Heave stiffness of a bag and finger skirt

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HEAVE STIFFNESS OF A BAG AND FINGER SKIRT

The bag and finger skirt, first introduced in 1966 for use on high-speed amphibious air-cushion vehicles, has been developed into a remarkably effective system. Nevertheless it is not free of problems. One is a tendency to produce a relatively rough ride, and a second is a dynamic instability known as "skirt bounce". Furthermore, the currently accepted method of suppressing this instability, an "antibounce web", is believed to limit the downward motion of the skirt, and thus its responsiveness or ability to filter out inputs to the craft dynamics created by motion over surface disturbances. In collaboration with scientists at the Marine Design and Research Institute of China in Shanghai, we have started a program of analysis and experiment aimed at understanding the factors that affect responsiveness and stability. Our work is focussed on the investigation of a simplified model; this is an uncompartmented two-dimensional section of the skirt confined between end-plates. Although this is a considerable simplification of the full three-dimensional geometry, it represents a compromise between the need to obtain data of immediate engineering interest on the one hand and the need to develop an analysis from first principles on the other. It is intended to provide basic insights which can guide selection of new geometries.

In this connection although, no doubt, the industry has expended considerable analytical and experimental effort in the development of the skirt, the accessible Western technical literature on air cushion technology appears to contain very little on this system. Significantly, one analysis of the dynamics of ACV's equipped with this skirt used empirical data on skirt deflections (Ref. 1), and as late as 1979 it was observed that the factors that affect frequency response were not adequately understood (Ref. 2). Thus we found ourselves investigating the most basic feature of the skirt: its static heave stiffness properties. This update describes progress on this modest first step; it gives an outline of the theory and presents a first comparison with measurements.

In developing a theory for the heave stiffness of this skirt system the fluid mechanics is straightforward; the challenge is to develop a simple but realistic model of the structural aspects of the skirt. Figure 1 is a cross-section of the skirt depicting the major features needed here. We are aware of two simple skirt models that have been suggested. The first is to model both the inner and outer parts of the bag, OB and BA respectively, as in elastic massless membranes, with OB being hydrostatically loaded by the difference between the bag and cushion air pressures p_b and p_c respectively, and BA being loaded by p_b. The finger DCB'B is modelled as a rigid body attached to the bag at B, and to the craft structure at E by means of a rigid link DE (Ref. 3). A difficulty with this model is that, although the upper part of the finger BD is not usually connected to that

part of the inner bag immediately above it, there may be contact and partial support, which render the membrane model of OB dubious. An alternative, proposed in Ref. 4, is to model the finger and that part of the inner bag it touches as a single rigid body, and to assume that the remaining part of the inner bag is attached to the link ED. In either case the motion of the skirt can be specified by using two degrees of freedom, taken here as the length "b" of the line OB and the angle "β" that OB makes relative to the horizontal. Both models are being used in our analysis.

To derive the equations of equilibrium of the skirt system a Lagrangian formulation and a basic principle of hydrostatics is used. If δV_{ob} is the volume swept out by the outer bag as a result of perturbations δb and $\delta\beta$, then the work δW_{ob} done by p_b acting over the arc AB is $\delta W_{ob} = p_b\{(\partial V_{ob}/\partial\beta)\delta\beta + (\partial V_{ob}/\partial b)\delta b\}$, and the associated generalized non-conservative forces are simply $Q_\beta = p_b\partial V_{ob}/\partial\beta$ and $Q_b = p_b\partial V_{ob}/\delta b$. Hence if the skirt is massless the equilibrium equations are:

$$p_b \frac{\partial V_{ob}}{\partial\beta} + (p_b - p_c) \frac{\partial V_{ib}}{\partial\beta} + p_c \frac{\partial V_f}{\partial\beta} = 0 \qquad (1)$$

$$p_b \frac{\partial V_{ob}}{\partial b} + (p_b - p_c) \frac{\partial V_{ib}}{\partial b} + p_c \frac{\partial V_f}{\partial b} = 0 \qquad (2)$$

where δV_{ib} and δV_f are the volumes swept out by the inner bag and the finger surface BB'C as a result of perturbations $\delta\beta$ and δb. For a given skirt geometry, all of the derivatives $\partial V_{ob}/\partial\beta$, $\partial V_{ib}/\partial\beta$, etc., are functions of β and b, and it is a straightforward, albeit tedious, exercise to derive the required functional forms for the two models.

The equations for the fluid mechanics are (i) an air supply system pressure-flow characteristic, (ii) a law for the flow from bag to cushion through the bag orifices N, and (iii) a cushion air escape law. The first is obtained by empirically fitting a polynomial to experimental measurements of p_b as a function of cushion flow:

$$p_b = A_o + A_1 Q_e + A_2 Q_e^2 + \ldots \qquad (3)$$

The coefficients A_i are functions of fan speed. The flows from bag to cushion and from cushion to atmosphere, both equal to Q_e, are assumed orifice-like. Thus the pressure drop from bag to cushion is calculated by

$$p_b - p_c = \frac{1}{2}\rho\left(Q_e/(C_{mb}A_b)\right)^2 \qquad (4)$$

where ρ is the air density, A_b is the bag orifice area, and C_{mb} is a discharge coefficient. Similarly,

$$Q_e = L_s h_f(h_e) \sqrt{2p_c/\rho} \tag{5}$$

describes the flow escaping to atmosphere. Here L_s is the total peripheral skirt length, h_e is the distance between the bottom tip of the finger C and the ground, and h_f is an effective flow height. Both the discharge coefficient C_{mb} and the flow height function $h_f(h_e)$ are determined from measurements, and include leaks at the model side plates and between segments. For the model we are testing, C_{mb} is about 1.0 when based on the nominal area of the orifices N. The function $h_f(h_e)$ is nonlinear, and as h_e increases from some negative value, because of leaks, h_f is at first constant so that dh_f/dh_e increases from zero to some positive value of about 0.55.

The two equations needed to complete the formulation are the cushion equilibrium equation relating model weight Mg to the cushion pressure and footprint area:

$$Mg = p_c L_M(B_b + 2x_s(\beta, b)) \tag{6}$$

and the cushion vertical motion equation

$$h_g = h_c + h_s(\beta, b) + h_e \tag{7}$$

In these equations, L_M is the model length, B_b is the distance between the inner attachment points E in Figure 1 and x_s is the lateral skirt deflection. The quantities h_c and h_g are the vertical downward distances of the craft base and ground from some datum, and h_s is the skirt height as defined in Figure 1.

Solutions to the equations, which include auxiliary functions describing h_s, x_s, $\partial V_{ob}/\partial\beta$, ..., as functions of b and β, are obtained numerically on a computer using a standard nonlinear equation solver routine. Note that if p_b and p_c are considered given quantities, then the skirt equilibrium equations constitute two equations for the two unknowns β and b. Note also that their form indicates that β and b, and thus the skirt geometry, depends on p_c and p_b only through the ratio $\bar{p}_c = p_c/p_b$.

Figures 2 and 3 give some preliminary results. Figure 2 compares predictions and measurements of vertical and lateral skirt deflection and Figure 3 gives an example of the effect of model weight on craft height. The agreement between theory and experiment is seen to be very good.

Much work remains to be done on such aspects as the effect of skirt geometry on skirt and cushion stiffness. The ultimate aim is to compare predictions of linear and nonlinear frequency response in heave with measurements obtained by using our servohydraulically driven heave table.

References

1. Reynolds, A. J. and Brooke, B. E., "The Roles of Skirt Planform and Deflection in Hovercraft Response", Journal of Mechanical Engineering Science, Vol. 19, Feb. 1977, pp. 1-12.

2. Wheeler, R. L., "Recent United Kingdom Hovercraft Development", Journal of Hydronautics, Vol. 12, Jan. 1978, pp. 3-17.

3. Mantle,l P. J., "Air Cushion Craft Development", U.S. Navy, David W. Taylor Naval Ship Research and Development Center, Bethesda, MD, DTNSRDC-80/012, Jan. 1980.

4. Ma, T. and Sullivan, P. A., "Linear Analysis of the Heave Dynamics of a Bag and Finger Air Cushion Vehicle Skirt", American Institute for Aeronautics and Astronautics, Paper AIAA-86-2361, Sept. 1986.

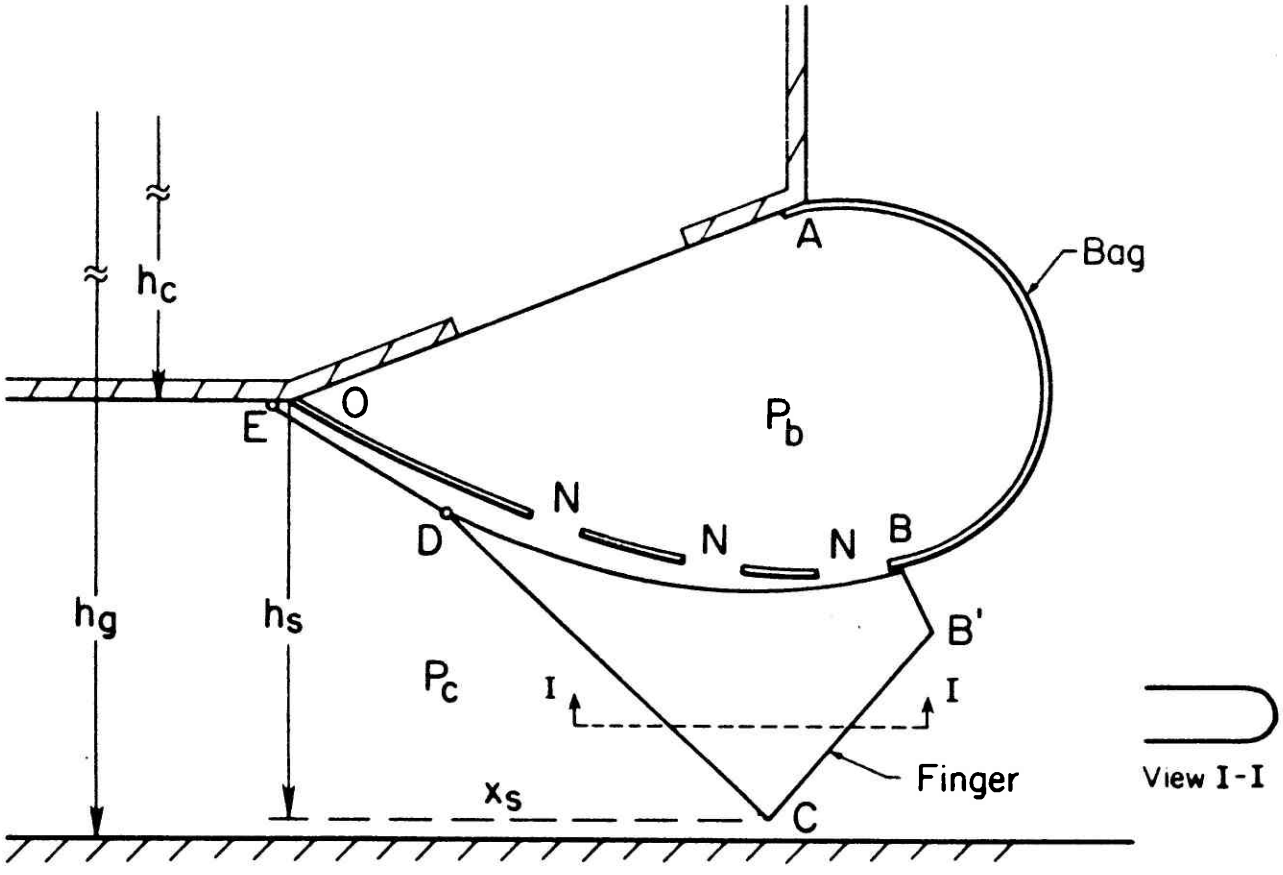
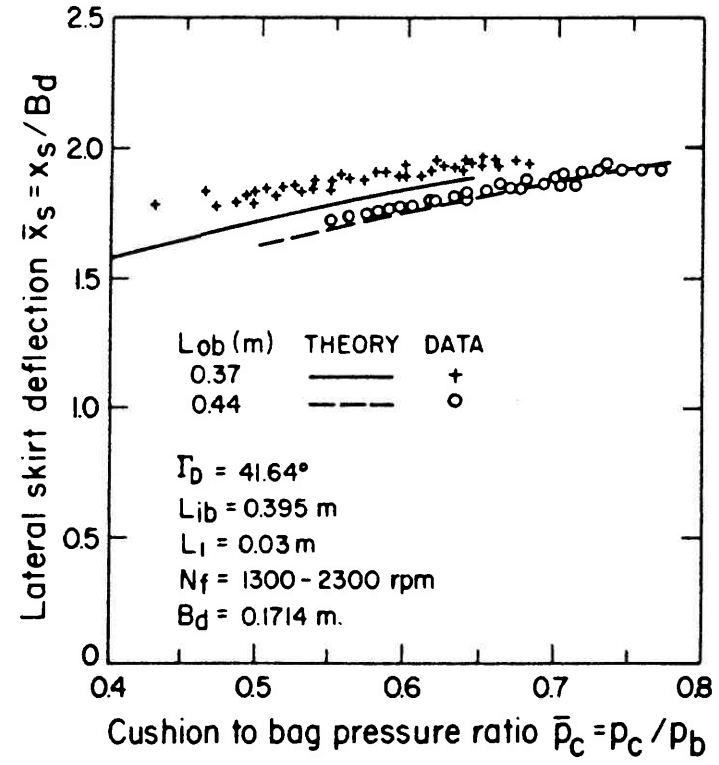


Figure 1. Basic configuration used in analysis and experiment.



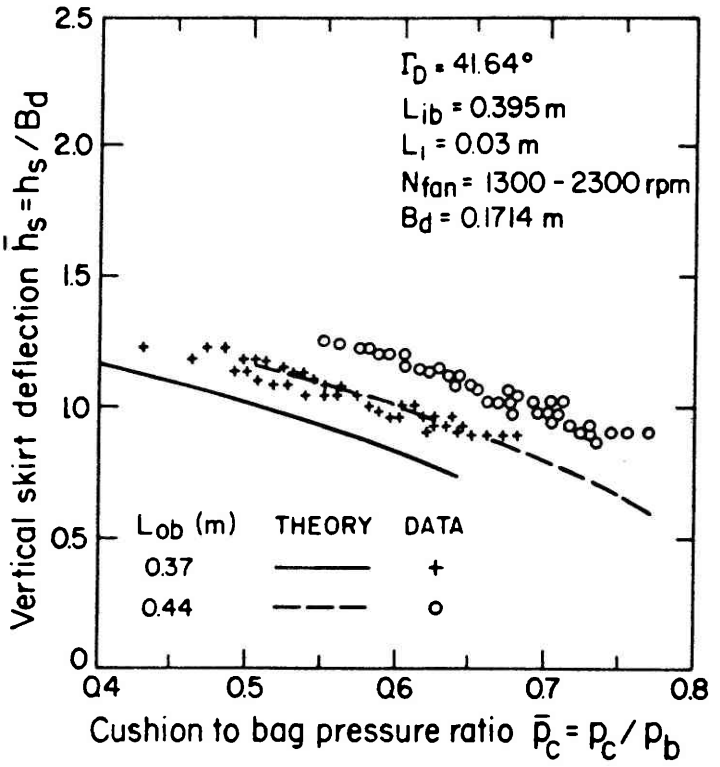


Figure 2. Predicted and measured lateral and vertical skirt deflections as a function of $\bar{p}_c = p_c/p_b$. In these diagrams Γ_D is the angle of the vehicle surface OA relative to the horizon, and B_d is the length of the horizontal projection of OA. L_{ob} and L_{ib} are the lengths of the outer and inner bags respectively, and L_l is a finger reference length.

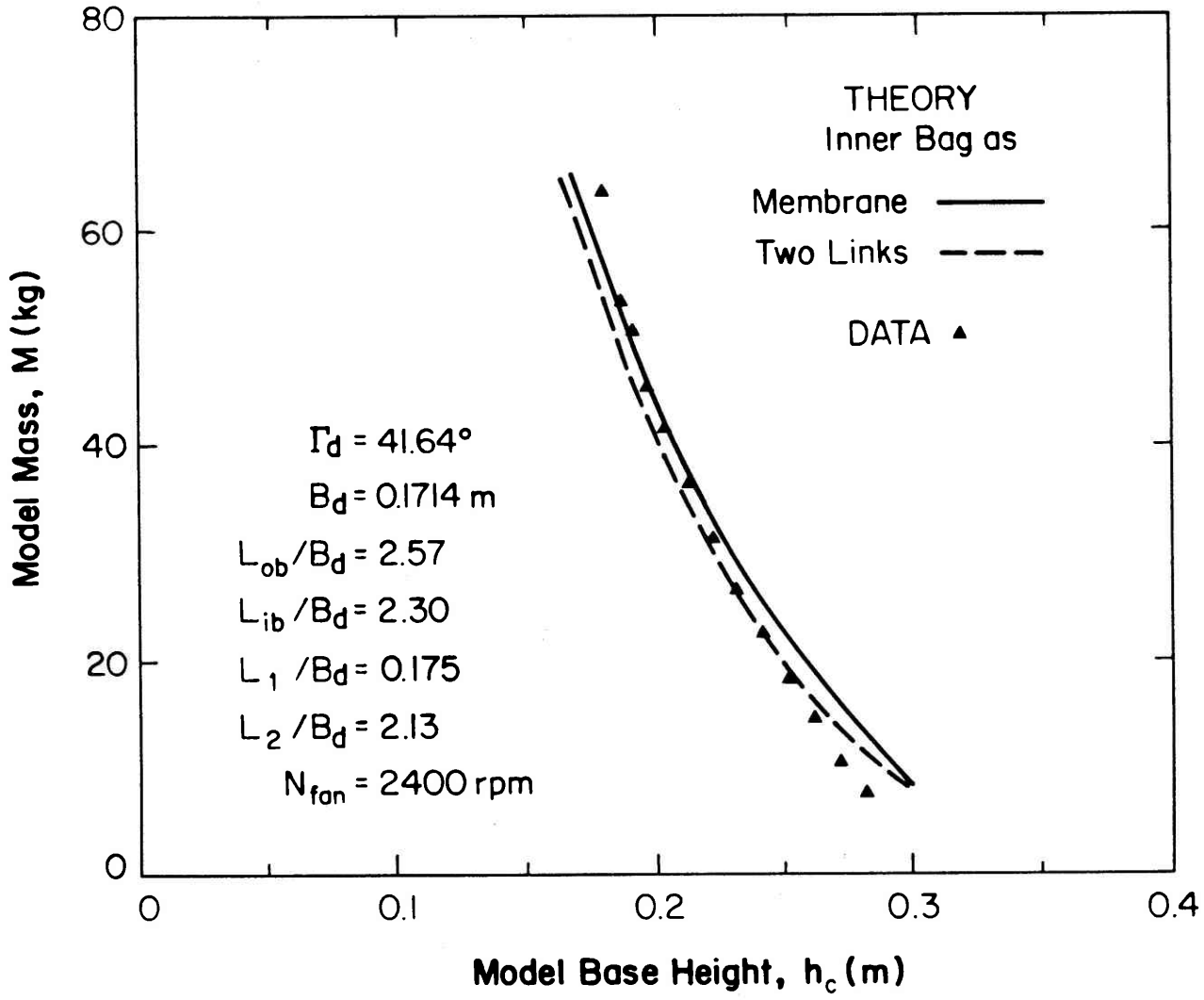


Figure 3. Predicted and measured static heave stiffness of bag-finger model.