NUMERICAL SIMULATION OF OVER WATER HEAVE MOTION OF A TWO-DIMENSIONAL HOVERCRAFT

(SIMULATION NUMÉRIQUE DU PILONNEMENT SUR L'EAU D'UN AÉROGLISSEUR À DEUX DIMENSIONS)

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ABSTRACT

A simulation of a two-dimensional hovercraft is made using a numerical model based on a Navier-Stokes description of water motion, which allows for non-linear behaviour. This is combined with the equations governing heave motion of a hovercraft to obtain cavity pressure oscillations. Results are compared with previous calculations by the author using the linear Lamb oscillation model, based on the dimensions of a small experimental hovercraft. Instability onset is correctly predicted by the simulation. The modulation of the lip air flow by the water motion is shown to have a destabilizing influence at low cavity pressures. While this approach shows promise, it requires a large capacity computer, which rules out the solution of three-dimensional cases at this time.

RÉSUMÉ

Une simulation du comportement d'un aéroglisseur au-dessus de l'eau est faite à l'aide d'un modèle numérique appliqué à un véhicule à deux dimensions. Le modèle numérique s'inspire des équations de Navier-Stokes, permettant de traiter des cas non linéaires, auxquelles sont ajoutées les équations décrivant le pilonnement d'un aéroglisseur. Les résultats sont comparés à ceux obtenus précédemment par l'auteur en utilisant le modèle linéaire oscillatoire de Lamb, basé sur les dimensions d'un petit aéroglisseur expérimental. Le début de l'instabilité a été correctement calculé par le modèle. De plus, il a été démontré que la modulation du débit d'air sous le rebord de la jupe, causée par le mouvement de l'eau, résulte en un effet déstabilisateur aux basses pressions dans la cavité du coussin. Cette méthode numérique semble prometteuse, cependant le temps de calcul nécessaire, plusieurs heures sur un VAX, rend improbable son extension à des cas à trois dimensions.

NUMERICAL SIMULATION OF OVER WATER HEAVE MOTION OF 2D HOVERCRAFT

by

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BACKGROUND

When a hovercraft is undergoing heave motion over water, its motion generates a pressure oscillation within its air cavity which in turn generates waves in the water surface. These waves modulate the volume of the cavity directly beneath the craft and the air flow directly beneath the skirt at the cavity lip. These in turn can modify the stability of the craft itself, mainly through an influence on the phasing of the craft motion with respect to cavity pressure. Hinchey and Sullivan [1] showed for 2D craft that the modulation of the cavity volume by the waves usually improves stability whereas the modulation of the leakage flow at the lip can have a large destabilizing influence at low cavity pressure or craft weight. They based their work on a potential flow water compliance model developed by Lamb [2]. Below, a different water compliance model is developed. It is basically a numerical simulation based on a Navier-Stokes description of the water motion. It allows one to consider nonlinear phenomena, something ignored in the previous work. It is used herein as a check on the earlier work.

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OUTLINE OF SIMULATION

A 2D hydrodynamics code, developed at the Los Alamos Scientific Laboratory [3], is used to track the water motion. The equations governing the motion are:

MOMENTUM EQNS

$$\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho} \frac{\partial p}{\partial x} + \nu \left[\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right]$$

$$\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = - \frac{1}{\rho} \frac{\partial p}{\partial y} - g + \nu \left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right]$$

CONTINUITY EQN

$$\frac{1}{\rho c^2} \frac{\partial p}{\partial t} + \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$

VOLUME OF FLUID EQN

$$\frac{\partial F}{\partial t} + u \frac{\partial F}{\partial x} + v \frac{\partial F}{\partial y} = 0$$

where x and y are spatial co-ordinates, t is time, u and v are velocities, p is pressure, F is a volume of fluid (VOF) function, ρ is the density of water, ν is its viscosity, c is the speed of sound in water and g is the acceleration due to gravity. The computational domain is shown in Fig. 1: the location of the hovercraft is denoted by a heavy line in the upper left hand corner of the bottom sketch. The momentum equations are used to update the velocities u and v step by step in time throughout the domain. The continuity or conservation of mass equation allows one to update the pressure p and make corrections to u and v. The VOF equation allows one to track the water surface: F is equal to unity within the water and zero outside. The cavity pressure is applied directly to the water surface in the simulation [3]. It is taken to be uniform within the cavity region and undergo a linear fall-off to atmospheric pressure at the lip. The latter can be abrupt or gradual: in other words, it can happen over a single or several computational cells. Each governing equation is put into the form:

$$\frac{\partial A}{\partial t} = B$$

Each is then integrated numerically across a time step Δt to obtain updated values of A:

$$A(t + \Delta t) = A(t) + \Delta t \; B(t)$$

where the various derivatives in B are discretized using finite difference approximations. The details of this can be found in [3].

The equations governing the heave motion of the craft are [1]:

NETWON'S SECOND LAW

$$m \frac{d^2 Z}{dt^2} = P\,S - mg$$

CONSERVATION OF MASS

$$C_p \frac{dP}{dt} = Q_{in} - Q_{out} - \frac{dV}{dt}$$

ORIFICE FLOW LAW

$$Q = C_d \, D\sqrt{\frac{2\Delta P}{\sigma}}$$

where m is the supported mass, Z indicates its position vertically from a rest state, P is the cavity pressure, S is the support area, Q is a volumetric flow, D is a flow area, V is the cavity volume, C_p is the cavity capacitance, C_d is a discharge coefficient and σ is the density of air. The motion of the water surface modulates V and D for the leakage flow. The craft equations are integrated numerically using a predictor-corrector procedure. At its lowest level, this is the same as the second-order Runge Kutta scheme. It is the highest order procedure consistent with the simulation of the water motion.

WATER SURFACE PROFILES AND STABILITY

HEX-5 was one of a number of small research craft developed by Fowler and his colleagues at NRC during the late seventies and early eighties. Its beam was 2.5 m and its cushion was 0.2 m deep. Hinchey and Sullivan analyzed the over water heave stability of a 2D section of HEX-5 using the water compliance model taken from Lamb [2]. They also used the water compliance model to study the water surface profiles generated when the cavity pressure was allowed to undergo a sinusoidal oscillation. Fig. 2 shows typical profiles generated for HEX-5: IN indicates a component in phase with pressure while OUT indicates a component 90° out of phase. Fig. 3 shows profiles generated by the simulation: HOLE indicates the depth of a trough directly beneath the craft created by a hydrostatic pressure and AMP is the amplitude of the cavity pressure oscillation about the hydrostatic level. Comparison with Fig. 2 shows that there is reasonable agreement. The duration of the simulation was typically around 10 seconds and the profiles given are for the last second of this. By this time, start up transients were no longer present. During the simulation, the water was discretized typically by 20 horizontal grid lines and 250 vertical lines: about 20 of the vertical lines were in the cavity region. This was considered to be adequate for the wave lengths generated. The grid was uniform throughout except for the far right hand side where it was allowed to expand horizontally so that reflected waves from a vertical wall there did not have a chance to form. For the profiles given, the drop-off in pressure at the lip occurred across the 4 vertical lines just outside the cavity. Finally, the water depth used in simulation was 2 m. For the frequency tested, this is basically deep water.

The simulation work to date on heave stability has been very exploratory in nature and much more needs to be done to verify and extend the predictions. For example, craft disturbances used to start the simulation have so far been kept small, in an attempt to avoid nonlinear phenomena. Also, in early runs, the hydrostatic trough due to craft weight was found to create very complex water flows near the lip and very erratic and perhaps unrealistic craft behavior. So, it has since not been allowed to form. Note that this makes the simulation more consistent with the earlier work which also ignored the trough. Finally, even with the above restrictions, runs are often computationally very expensive, sometimes taking several hours of VAX CPU time to complete, even with coarse grids and short duration times. This is a very serious drawback of the simulation. It effectively rules out 3D computations at this time.

Fig. 4 shows simulation traces for a case where the rest gap was 4.5 mm and the water motion was not allowed to influence craft heave motion so that the craft operated as if it were over land. Routh Hurwitz calculations for this case indicate that instability would occur if the cavity pressure was increased beyond 70 cm H_2O. The simulation traces are in agreement with this. To some extent, this proves that the predictor-corrector scheme adopted is adequate. The earlier work on stability suggested that volume modulation due to waves would improve stability at 70 cm H_2O. Fig. 5 shows a preliminary trace from the simulation which shows this improvement in stability. Note that the frequency of the oscillation is basically unchanged by volume modulation. This is as predicted by the earlier work. The trace shown is not overly sensitive to things such as the spatial or temporal grid size used by the simulation or the details of the pressure variation (gradual/abrupt) near the lip. So, the improvement in stability is genuine. The earlier work also suggested that leakage flow modulation due to waves can degrade stability at low cavity pressures and make the craft undergo many stability transitions. For example, for the present geometry, it predicted a transition near 30 cm H_2O. Fig. 6 shows preliminary traces from the simulation which show such a transition. However, these traces are very sensitive to things such as the pressure variation near the lip: so more work needs to be done to confirm the trend. Note in each trace that the frequency of the oscillation is much lower than that of the overland traces. This is as predicted by the earlier work. The simulation is now being used to explore nonlinear phenomena.

REFERENCES

1. M.J. Hinchey and P.A. Sullivan, "On the Heave Stability of Hovercraft Hovering Over Water", Submitted to the Journal of Sound and Vibration, November 1988.

2. H. Lamb, "On Deep Water Waves", Proceedings of the London Mathematical Society, Series 2, Volume 2, November 1904.

3. B.D. Nichols, C.W. Hirt and R.S. Hotchkiss, "SOLA-VOF: A Solution Algorithm for Transient Fluid Flow with Multiple Free Boundaries", Los Alamos Scientific Laboratory, LA-8355, 1980.

ACKNOWLEDGEMENT

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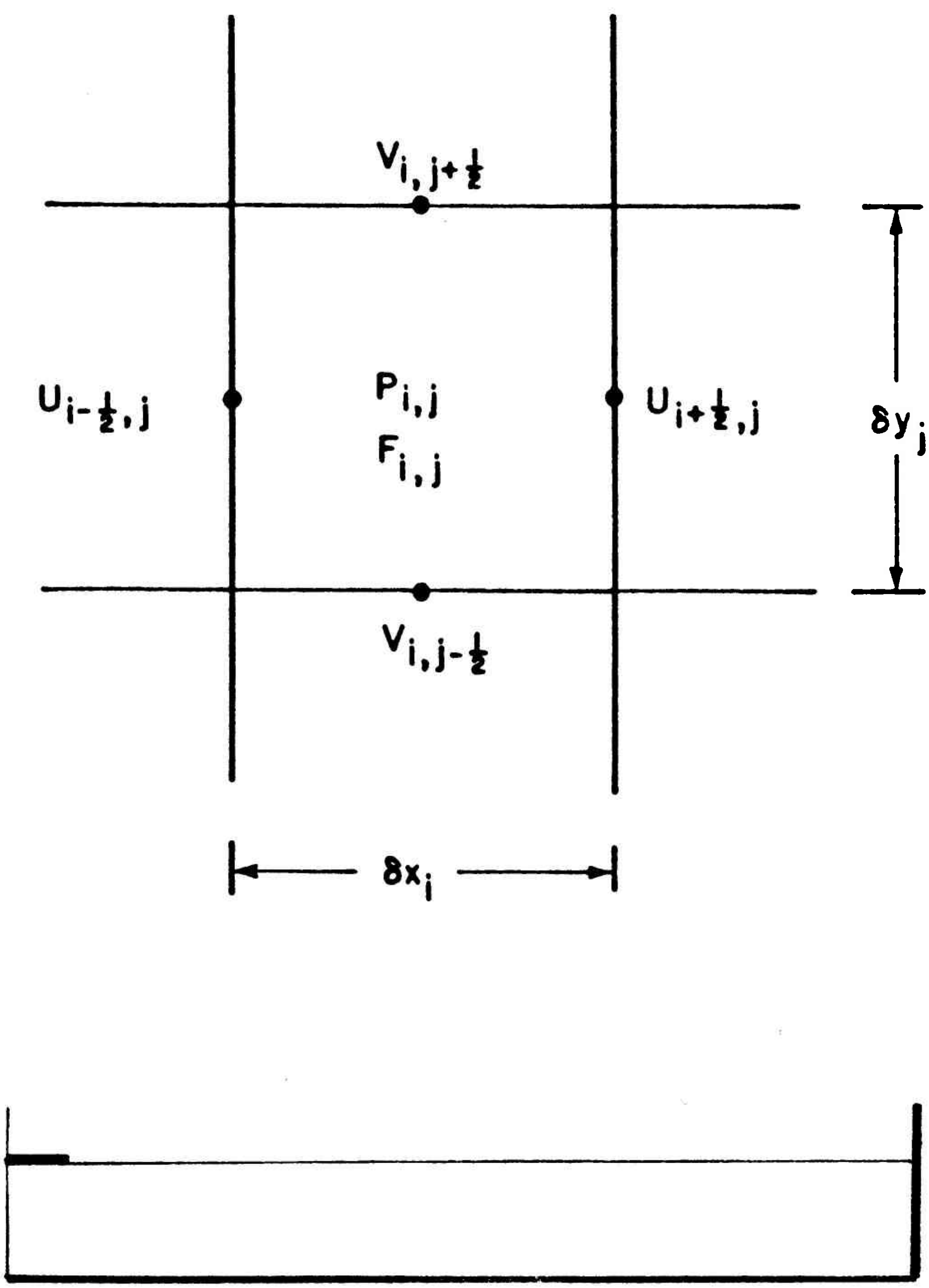


Fig. 1. Computational Domain for Hovercraft Simulation.

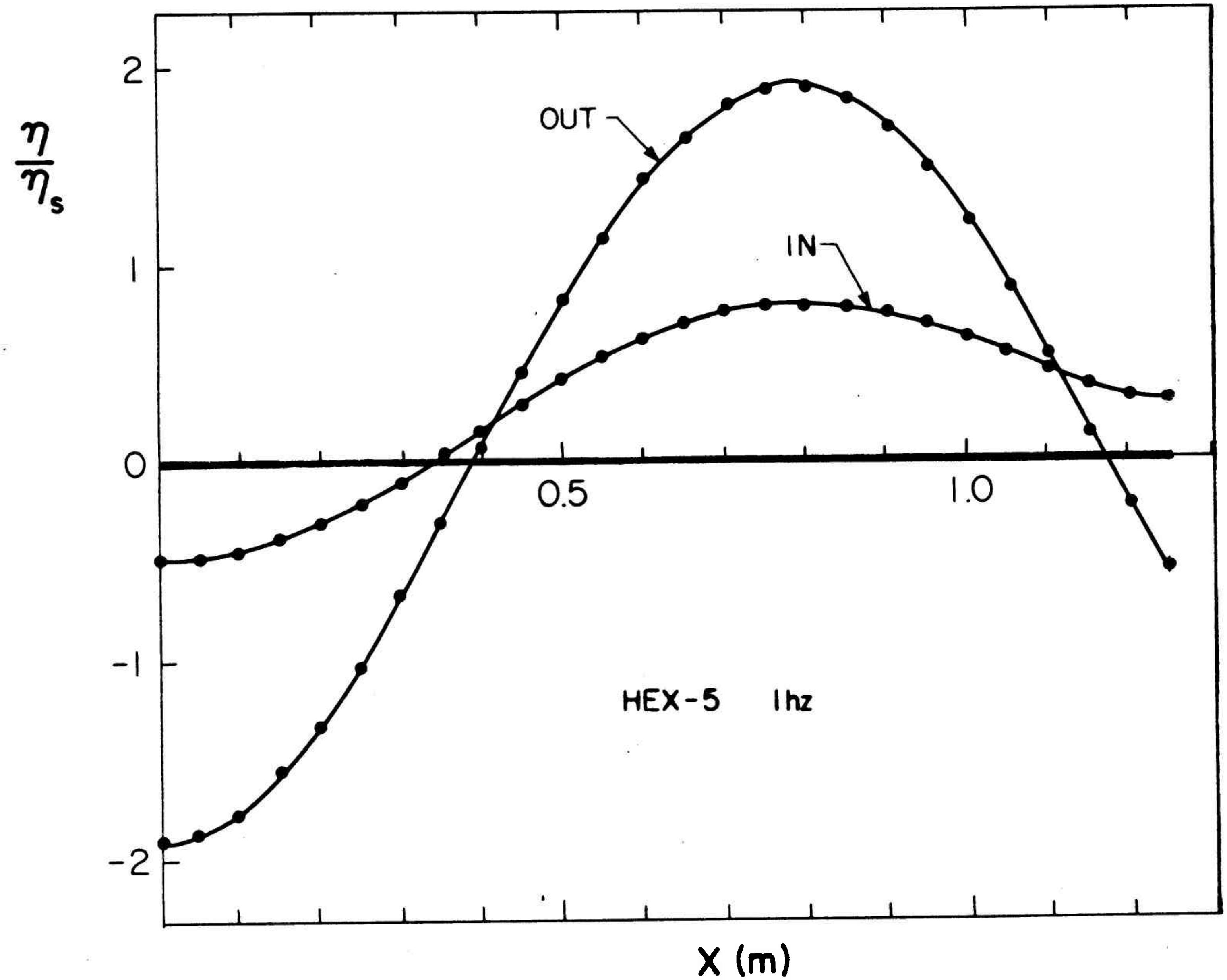


Fig. 2 Water Surface Profiles for HEX-5 from Lamb.

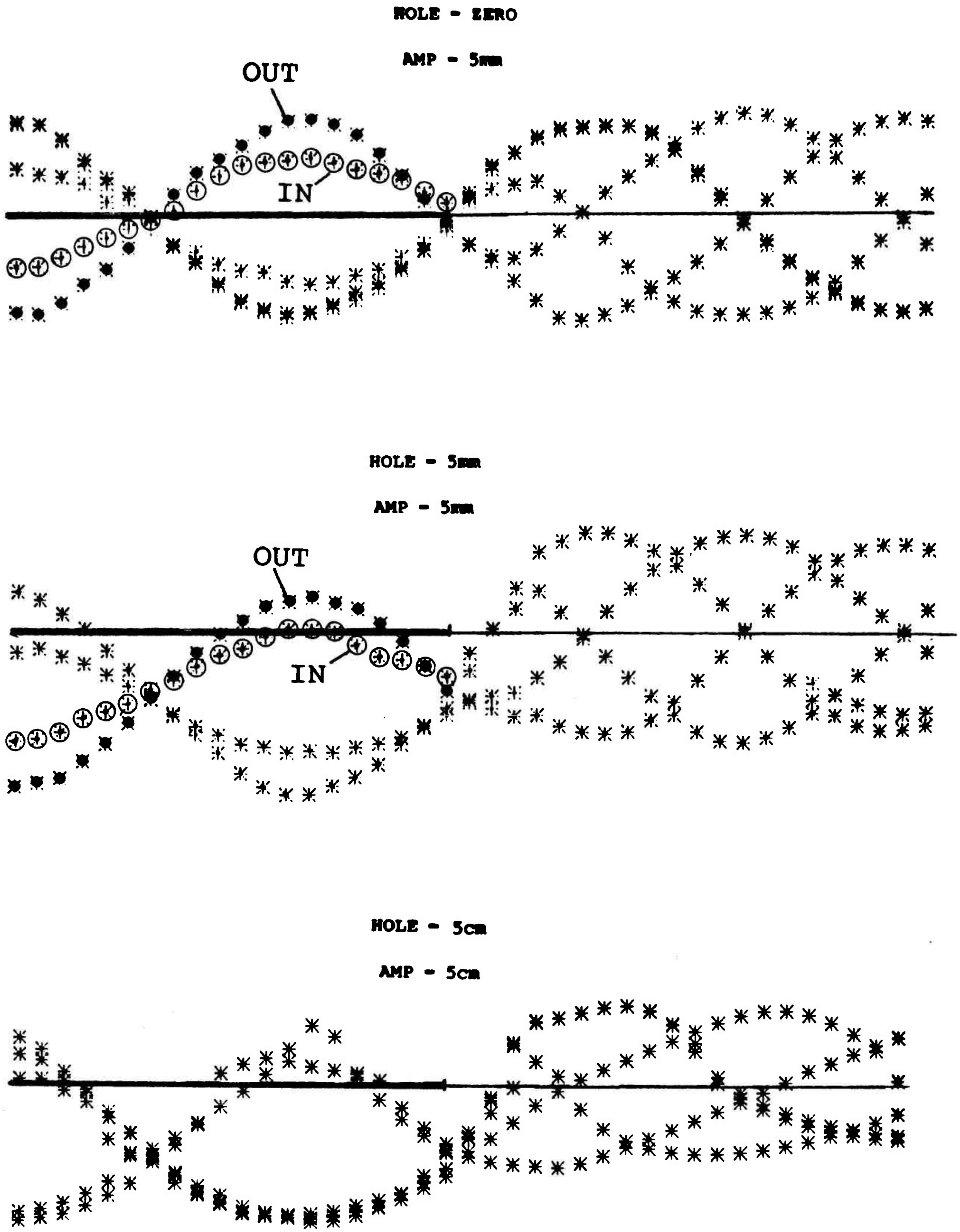
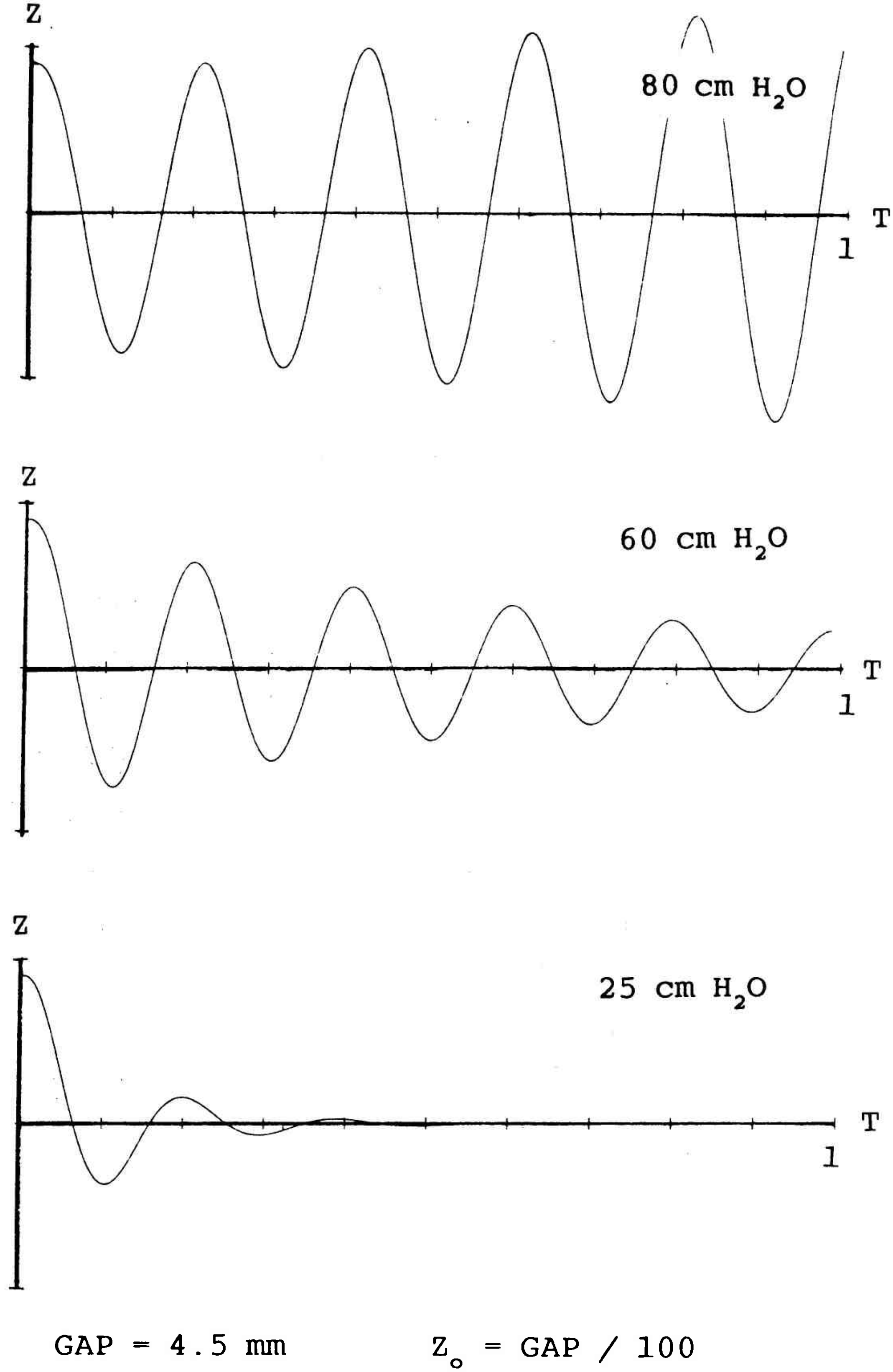


Fig. 3 Water Surface Profiles for HEX-5 from Simulation.



GAP = 4.5 mm $\qquad Z_o$ = GAP / 100

Fig. 4 HEX-5 Overland Simulation Traces.

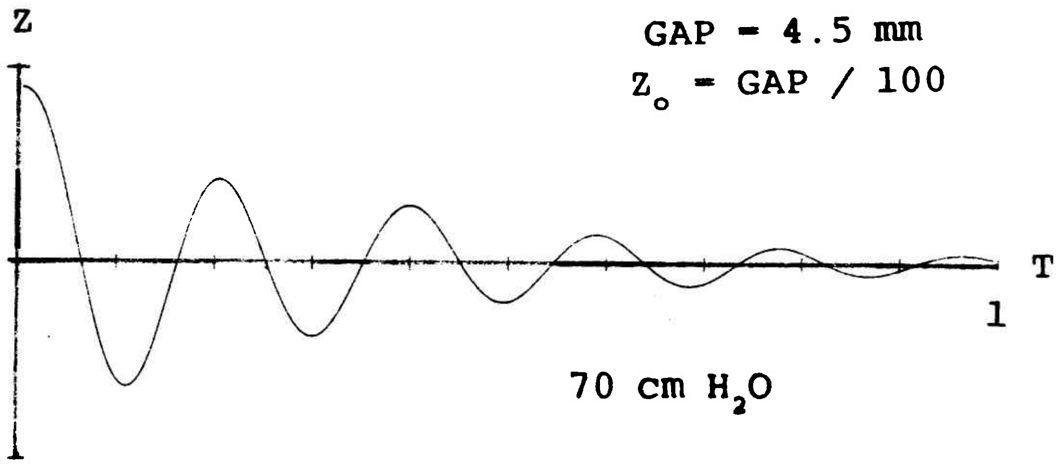


Fig. 5 HEX-5 Overwater Simulation: Cavity Volume Trace.

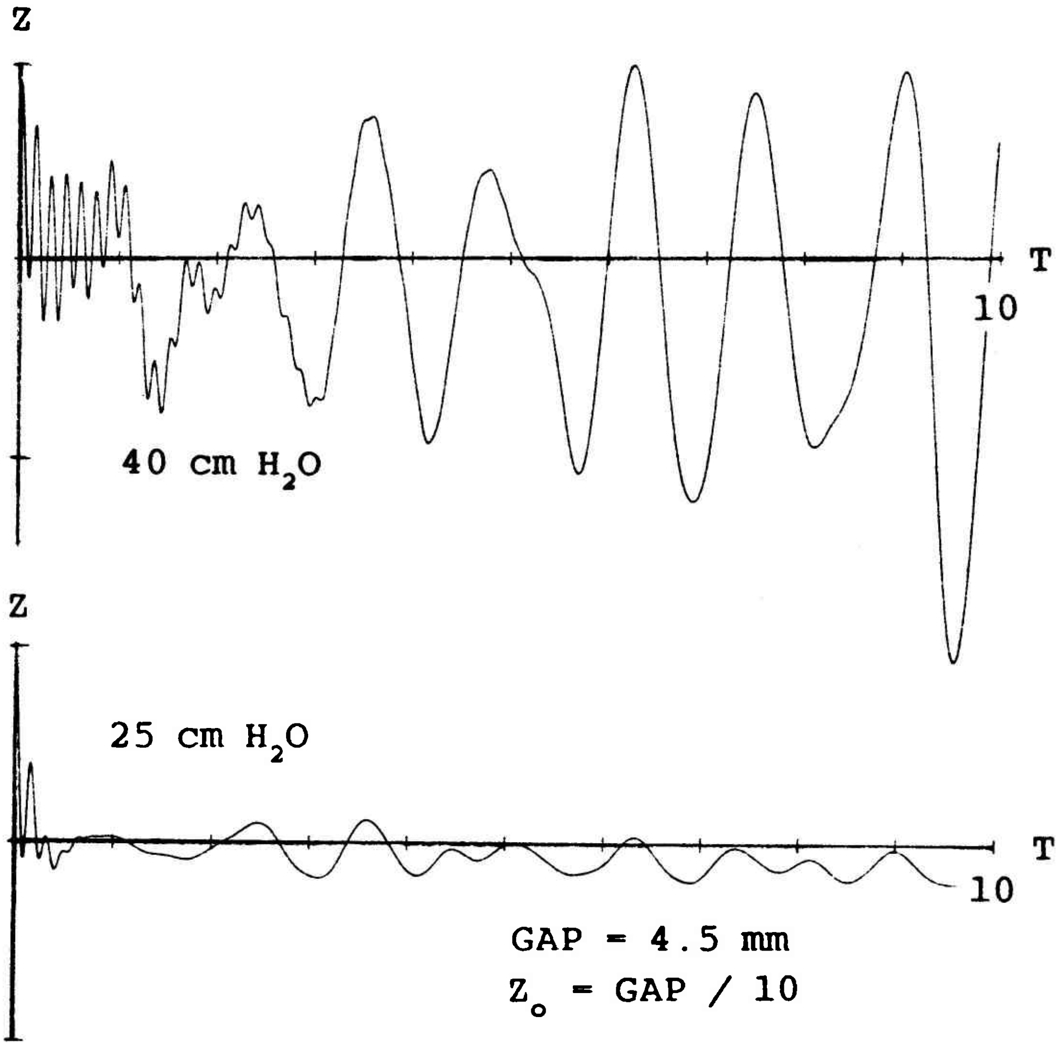


Fig. 6 HEX-5 Overwater Simulation: Leakage Flow Traces.