Umbrella-type canopies are very prone to wind excited oscillations and need to be carefully designed if they are not to be troublesome in practice.

Column stiffness determined by static wind loads alone may be insufficient to prevent oscillations.

The exact aerodynamic behaviour will depend on shape details, but some general guidance can be obtained from the three shapes tested here.

References

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4. Vickery, B.J. A model of atmospheric turbulence for studies of wind loads on buildings. 2nd Australas. Conf. on Hydr. & Fl. Mech. 1965.

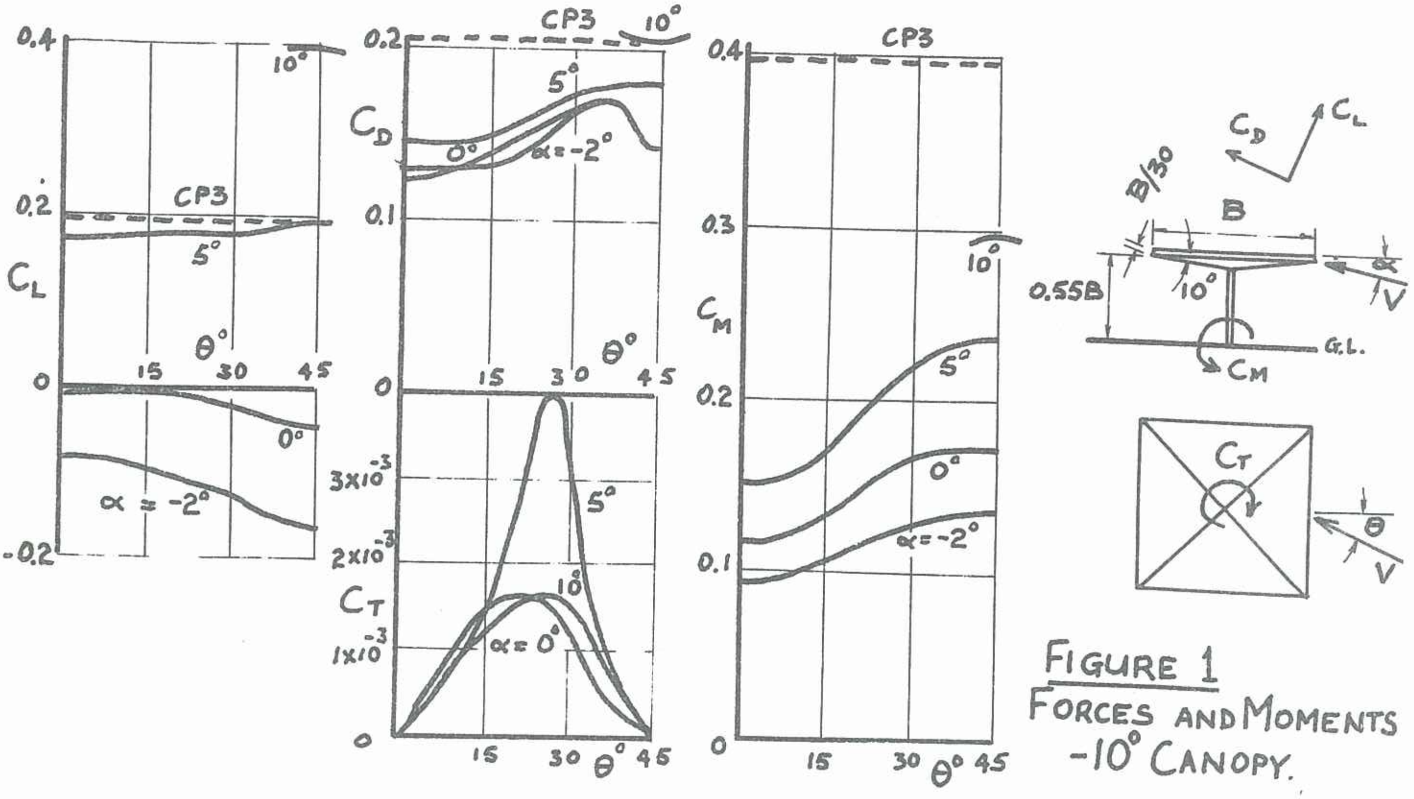

FIGURE 1
FORCES AND MOMENTS
-10° CANOPY.

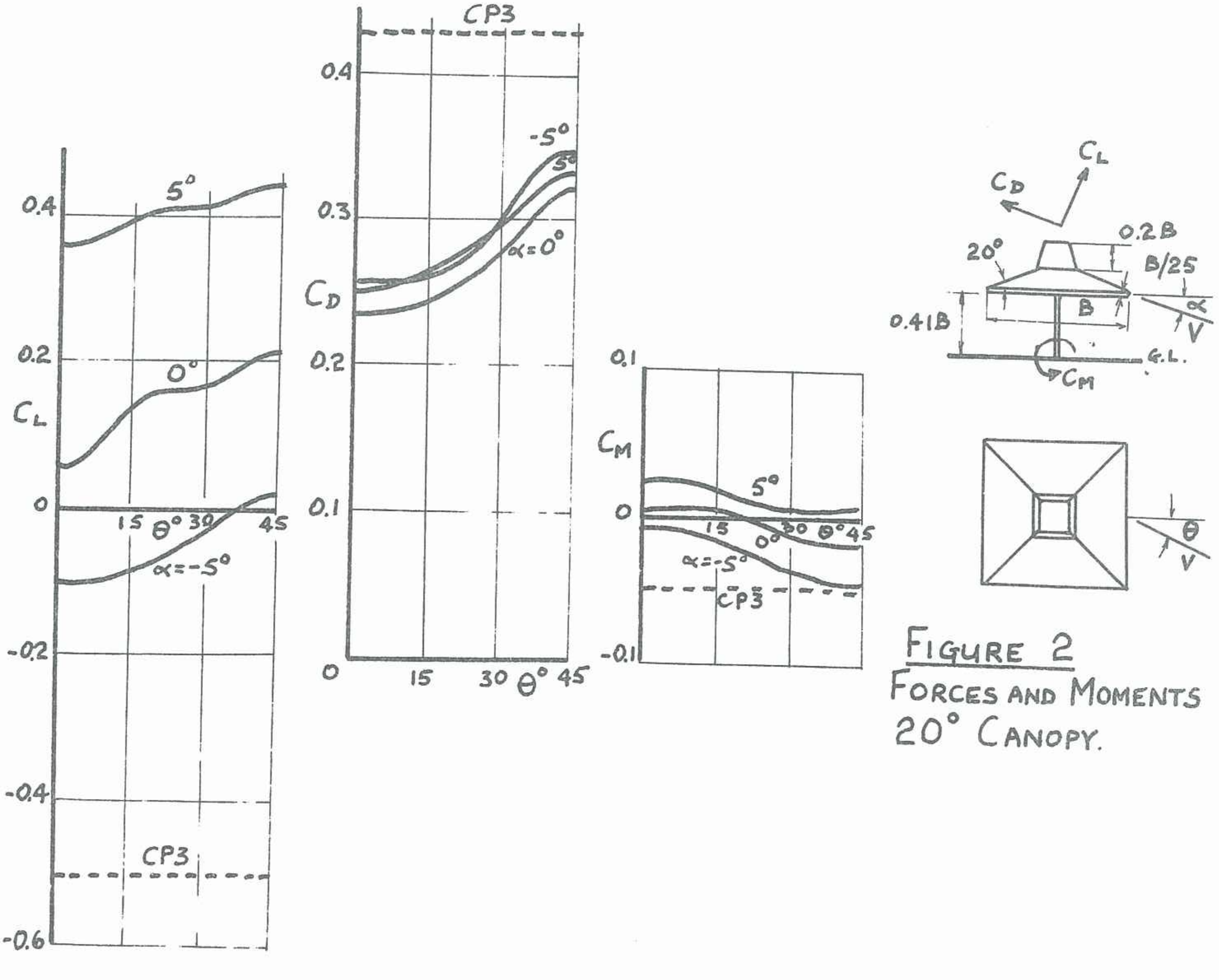

FIGURE 2
FORCES AND MOMENTS
20° CANOPY.

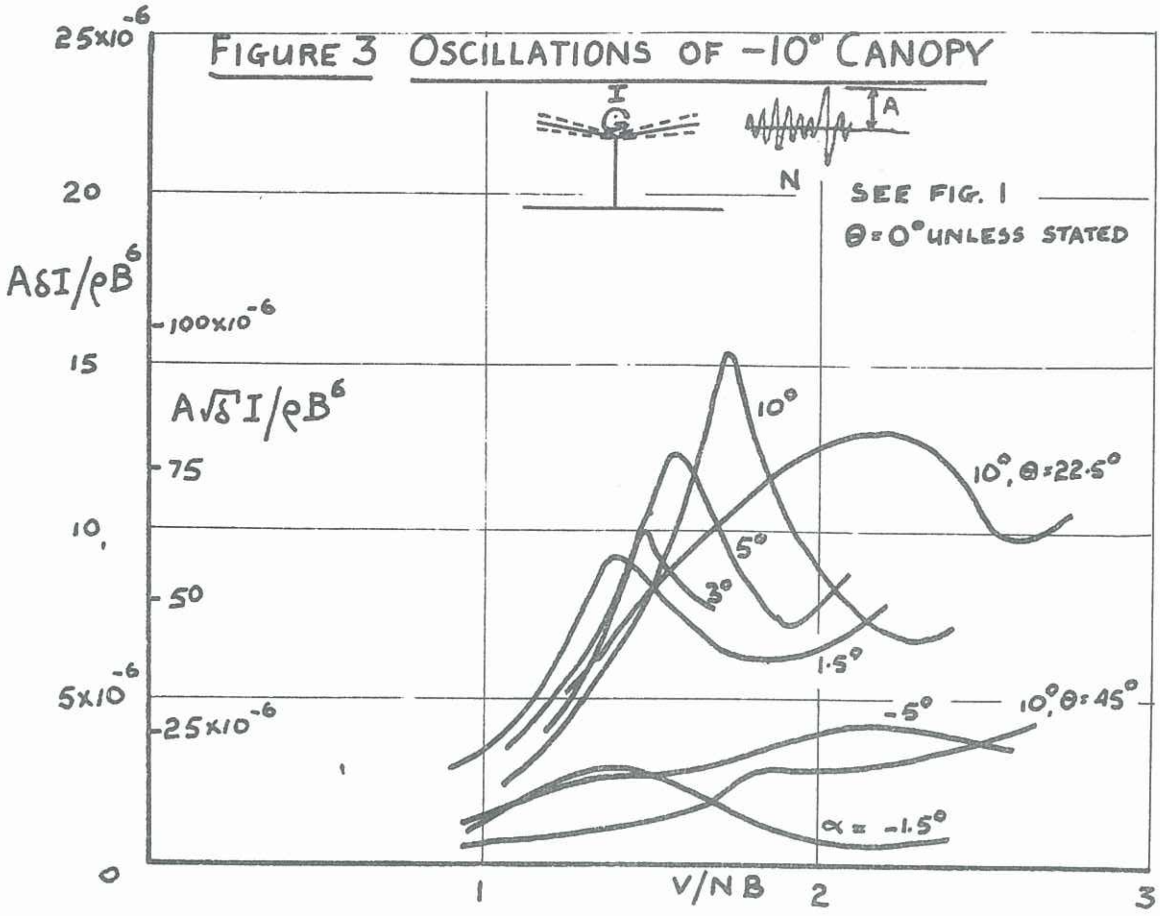

FIGURE 3 OSCILLATIONS OF −10° CANOPY

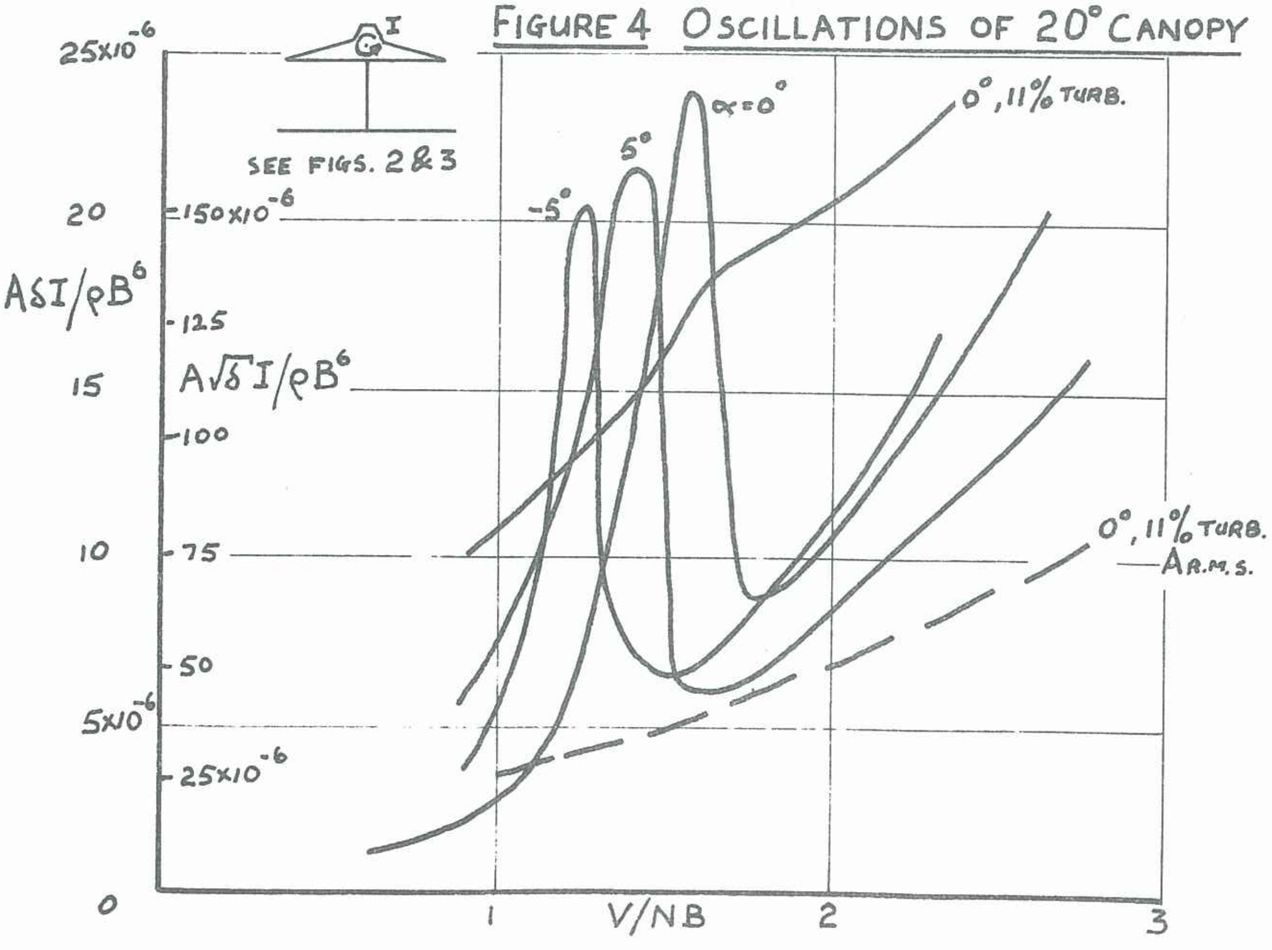

FIGURE 4 OSCILLATIONS OF 20° CANOPY

FIGURE 5 OSCILLATIONS OF A FLAT PLATE

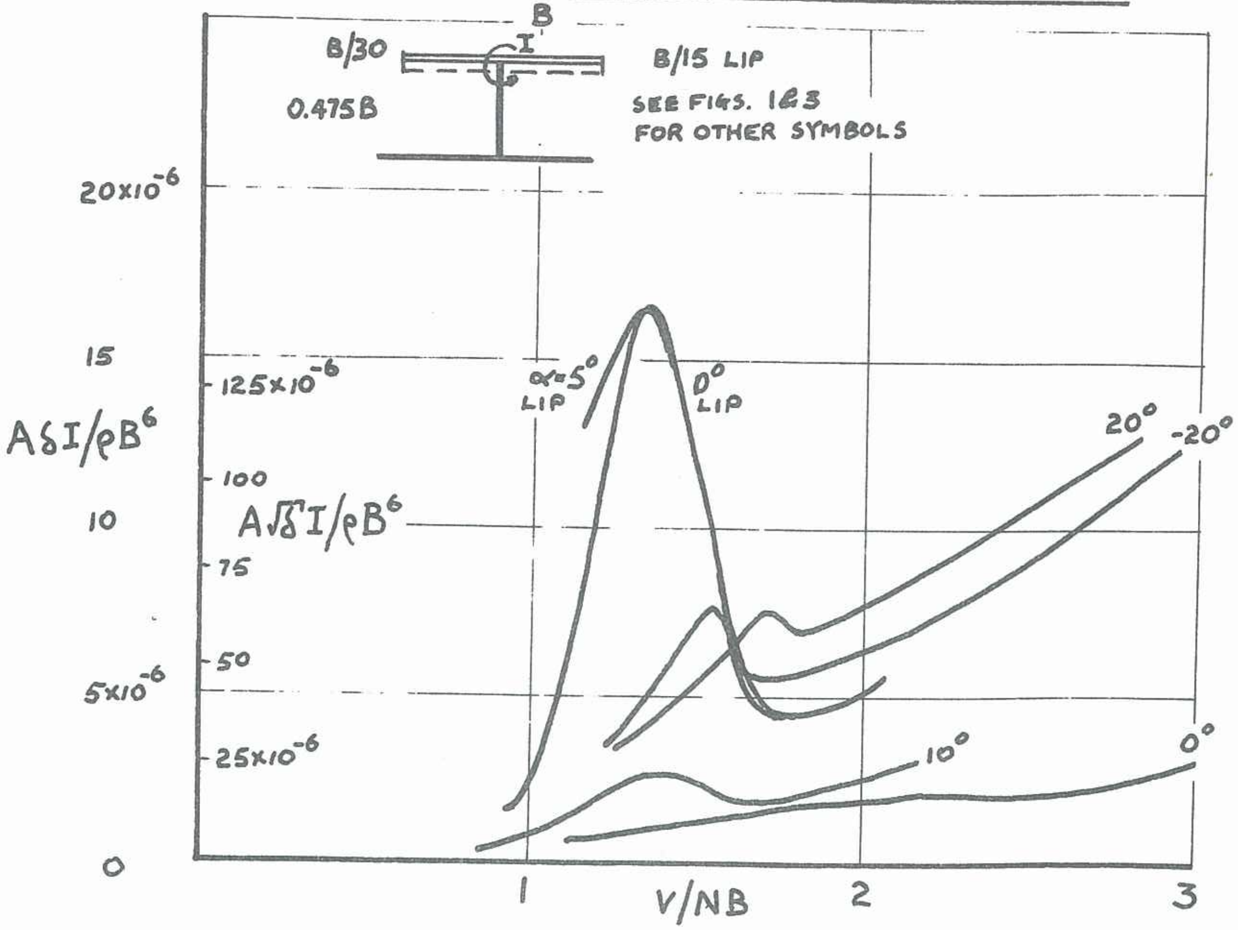

FIGURE 6 LOGARITHMIC DECREMENTS
FULL SCALE CANOPIES