S E C T I O N I I

TECHNOLOGICAL AND MANUFACTURING DEVELOPMENTS

ADDITIONAL PAPER

THE UTIAS AIR CUSHION TECHNOLOGY PROGRAM AN OVERVIEW

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INTRODUCTION

Research at the Institute for Aerospace Studies, University of Toronto (UTIAS), related to air cushion vehicles (ACV's) can be traced back to the mid fifties, ten years before the author joined the UTIAS staff. This was not long after the period in which Cockerell in Britain, and Bertin in France were developing their ideas. In common with much of the university research of that period, the basic peripheral jet cushion was studied at UTIAS (Ref. 1, 2). However, Professor Bernard Etkin (now Dean of the Faculty of Applied Science and Engineering at U. of T.) had developed a distinguished program in flight dynamics, and it was a natural extension of that work to investigate the dynamics of a vehicle built something like the pioneering British SRN1. The feasibility of using a circular track for this purpose was explored (Ref. 3), and a 6.7 metre diameter track was built. Some data on stability derivatives for an unskirted peripheral jet model was obtained (Ref. 4). However, instrumentation was limited to time resolved photography of the vehicle motion relative to a marked background, so that the data contained large errors. It was clear that, to be of any real value, such a facility would have to be large enough to allow the use of on-board instrumentation such as accelerometers and rate gyros. Ultimately fifteen reports and technical notes were produced from the UTIAS activities, but the work came to a halt by the end of 1965 mainly because of a lack of interest in Canada.

Renewed Canadian interest in the late 1960s resulted in a proposal by UTIAS to the National Research Council of Canada (NRC) for construction of a 30 metre diameter circular track capable of testing models up to 5 metres long and weighing 500 kg. Two reasons were cited for this size: one was the instrumentation problem mentioned previously, and the other was the difficulties arising from the attempts to model at small scale the elastomer fabric composite materials used in the flexible skirts, which had by then become an intrinsic part of the ACV. NRC ultimately responded by requesting that a study be undertaken to define research problems that should be investigated in Canada in the light of perceived potential applications (Ref. 5) and existing research activities in other countries. A small grant was awarded in 1969 to defray the costs of the study, and the author, assisted by Mr. R. Placek, undertook the work. There were two principal conclusions (Ref. 6). First, there were many potential applications of the air cushion principle that might be exploited in Canada, both as elements in a transportation system and in manufacturing for export. Such applications might include:

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(i) the classical aerodynamically propelled ACV for lightering and re-supply purposes in the Arctic,

(ii) towed rafts or trailers for use on tundra and in other off-road transportation (TACR),

(iii) landing gear for aircraft intended to fly into poorly prepared or even unprepared landing sites (ACLG),

(iv) suspension systems for guided ground transport (HSGT-TACV) possibly operating at speeds up to 500 km/hr,

(v) materials handling in warehouses.

The second conclusion was that, although there was interest in and even some Government or industrial activity related to all these applications in the early 1970s, it was far from clear which might enter revenue service, or become an actively exporting manufacturing industry. Consequently, at least some research was required to help in the decision making process, even if it was only to help understand the implications of foreign developments. Also it was felt that any research program that was set up should be broadly based and capable of reorientation as the application picture developed. It was clear that university research had a role to play, but that unless care was exercised in the choice of projects, there was a dnager that this research could go the way of the university investigations of the peripheral jet: interesting but ultimately irrelevant.

Following the study, application was made by UTIAS to NRC for a negotiated development grant to set up facilities and programs in four areas:

(i) cushion and vehicle dynamics,

(ii) skirt materials studies,

(iii) ACV-human pilot research,

(iv) propeller noise.

Perhaps the most controversial aspect of the UTIAS request was a renewed proposal for a 42 metre diameter circular track. The author undertook to switch his research interests to this area from hypersonic aerodynamics. NRC announded the award of funds in August 1971, to allow construction of the facilities requested by UTIAS and to start some "orienting" research in all of the above areas. These funds lasted until April 1974, and some very interesting results were obtained (Ref. 7, 8). For example, it was found that multicell type cushion systems could, under certain circumstances during overland operation, be subject to a roll hysteresis which would cause a catastrophic loss in roll stiffness. Also, skirt materials were shown to be highly strain-rate dependent at only moderately high frequencies. This might not be important for the low frequencies involved in vehicle dynamics, but could have a major effect on wear generated by self excited skirt oscillations. In the work on propeller noise, it was found that the "dirty" inflow

arising from the typical ACV geometry was adding considerably to the overall noise.

Since the termination of the negotiated grant in April of 1974, the predominant research effort has been in cushion and vehicle dynamics, and funding has been supplied mainly through contracts from the Transportation Development Agency, the Canadian Ministry of Transport (TDA, now TDC). The author's own NRC operating grant has also continued to support this research effort.

DEFINITION OF RESEARCH PROGRAM

In the basic sciences, the sole criterion for the excellence of a research project is the extent to which it contributes to man's perception of the world around him. Consequently, measurement of small differences, such as in the classical Michaelson-Morley experiment of 1889 - which attempted to detect the velocity of the earth relative to a supposed medium called the "aether" - can have profound significance. The null result of this famous experiment was one of the basic links in the chain that led to Einstein's theory of relativity. In contrast, engineering research often works in a framework in which the essential physics is known, but the extent of the interplay of various factors is unclear. The task is to obtain mathematical models which have sufficient accuracy for design purposes and which are applicable to a wide range of configurations, and yet which are as simple as possible. In that context, good or relevant engineering research is concerned in the first instance with effects that have a current practical significance. Also, in the long run, the role of engineering in transportation is to improve the economics of some transportation task, so that one can, in principle at least, measure the significance of a research problem in terms of some economic criterion. However, in the early stages of the development of a technology, since the applications may not yet be defined, it may not be possible to apply explicit economic criteria, and the questions revolve around basic technical practicability.

In an attempt to use economic considerations to obtain guidelines for research, the author investigated the possible transportation roles of certain applications of the air cushion by using some elementary transportation economics and technological forecasting ideas (Refs. 9, 10). One point made in those studies was that the traditional market survey, such as that attempted in Canada for NRC (Ref. 5) was inadequate for prediction of market penetration in that it usually did not allow for the economic impact of technological development. Consequently, though conservative and "safe", it could be hopelessly pessimistic. It was observed that the predominant cause of the high cost of using the classic amphibious ACV - its first cost - could fall given development equivalent to that already attained by established technologies, and thus alter the somewhat bleak economic picture more in its favour. Also it seemed possible that ACLG, originally conceived for operation of aircraft into a frontier environment, might have some significant economic impact on commercial aviation operating from conventional runways. Another interesting conclusion was that, although magnetic levitation for guided ground transport was considered by many groups to be "better"

in some sense than TACVs, economic studies clearly showed that the predominant item in the system cost was that of the guideway and other fixed structures. Consequently, the suspension choice should be made on the basis of fixed structure costs, and viewed from this perspective, it was not at all clear why a "maglev" suspension was better than an air cushion.

In spite of the fact that such economic studies personally gave the author some useful insights, they were in one sense unsatisfactory. They were apparently regarded by his academic colleagues as intellectually "lightweight" and unsuitable as a scholarly activity, and by his industrial colleagues as unrealistic, possibly subject to large errors in cost estimation which were beyond the author's control, or just plain naive.

Consequently, in attempting to define a relevant research program, a somewhat less esoteric approach was adopted. It was decided to investigate a number of cushion systems representative of designs then being contemplated for amphibious hovercraft, tracked air cushion vehicles (TACV), towed rafts (TACR) and materials handling. The aim was to establish the extent to which the static and dynamic performance of these systems could be predicted by simple analytical models. It was hoped that these investigations would also lead to the definition of research topics which would be both suited to the university environment and at the same time have some use for design purposes in current Canadian activities. The five cushion systems chosen were:

(i) a multicell system reminiscent of early Bertin-Sedam designs,

(ii) a Canadian development of the multicell called the Flexicell intended for low speed operation overland,

(iii) a loop and segment skirt related to Hovercraft Development Limited (HDL) designs,

(iv) a hinged-lip orifice-cavity damped system,

(v) an open loop or bag skirt.

The first three systems were thought to be applicable to Canadian overland operations, while the fourth has been used by the Société Aérotrain for TACVs. The fifth system was developed by General Motors for use on very smooth surfaces, and thus is relevant to both TACVs and materials handling in warehouses. Research on the first three was funded by TDA in support of current programs on towed rafts, and on the fourth as part of its mission of monitoring HSGT development. In all cases, very interesting results have been obtained.

A second approach to the "relevant research" problem was also tried. A colleague of the author, Mr. M. Hinchey, undertook to work as an engineer for a Canadian company on heave instability problems while pursuing his Ph.D. at UTIAS on a part-time basis. The aim was to ascertain by undertaking suitable experiments the extent to which existing theories for heave instability, as developed at M.I.T. (q.v., e.g. Refs. 11, 12)

and elsewhere, were adequate for design purposes. It was intended to isolate deficiencies which would in turn be studied as part of a Ph.D. program. As will be seen, this has also led to some very interesting research.

PRINCIPAL RESULTS

A theory for the static stiffness in roll of the multicell skirt was developed by Hinchey (Ref. 13). This theory, which assumed that the skirt material was an inelastic membrane incapable of sustaining any compression, verified the earlier scaling arguments given by the author and suggested that a constant mass flow source gave increased rolling moment as compared to a constant pressure source. This effect is shown in Fig. 1. The notation is that defined in Ref. 13. At first, only very limited agreement was obtained between theory and some experiments on a 2.44 metre by 1.22 metre cushion, and in addition very significant hysteresis was found in the roll stiffness curves. This is shown in Fig. 2, and it is important to note that the material thickness used on the model is about roughly in proportion to that used on a full size vehicle. Also the theory predicted that, if a non-dimensional cushion air flow coefficeint C_{QC} as defined in Ref. 13 (here C_{QC} = LAC as defined by Fowler (Ref. 14) for 2:1 planform) is the same for two different gross weights, then the rolling moment coefficeint, expressed as an equivalent centre of pressure shift, is independent of gross weight. It is clear from Fig. 2 that this is not the case, and the source of this was eventually traced to the presence of small but significant compression loads in the skirt walls (Ref. 15). At times the roll hysteresis was found to lead to complete loss of roll stiffness at sufficiently large roll angles, as shown in Fig. 3. The author vividly remembers the concerns that were expressed at the time that these effects might be spurious, or associated with some peculiarity of the experimental apparatus. However, similar effects were subsequently observed on the UTIAS circular track test vehicle, Vampire 1, which has a 4.11 x 2.05 metre planform and weighs over 600 kg. At about the same time Fowler (Ref. 14) observed it on the CASPAR field trials vehicle.

It is now clear that this catastrophic hysteresis phenomenon is associated with failure in buckling of the conical cells that are used in the multicell cushion, together with venting and associated loss of cell pressure. However, the details of the way in which this occurs are still not clear. For example, Fowler (Ref. 14) suggests that the destabilizing mechanism is a shear force generated by skirt-ground friction arising from vehicle motion. In contrast, some experiments at UTIAS, which used a moving ground board to eliminate any possible skirt-ground friction suggested that friction may not play a significant role. A theoretical model based on the idea that the destabilizing force is the internal asymmetric pressure loading as shown in Fig. 4 is being developed at UTIAS. This theory assumes that the state of stress in the cell is the same as that which would be generated if the cell was cut arbitrarily close to, but not touching, the ground. The bottom then becomes a free edge and it is possible to greatly simplify the stress analysis. However, experimental results, which compare actual "cut-skirt"

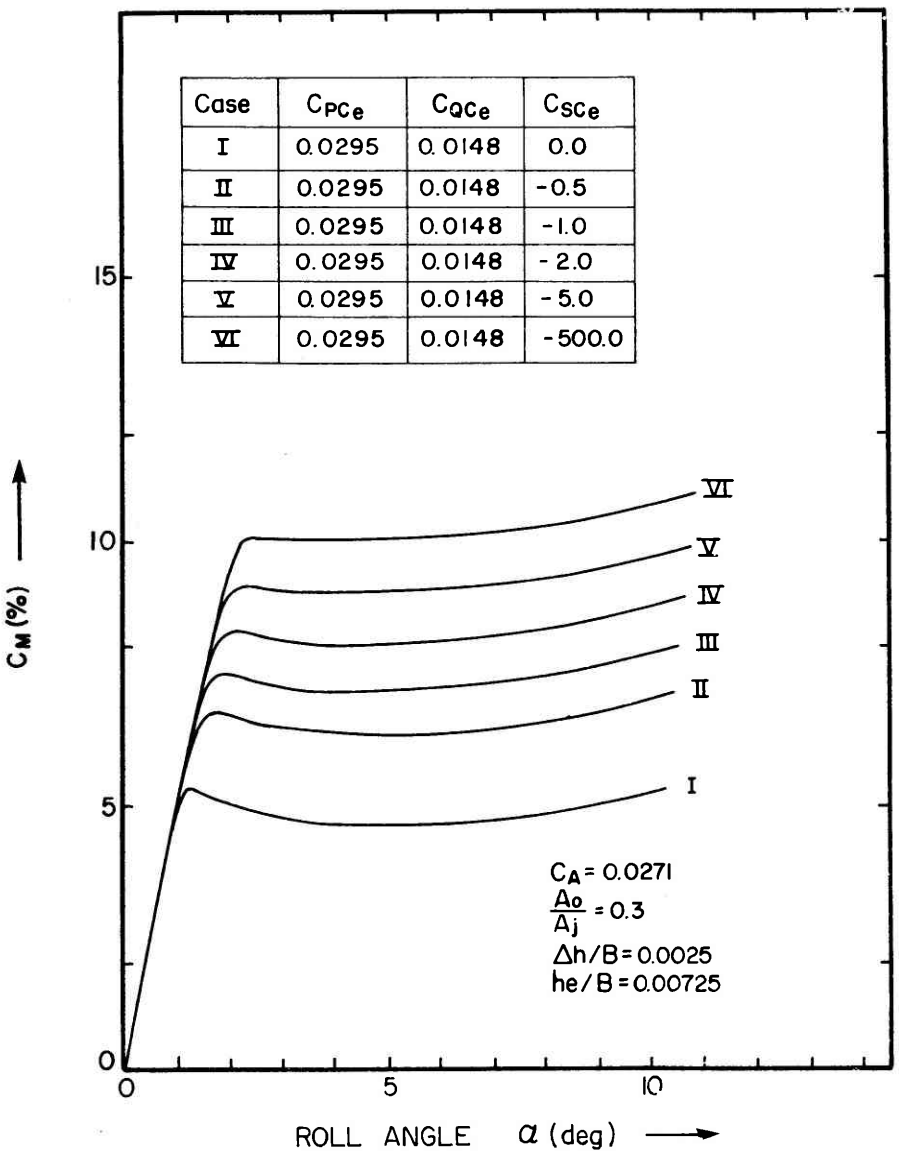


FIGURE 1

Effect of static fan characteristic local slope, expressed nondimensionally as C_{SC} on predicted roll stiffness of a resistance orifice fed multicell skirt hovering over a smooth flat surface. C_{SC} = 0 corresponds to fixed fan pressure as total volume flow varies, while C_{SC} = -500 approximates a constant volume flow characteristic.

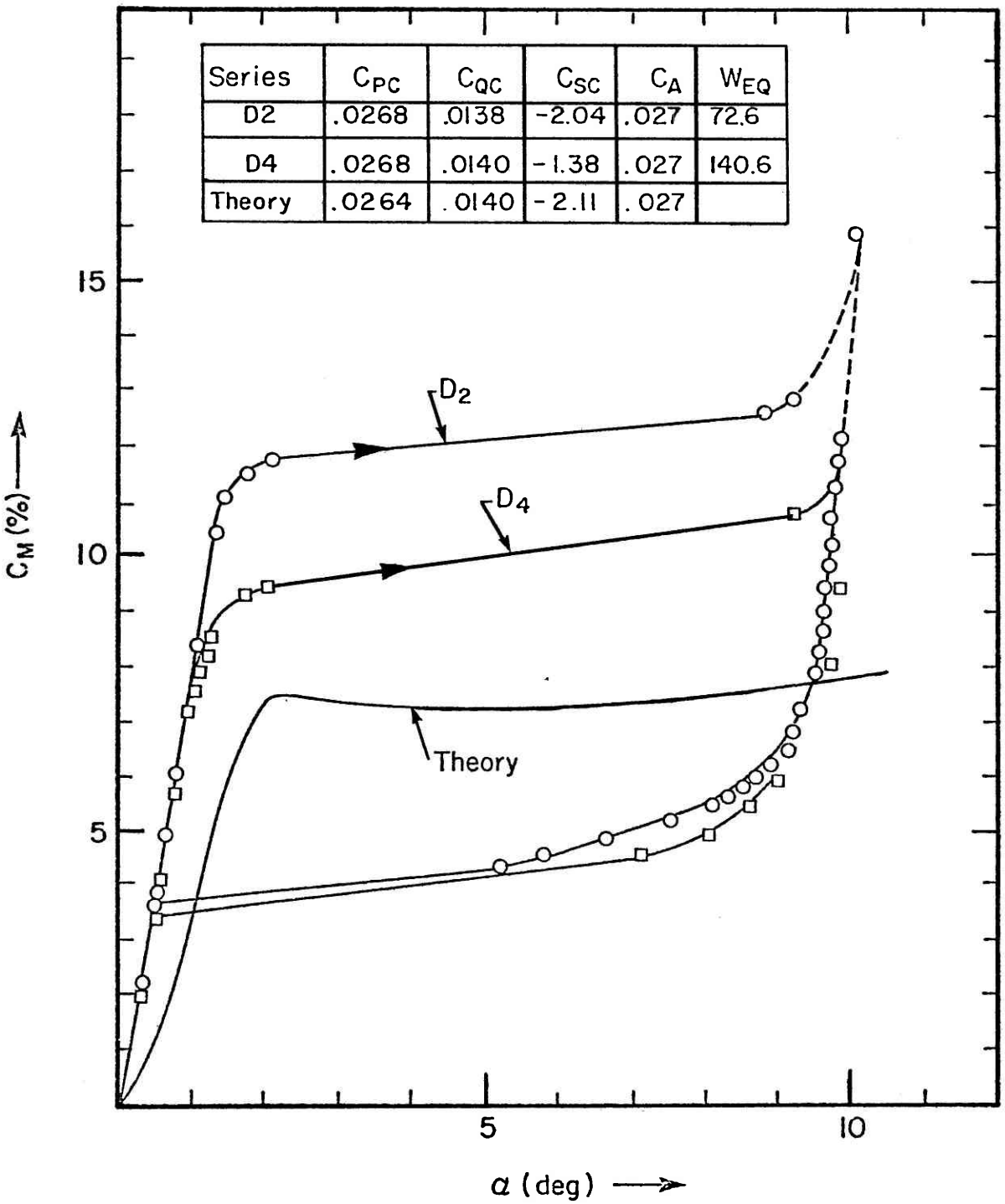


FIGURE 2

Comparison of theoretical prediction of roll stiffness of a multicell cushion with experiment. Skirt material thickness = 3.77×10^{-4} of model width.

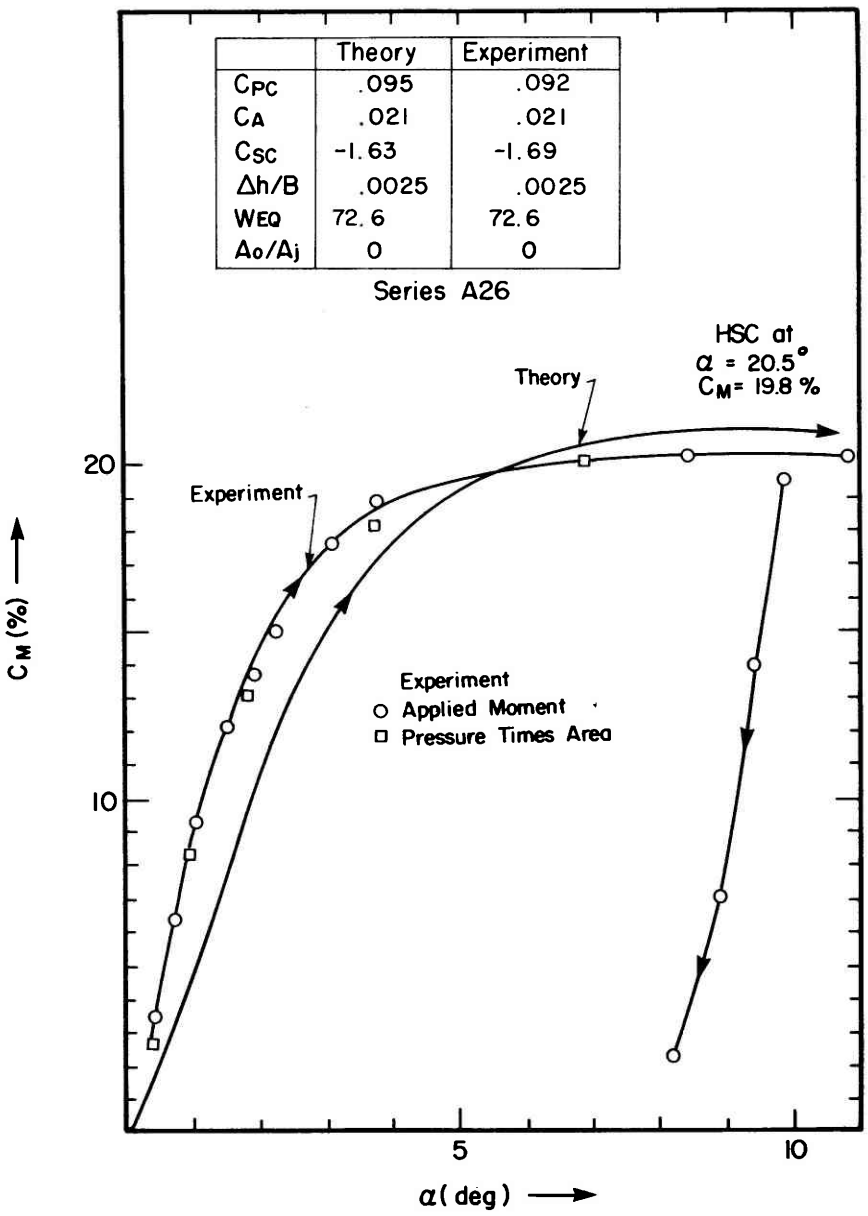


FIGURE 3

An example of catastrophic hysteresis in roll stiffness. For these tests skirt material thickness $= 1.88 \times 10^{-4}$ of model width.

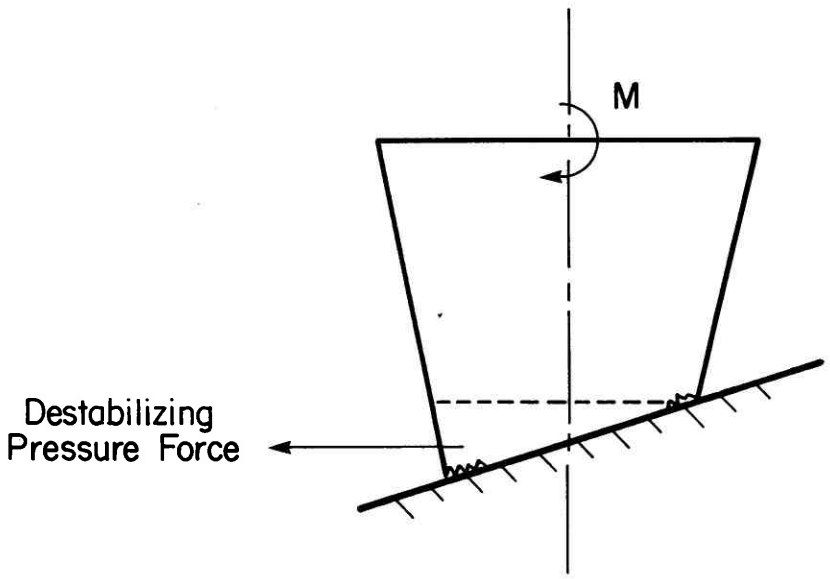


FIGURE 4

Postulated buckling mechanism for tapered air cells. The internal pressure forces create a destabilizing moment M about the top of the cell.

buckling loads with those obtained on a cell which was similar in every respect, but uncut and therefore touching the ground imply that, in contradistinction to the suggestions made by Fowler (Ref. 14), contact with the ground actually stabilizes the skirt (Fig. 5).

Recent experiments on a model which used just two tapered cells, in contrast to the eight cells and outer skirt used on the original multicell cushion, has confirmed that there are at least two hysteresis mechanisms, one of which tends to disappear if the skirt material is made thin enough, while the other - buckling and venting - is more likely to occur as the material is made thinner. It seems clear that the buckling-venting mechanism is a problem at full scale, but it might be avoided by a suitable modification of the cell geometry (Ref. 13). However, it is not clear that the other will disappear at full scale. For example, Fig. 6 shows results obtained when 0.127 mm thick polyethylene material was used on 0.50 metre diameter 8^{0} tapered cells. This shows that the hysteresis has largely disappeared. On the other hand, some experimental results obtained for a "pericell" type cushion fitted to the Vampire 1 and made of the same 0.127 mm polyethylene showed significant hysteresis (Fig. 7). In practice this hysteresis affects the vehicle dynamics as would a linear viscous damping term.

In concluding this brief discussion of a nominally simple, yet in practice quite complicated cushion system, it is worth noting that the somewhat unexpected result predicted by Hinchey's theory, (Ref. 13), namely that a constant pressure source (that is - "large fan") gives lower roll stiffness capacity than a constant mass flow source ("small fan") on a smooth flat surface clearly occurs in the experimental results shown in Fig. 6. However this is an effect which is probably of only "academic" interest. As has been recently observed by Fowler (Ref. 16), multicell type cushion systems can be subject to a large loss of stiffness when operated over practical terrain such as grass or other vegetation, and the only way this loss can be recovered is by pumping additional air through the cushion.

The other major multicell type of cushion tested at UTIAS was a Canadian development known as the Flexicell. This design is an advance in ideas, since it incorporates a hinging mechanism in the cells to reduce snagging on obstacles such as tree stumps, and eliminates the troublesome outer skirt characteristic of the earlier multicell design. The UTIAS tests suggested that it might achieve about twice the roll stiffness of the original multicell at a given C_{QC} or LAC. Hoever, it is subject to some of the problems inherent in all multicell type systems, such as loss of stiffness over grass.

Another cushion system which is currently receiving attention in Canada is the segmented type cushion related to HDL designs. Although we acquired a loop and segment model several years ago, fascination with the characteristics of multicell skirts led us to put this to one side. We have recently returned to it, and are obtaining interesting results. For example, although the 2.44 metre by 1.22 metre model employs an elastomer-fabric composite skirt material which is only 0.23 mm thick, recent results have shown significant dependence of roll stiffness on

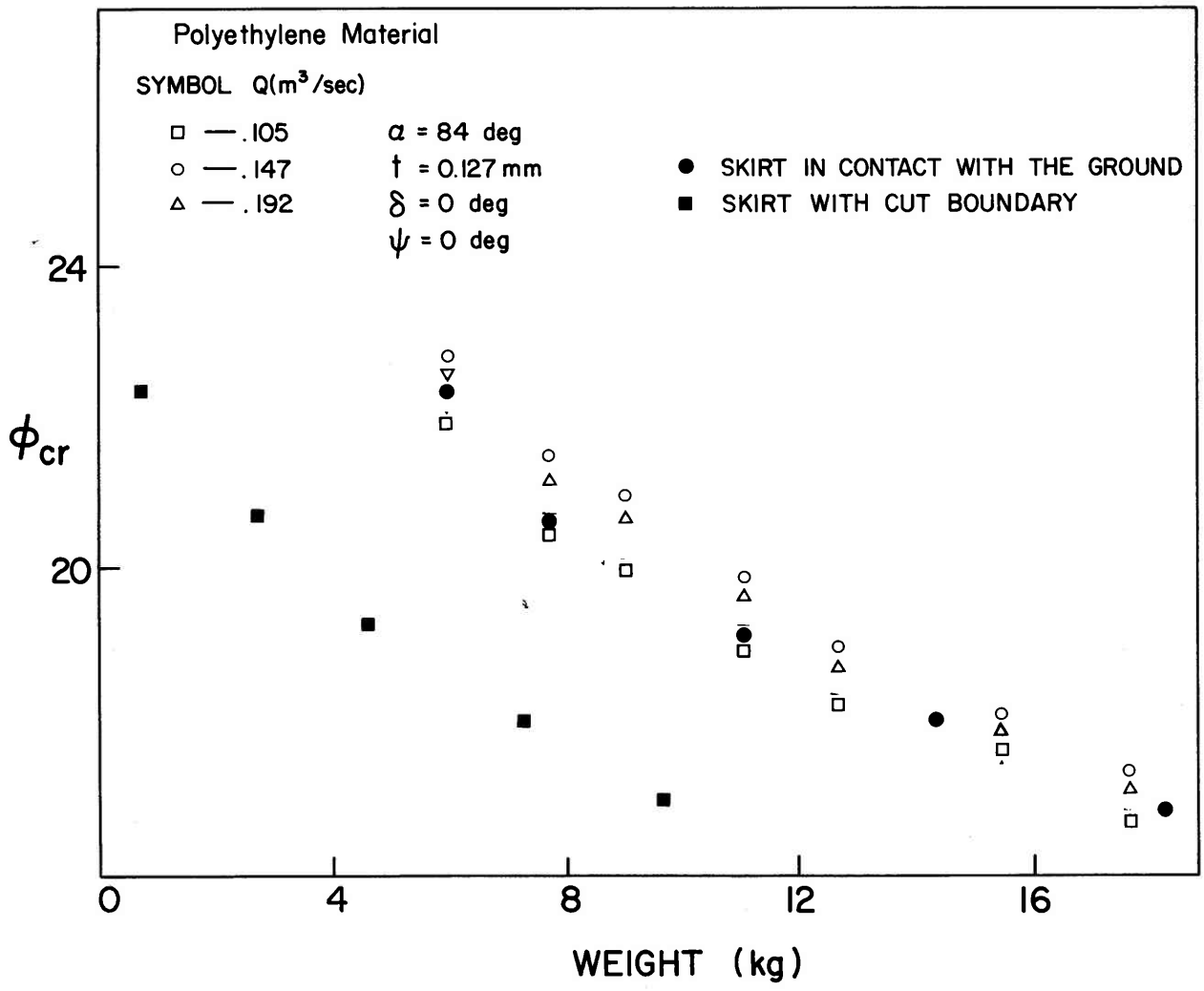


FIGURE 5

Effect of contact with the ground on buckling load at a given critical roll angle ϕ_{CR}. Material, polyethelene 0.127 mm thick. Cell geometry and size same as in Figures 1, 2 and 3. Cell top diameter = 0.508 m. Open symbols refer to test done on three cells, each having nominally the same size and geometry and shows the insensitivity to manufacturing imperfections. The closed symbols refer to cells which were tested, subsequently cut and then retested.

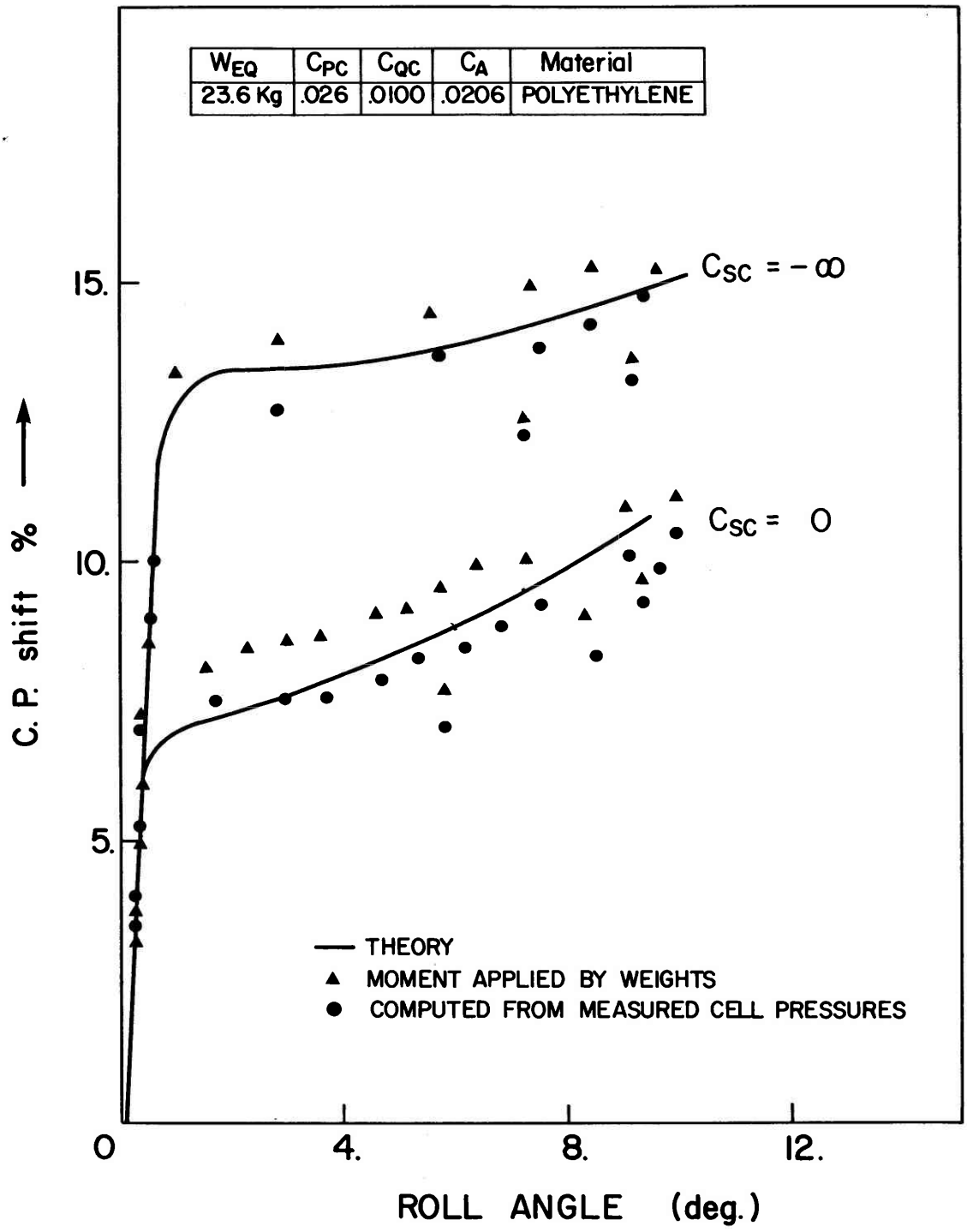


FIGURE 6

Effect of local fan slope on roll stiffness of a two-cell system as predicted by theory and as obtained by experiment using a skirt material which is about 10^{-4} of model width. Experimental points are given for two methods of measuring moment.

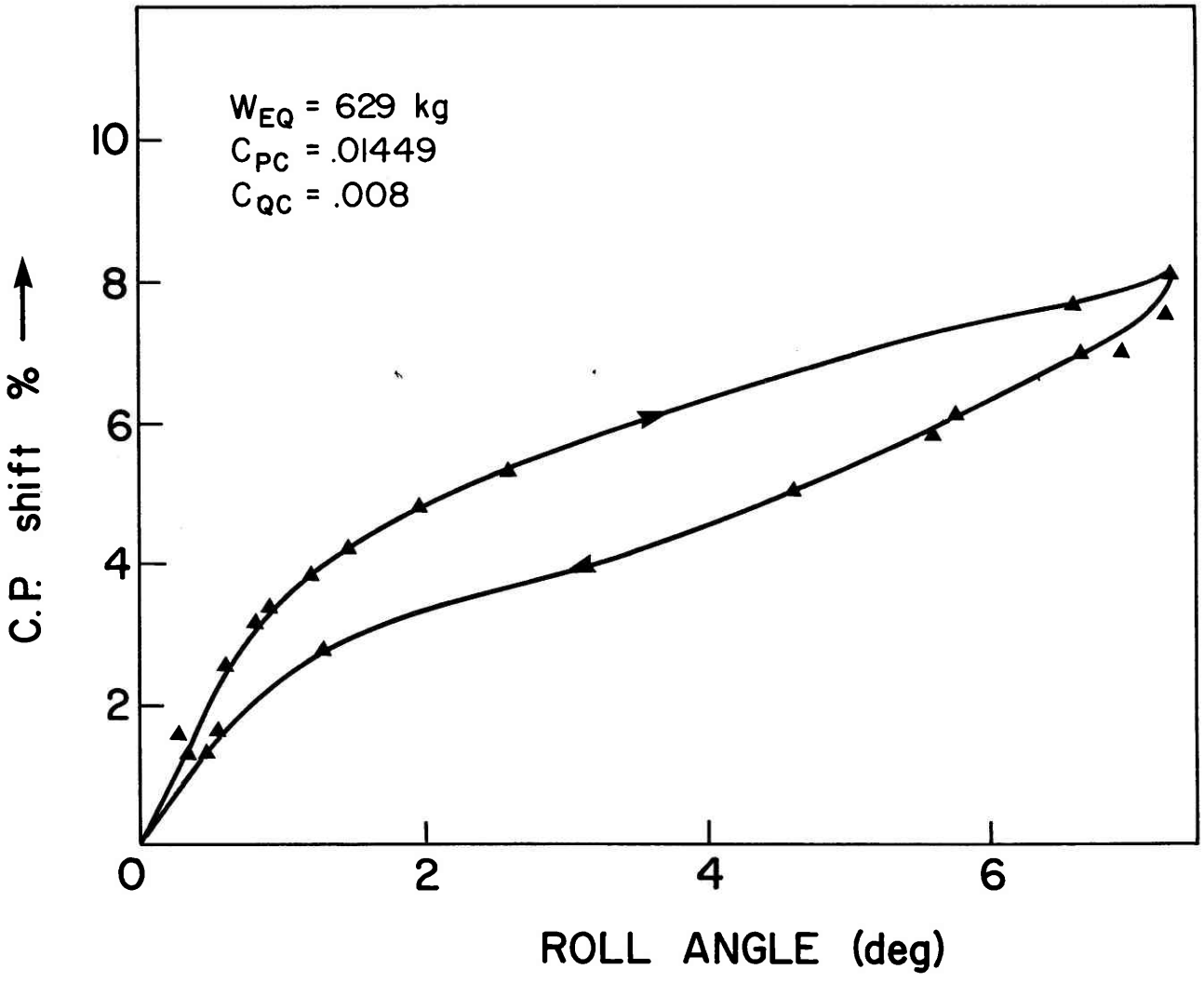


FIGURE 7

Measured roll stiffness for a "Peri-cell" type skirt mounted on Vampire 1.

weight and considerable hysteresis. Also the moving ground-board test seems to show a large effect. These results are shown in Figs. 8 and 9 respectively; again it remains to be determined if such effects are important at full scale. The HDL type skirts currently being developed in Canada do not use a loop, and this appears to have some effect on their suspension characteristics. We are currently testing this latest design skirt on Vampire 1.

The hinged lip TACV type cushion investigated at UTIAS had the geometry shown in Figure 10. A characteristic feature of a TACV application is that the wavelengths of the important disturbances imposed by the guideway are long compared to the cushion length, so that the motion along the guideway can be simulated by oscillating a flat surface vertically in heave under the cushion. A hinged lip cushion model was tested on the UTIAS servohydraulically driven heave table, and Figure 11 gives the amplitude of the cushion heave motion (Y_{rms}) compared to the table motion (Z_{rms}) as a function of the input frequency for two ratios of the damper inlet area to the cushion inlet area A_d:A_c as defined in Figure 10. This shows that an orifice-cavity combination can contribute considerable damping to the cushion. Also, it indicates that there is an optimum value of A_d for maximum damping since, in the limit $A_d = 0$, there is no flow interchange and therefore no damping. A theoretical model for this cushion system which incorporates a Bernoulli quasi-steady orifice-flow model for the damper has been developed, and reasonably good agreement between theory and experiment has been obtained (Ref. 17). However, the author has not plotted these results in Figure 11, because there is a very interesting question related to this model. That is, the flow through the orifice A_d is inherently unsteady since, in contrast to the flow through A_c, the time-averaged flow is zero. Consequently it could be argued that a lossless Helmholtz resonator model is more appropriate. An analysis which incorporates the Helmholtz model is currently underway and we are awaiting results.

The fifth type of cushion examined in the definition phase of the UTIAS air cushion technology program was the open loop skirt, and this provides an interesting example of the serendipitous nature of research. As part of a consulting obligation, the author attempted to estimate the effectiveness of such a cushion in providing adequate ride comfort in a TACV moving on a guideway with a given power spectral density distribution of roughness, using a linear model and random process theory. The attempt did not get very far, since it was based on an assumption that an available analysis provided the necessary model. It was found that this model was incomplete in one important respect; it did not model the nozzle region - shown in Figure 12 - which plays a basic role in the skirt action. Consequently the consulting objective was not achieved, however the author did develop an appropriate analysis of the nozzle region, which has since been published (Ref. 18). The analysis showed that the nozzle region could be large; however even when it is small, it cannot be omitted. Also it was concluded that, for very low mass flows the stiffness in heave would be very much less than that of an equivalent rigid wall plenum chamber. The co-author of Ref. 18 attempted an exper-

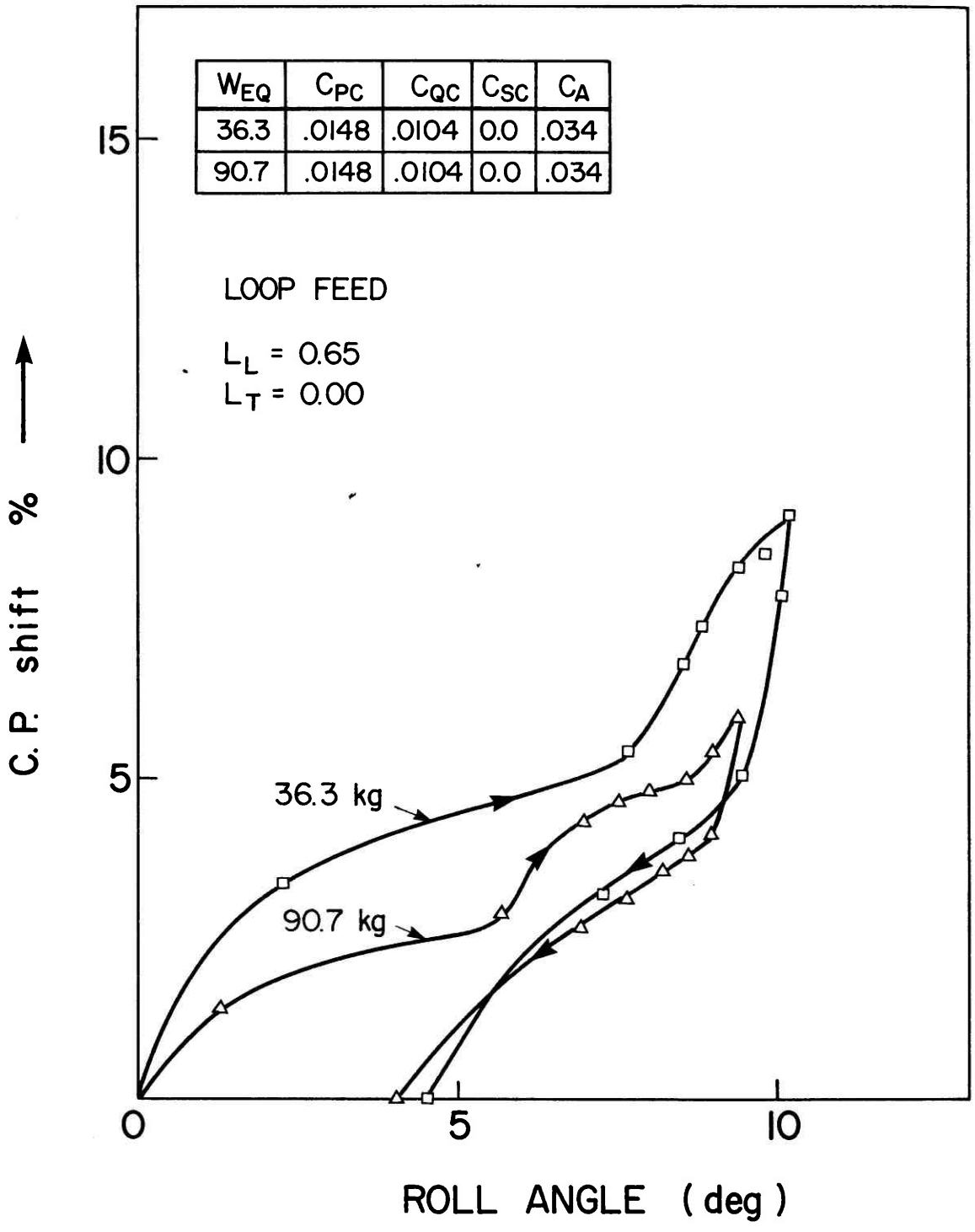


FIGURE 8

Effect of model weight on measured roll stiffness of loop and segment skirt material thickness - 1.88×10^{-4} of model width.

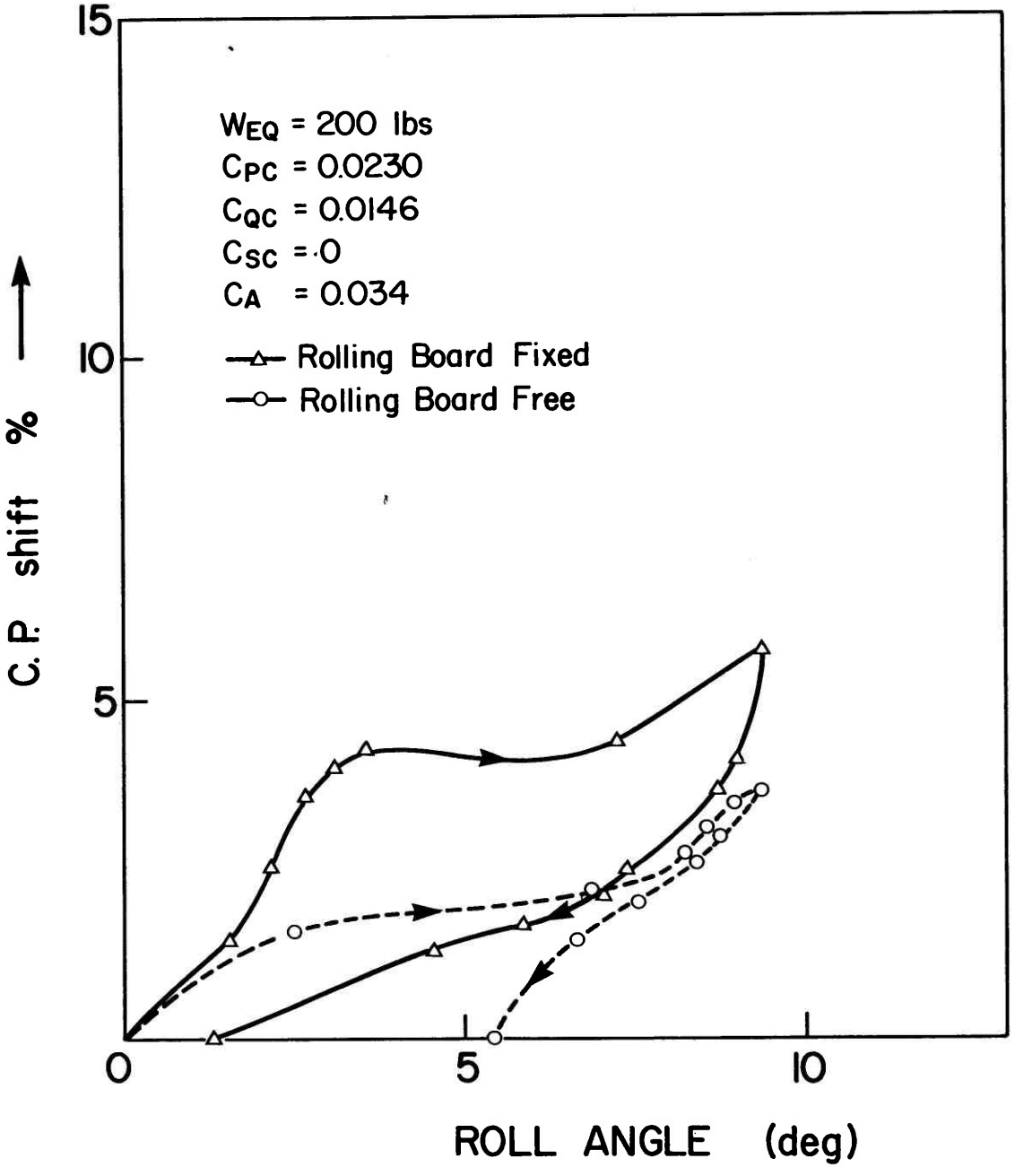


FIGURE 9

Effect of using "frictionless" rolling board on measured roll stiffness of loop and segment skirt.

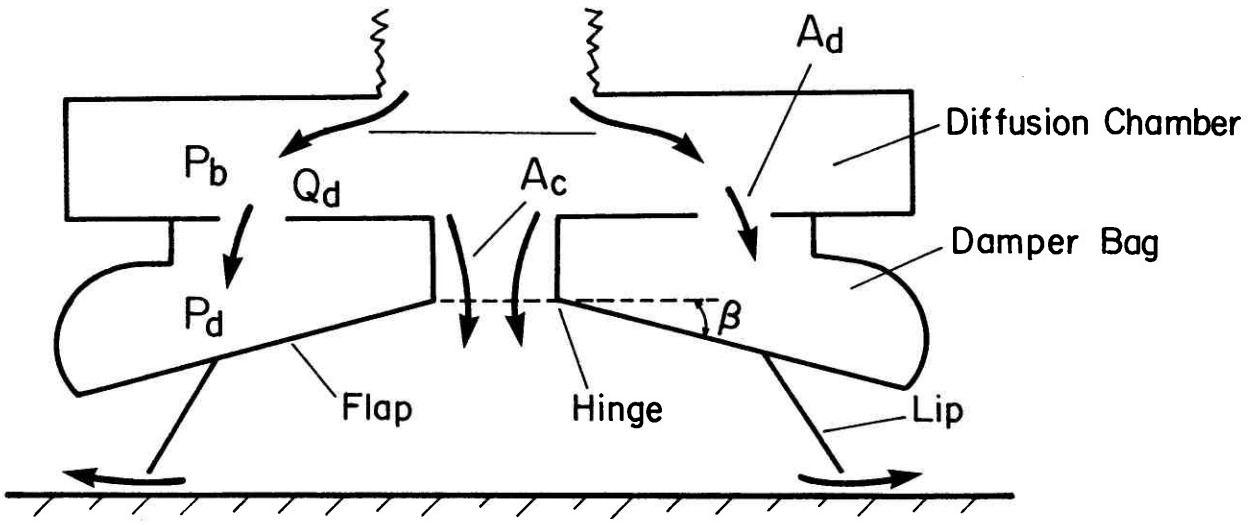


FIGURE 10

Geometry of hinged-lip TACV type cushion tested at UTIAS.

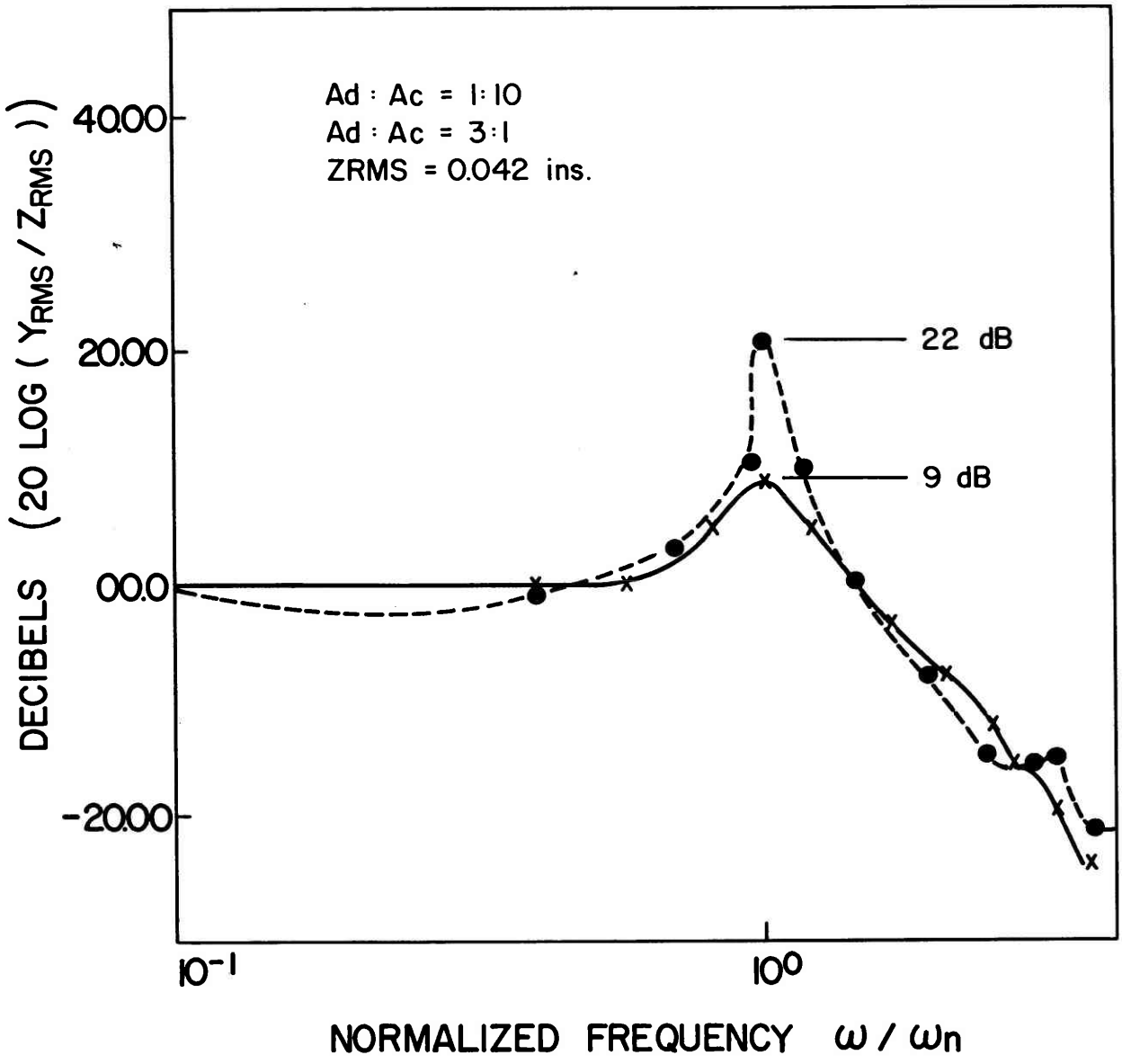


FIGURE 11

Typical measured amplitude response of hinged-lip cushion at two damper inlet areas.

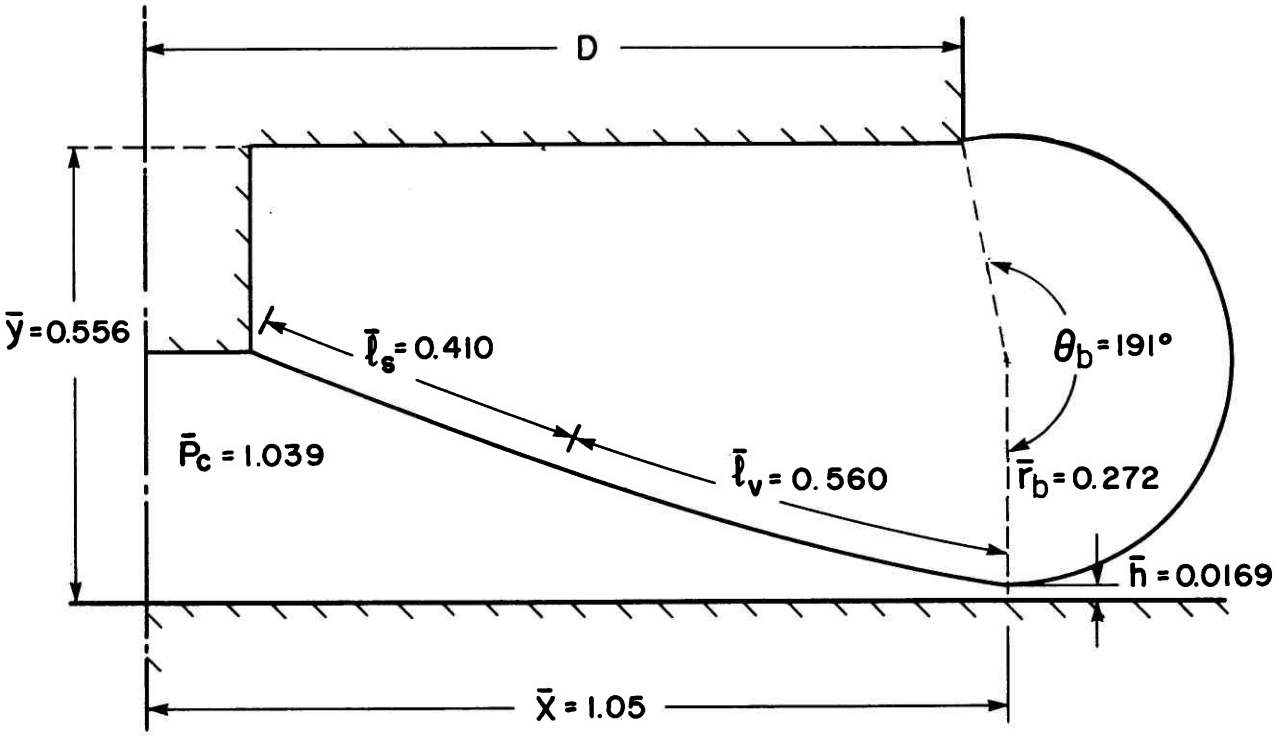


FIGURE 12

Typical geometry predicted for loop skirt on smooth ground at moderately high volume flow. The geometrical quantities with bar on top are expressed as fractions of the hard structure half-width D. The pressure is expressed in terms of W/2D, where W is applied load.

iment to verify the theory; however the test model was found to be subject to severe self-excited loop oscillations, commonly known as "skirt-buzz". Owing to general lack of interest, research on this skirt has since been discontinued, but it is interesting to note that the original question posed as part of a consulting contract does not appear to have been answered in the open literature.

The early work on heave instabilities undertaken in a co-operative effort with an industrial group seemed to suggest that, of the various phenomena not covered by available theory, the behaviour of the internal flow within a plenum chamber seemed to be the dominant factor affecting stability boundaries. Before discussing the principal technical results obtained so far, it is worth digressing to discuss this problem in terms of its relevance. Now the internal flow in a plenum chamber is turbulent and eddying, and it is obvious that if enough air is pumped through the cushion, the eddies can be made strong enough to influence the lift generated by the cushion. Indeed, in the limit of very large flow, one can think of a plenum chamber as a device to augment the lift of a jet of air directed vertically downward. However, for some time it has been known that, for practical values of volume flow rate, the lift generated by the cushion can be computed by assuming that the air in the plenum chamber is at rest, and that the flow into and out of the cushion can be reasonably accurately calculated by one-dimensional orifice flow laws. Hence, insofar as lift computation is concerned, studying the details of the internal flow is currently irrelevant. In the case of heave instabilities, effort was made to ascertain if the internal flow effect was important at practical values of volume flow.

Because the initial experiments seemed to suggest that it is important, it was decided that, in order to define a project suitable for a Ph.D. thesis, we should investigate the applicability of modern numerical methods for predicting turbulent flows. In particular, considerable attention was given to the currently fashionable finite-element method. As a learning exercise, the finite-element technique was applied to the much simpler duct problem.

Somewhat to our surprise, the results obtained for the duct problem suggested that the relatively short ducts that would be used on TACR's or amphibious ACVs might have a very large effect on heave stability boundaries at practical values of volume flow. Figure 13, taken from Ref. 19 shows the cushion pressure at the onset of instability, as predicted by linear theory, as a function of cushion flow expressed as an equivalent nondimensional hovergap h_e/D_p for several duct geometries. The hatched side of the curve indicates instability. All six ducts have the same volume, so that a purely lumped capacitance model would show no effect. Curve 1 correspondends to a lumped capacitance model with a constant pressure source ($c = 0$), and the lumped capacitance model with a constant mass source ($c = \infty$) is given for reference. For curves 2 to 6, the duct length-to-diameter ratios are 3.96, 7.95, 11.21, 15.67 and 63.2 respectively. It is clear that, as the volume flow and hence h_e/D_p is decreased, the duct effects become extremely large. These results are implicit in an earlier analysis of the problem based on the classic wave equation and developed for TACV geometries (Ref. 12), however, the magnitude for short ducts was not pointed out. Also, in one

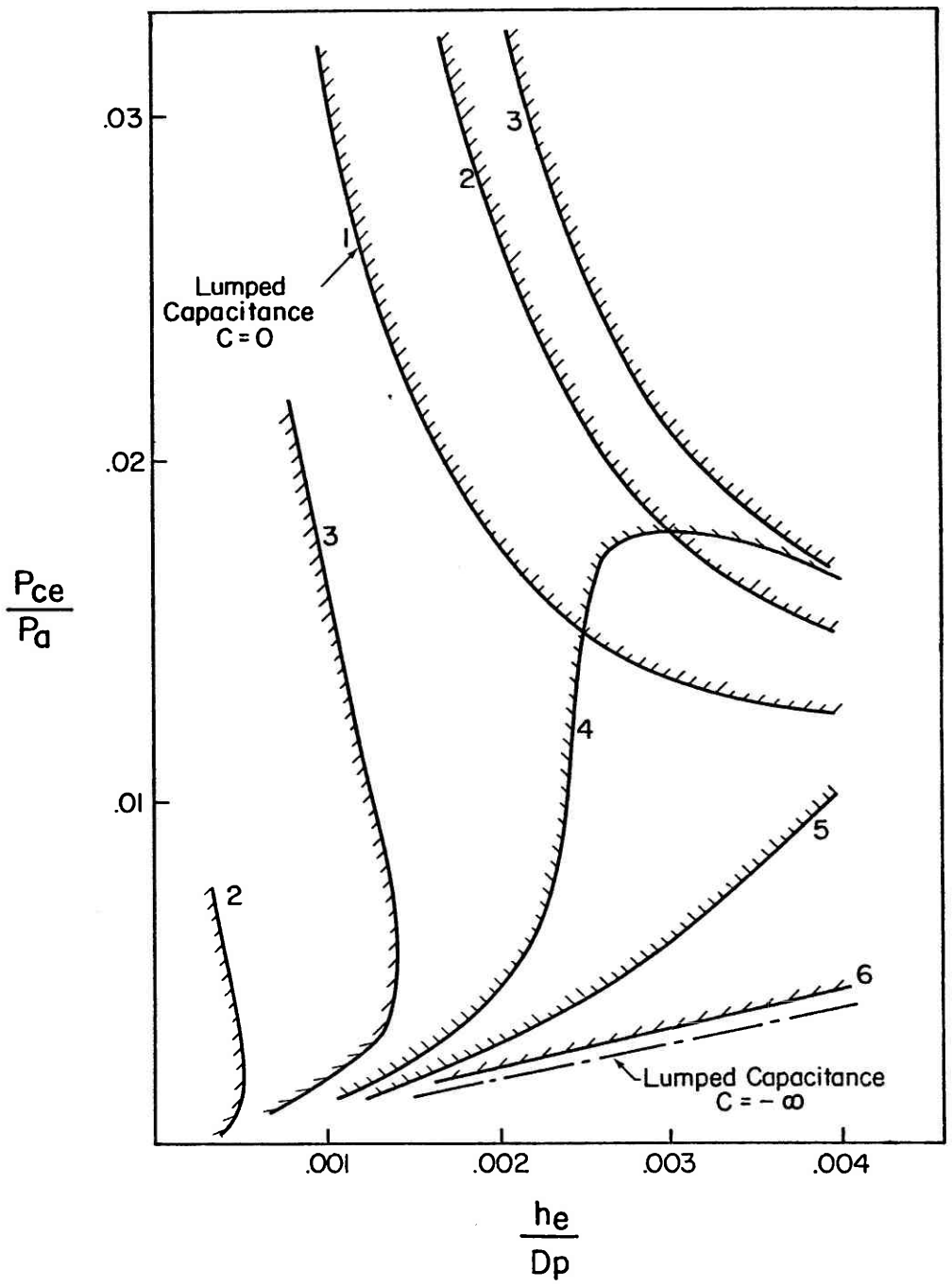


FIGURE 13

Effect of cushion flow as expressed in terms of non-dimensional hovergap h_e/D_p for various duct geometries. Here $C = dP_{fan}/dQ_{fan}$. The curves 2 to 6 refer to duct length-to-diameter ratio equal to 3.96; 7.95; 11.21; 15.67 and 63.2 respectively. Duct volume fixed.

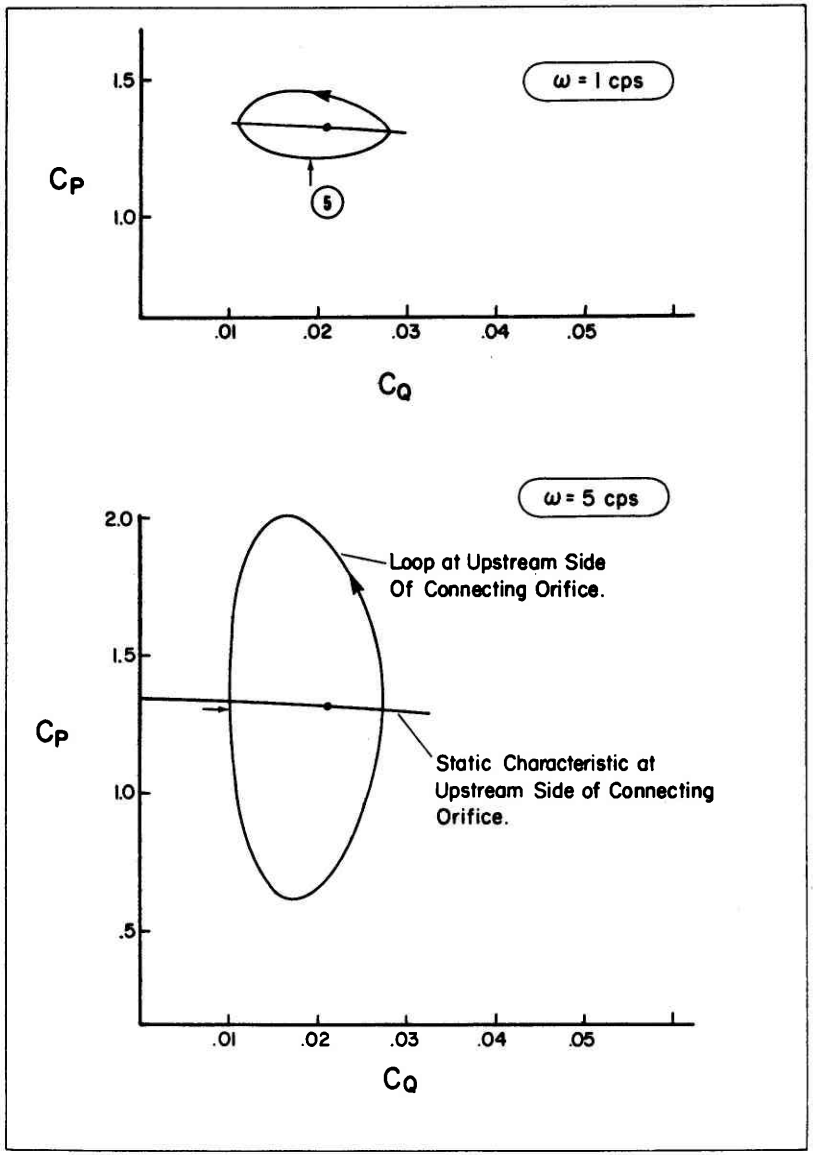
sense, it does not seem reasonable that propagation of pressure waves along the duct could have a significant effect for the relatively short ducts and low oscillation frequencies occurring on TACRs and amphibious ACVs. In fact, as is duscussed in Ref. 19, the duct effect arises from the inertia of the air in the duct oscillating on the compressible air in the plenum, in other words it is a type of Helmholtz resonator phenomenon. The analysis of Ref. 12 gives an inertance effect for sufficiently short ducts.

Work on other aspects of the heave instability problem is progressing, however investigation of the original motivating difficulty - internal flow effects - has been delayed in part by the effort made to understand the duct problem. In closing, it is worth noting that the duct flow inertance can have a very large effect on the equivalent fan characteristic as seen by a cushion undergoing finite amplitude dynamic motion. Figure 14 shows the equivalent fan characteristic generated at the cushion by a sinusoidal cushion exit area variation caused by heaving with an amplitude of 50% of its mean value for four frequencies. C_q and C_p are respectively the usual nondimensionalized fan volume flow and pressure flow coefficients.

CONCLUDING REMARKS

In this review, little has been said about the role of the most controversial aspect of the UTIAS air cushion technology program: the circular track experiments. This is because almost all of the research results obtained to date have been obtained by analysis or using the other facilities. However, under our most recently completed TDC contract, some data on the effect of forward speed on static roll stiffness and on dynamic response to a ramp disturbance for a multicell cushion was obtained. But owing to the geometric complexities of this cushion and other limitations, a theoretical analysis was not available. In this connection, for the work being undertaken on the track, our aim is the same as for our other efforts, that is, we do not regard it as fully successful university research unless we can compare the experiments with the predictions of a well founded theory. The current cushion system being investigated - a segmented skirt - is much simpler to analyse, and we are currently setting up the relatively sophisticated computer programs required to enable the noisy data obtained from the accelerometers and angular rate gyros on Vampire 1 to be interpreted in such a way as to extract information on such quantities as damping coefficients. One point has been firmly established. The problems experienced to date with scaling of skirts have clearly indicated that the decision to build a facility of this size was basically sound. Furthermore, in terms of original and operating costs, it is comparable to a moderately large subsonic wind tunnel employing relatively sophisticated instrumentation.

At the technical level, most of the UTIAS effort to date has been focussed on multicell-pericell type skirts, and the author believes that this has contributed to the on-going debate about their possible role in various Canadian applications. As has been pointed out by Fowler (Ref. 16), they are subject to certain serious difficulties that do not



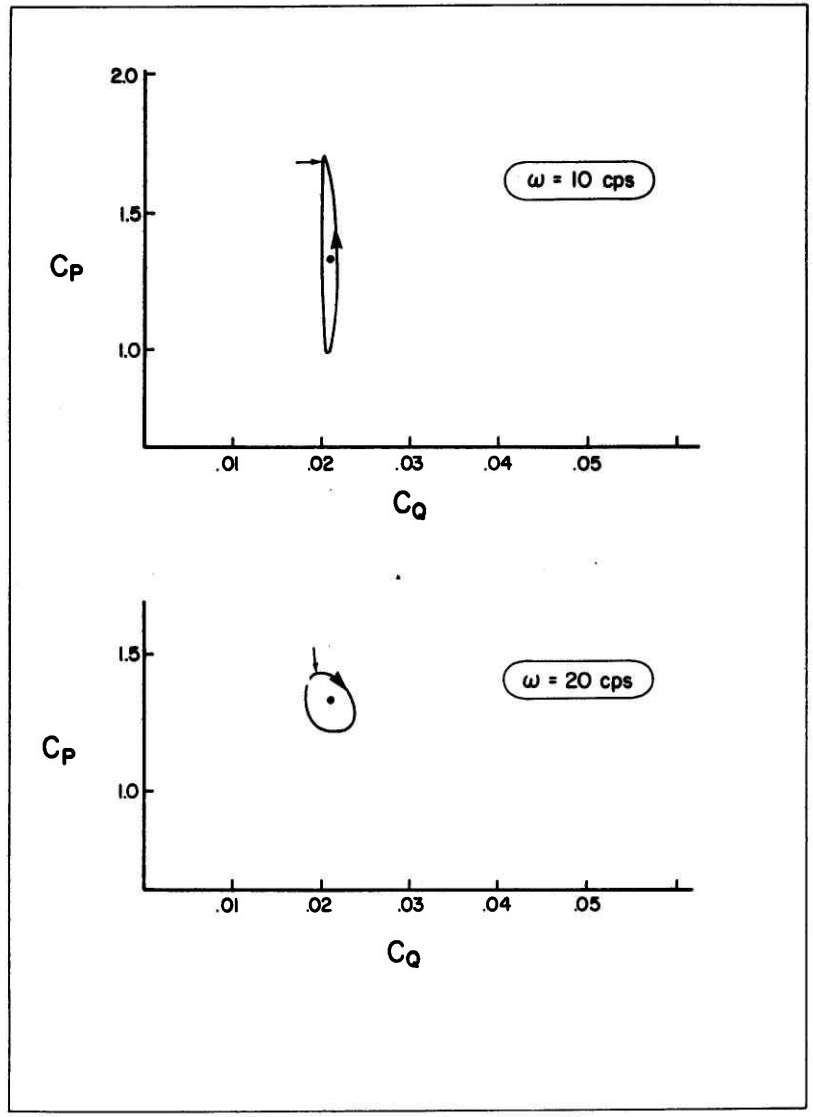


FIGURE 14

Effect of ducting on equivalent dynamic fan characteristics
as seen at cushion inlet for a
heave oscillation equal to 50% of average hovergap at four frequencies.

occur on a segmented skirt. Some of these can clearly be circumvented by an appropriate choice of cell geometry. Others can only be corrected by pumping sufficient air through the cushion, so that the multicell skirt would be subject to an operating cost penalty relative to the segmented skirt. However, the roll stiffness that a segmented skirt can generate is limited by geometrical considerations, whereas a cellular skirt is not, so that for certain applications, it may have a role to play. One such possibility would be on a vehicle having a relatively high centre of gravity or narrow beam width.

The author believes that our active involvement in providing background information on multicell cushion systems indicates that our research effort is about as relevant as university research can be. It has also been successful from a university professor's viewpoint, in that it has provided us with many problems which have the intellectual content suitable for graduate student research. Also, after a dormant period, we are now beginning to perform in terms of the criterion which seems to be so basic to the university way of doing research. In the last year, three papers have been accepted for publication in appropriate journals.

Finally, the author would like to make one more point about the relevance of university engineering research. As discussed above, we are developing a strong interest in the self excited oscillation problem, and in this connection some of our research projects in this fascinating area may not be directly relevant to current Canadian industrial activities. However these exercises have the effect of improving our general understanding of the problem and of making us relatively familiar with the available work. In this connection we recently estimated stability boundaries for certain configurations for a Canadian industrial group, and the theory used in the analysis was developed at M.I.T. several years ago (q.v. e.g., Ref. 11). But, since such calculation procedures are relatively new to air cushion technology, our familiarity with the available literature and with the limitations of existing analytical models has enabled us to undertake such calculations with a degree of confidence that the harassed engineer on a development project may generally not be able to attain. The underlying point is that, for the university researcher to be able to help on some current development problem, it is often not necessary for him to be doing research on that specific problem. If he is exercising his understanding in the general area or on related problems, he still may be able to provide valuable assistance. Hence the desire for immediate relevance of university research should be balanced against the equally basic need to have on-going university efforts working at a sufficiently taxing intellectual level to ensure that the researcher is probing the frontiers of the subject.

ACKNOWLEDGEMENTS

The strenuous task of establishing oneself in a new research area has involved long, hard work, and has been hectic and very stimulating; and the author is conscious of the debt he owes many people for the help, guidance and support they have given him. To single out particular names is perhaps being unfair to others; however, the author feels

he must. First of all, Dr. G.N. Patterson, the founder of UTIAS, provided the environment. Of his UTIAS colleagues, Dean B. Etkin and Dr. J.H. de Leeuw deserve special mention for their help and guidance. Of those in the Canadian Government Service, Dr. R.D. Hiscocks, Messrs, P.L. Eggleton, H.S. Fowler and J.E. Laframboise have been very active in their support. The author has also been fortunate in having several good students, without whose help this effort would not have been possible. Mr. M. Hinchey is first among them.

REFERENCES

1. Dau, K., Etkin, B. and Surrey, D., "Aerodynamics of a Rectangular Wing with a Peripheral Jet for Air Cushion Takeoff and Landing". Report 65-59, AFFDL, Wright Patterson AFB, Ohio, September 1962.

2. Sridhar, K., "An Experimental Investigation of the Flow in and Behind Two Dimensional Sheets Bounding a Cavity". UTIAS Report No. 94, August 1963.

3. Liiva, J., "A Facility for Dynamic Testing of Airborne Models with Ground Effect". UTIAS Tech. Note No. 53, October 1961.

4. Kurylowich, G., "The Determination of Aerodynamic Characteristics of Airborne Vehicles in Ground Effect using Self Propelled Models". UTIAS Report No. 110, September 1965.

5. German, A.B., et al, "Air Cushion Vehicles: Their Potential for Canada". Canadian Government Printer, Ottawa, December 1969.

6. Sullivan, P.A. and Placek, R., "A Review of the Status of Air Cushion Technology". UTIAS Review No. 33, May 1971.

7. Sullivan, P.A., "The Air Cushion Technology Program at the University of Toronto". Canadian Aeronautics and Space Journal, Vol. 20, No. 6, June 1974.

8. Sullivan, P.A., "Air Cushion Technology Research at the University of Toronto". Hovering Craft and Hydrofoil, Vol. 14, No. 8, May 1975.

9. Sullivan, P.A., "Air Cushion Technology: The Prospects for a Canadian Industry". Canadian Aeronautics and Space Journal, Vol. 19, No. 2, February 1973.

10. Sullivan, P.A., Van der Straeten, R., "On the Cost Benefits of Air Cushion Landing Gear to Civil Aviation". Proceedings of the First Air Cushion Landing Systems Conference, University of Tennessee Space Institute, December 1972.

11. Captain, K.M., Richardson, H.H., "Heave Dynamics of Flexible-Base Fluid Suspensions". M.I.T. Dept. of Mechanical Engineering Report, January 1969.

12. Sweet, L.M., Richardson, H.H., Wormley, D.N., "Linearized Models, Stability Criteria and Experimental Verification for Plenum Air Cushions with Compressor-Duct Interactions", M.I.T. Dept. of Mechanical Engineering Report, 1974.

13. Sullivan, P.A., Hinchey, M.J., Delaney, R.G., "An Investigation of the Roll Stiffness Characteristics of Three Flexible Skirted Cushions". UTIAS Report No. 213, March 1977. Condensed version published in Journal of Terramechanics, in press.

14. Fowler, H.S., "CASPAR ACV Research Project Report No. 4: The Multicell Skirt - A Summary". National Research Council of Canada, Associate Committee on Air Cushion Technology, Technical Report 5/76, October 1976.

15. Sullivan, P.A., Murra, I., "Problems in the Use of Multicell Air Cushion Systems in Overland Operation". UTIAS Technical Note to be published.

16. Fowler, H.S., "The CASPAR ACV Research Project Report No. 5: The Multicell Skirt with a Cell-Sealed Perimeter and Central Pressurized Cavity in Overland Operation". National Research Council of Canada Associate Committee on Air Cushion Technology, Technical Report No. 3/77, June 1977.

17. Sullivan, P.A., and Parravano, G.J., "Dynamic Model of a Hinged Lip TACV Cushion", Contract Report to TDC, File D-500-210, March 1977.

18. Sullivan, P.A. and Parravano, G.J., "Analysis of a Loop Type Flexible Skirt Air Cushion", Canadian Aeronautics and Space Journal (Transactions) Vol. 23, No. 6, November/December 1977.

19. Hinchey, M.J., and Sullivan, P.A., "Effect of Ducting on the Heave Stability of Plenum Air Cushions". Journal of Sound and Vibration (to be published).