Water-Entry Pitch Modeling

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Water-entry pitch modeling studies were made using Froude- and cavitation-number scaling with and without gas-density scaling. Prototype missiles consisted of full-scale dummy Mk 25 aircraft torpedoes with 1.5- and 3.5-caliber ogive, a hemisphere, disk 0.25- and disk 0.1-caliber ogive, and disk-cylinder heads. These were launched at atmospheric pressure and nominal water-contact conditions of 400-fps velocity, −20.5-deg trajectory angle, and zero angle of attack. Two-in.-diam models were used but facility restrictions limited studies to approximately 5 calibers of missile water penetration. With Froude- and cavitation-number scaling, modeling to within the accuracy of the prototype data was obtained for all heads except the disk 0.1-caliber ogive, which showed the least change in water-entry pitch. The technique may be questionable for heads that show small change in water-entry pitch. Modeling obtained when Froude- and cavitation-number and gas-density scaling tests were made on the hemisphere, disk 0.1-ogive, and disk-cylinder heads. It is concluded that the technique is adequate for water-entry pitch modeling and can also be used to model missile water-entry and underwater trajectory in cavity behavior simultaneously.

Nomenclature

d	= diameter of missile body, in.
F	= Froude number, $F = v/(dg)^{1/2}$
g	= acceleration of gravity, ft sec^{-2}
h	= depth of missile below water surface, ft
I	= moment of inertia of missile about any transverse axis through the c.g., slug ft^2 or lb in.^{2}
l	= distance from nose to c.g. of missile, in.
m	= mass of missile, lb
p_a	= atmospheric (air or gas) pressure, lb ft^{-2}
$p_a + \rho_w gh$	= sum of hydrostatic and atmospheric pressures acting to collapse cavitation bubble, lb ft^{-2}; absolute pressure in undisturbed liquid
p_g	= sum of gas and vapor pressures in cavitation bubble acting to keep bubble open, lb ft^{-2}
R	= Reynolds number, $R = vd/\nu$
s	= missile water penetration measured along trajectory from point of water contact, ft
t	= time from instant of missile water contact, sec
v	= velocity of missile, ft sec^{-1}
v_g	= velocity of gas, ft sec^{-1}
α	= missile angle of attack in pitch, deg; angle in vertical plane between missile axis and direction of motion, positive in sense of nose-up rotation
λ	= modeling scale factor, $\lambda = d_m/d_p$
ν	= kinematic viscosity, ft^2 sec^{-1}
ξ	= trajectory angle of missile, deg; path angle with respect to horizontal plane, positive in climb
θ	= missile angle of pitch, deg; angle between missile axis and horizontal plane, positive in sense of nose-up rotation
$\dot{\theta}$	= pitch velocity, deg sec^{-1}
ρ'	= ratio of density of gas (irrespective of its associated conditions of temperature and pressure) to that of air at 20°C and 740 mm mercury pressure
ρ	= density of gas, slug ft^{-3}
ρ_w	= density of water, slug ft^{-3}
σ	= cavitation number, $\sigma = (p_a + \rho_w gh - p_g)/\frac{1}{2}\rho_w v^2$

Subscripts

m	= model missiles
p	= prototype missiles

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Introduction

THEORETICAL treatment of the water-entry modeling problems[1,2] indicates, that while Froude-number scaling† is necessary to scale inertial forces, cavitation-number scaling may also be needed to scale the pressure reduction in the undercavity of missiles entering water obliquely (underpressure effect). In addition, gas-density scaling may also be necessary to scale the gasdynamic pressure $\frac{1}{2}\rho v_g^2$, which could affect undercavity seal and therefore underpressure.‡ The Reynolds number, which is an index to boundary-layer condition, is not scaled, but for sufficiently high prototype and model velocities, the Reynolds number will correspond to transition close to the nose and the effect may be negligible.

The inadequacy of Froude-number scaling in water-entry pitch modeling[3] and the necessity for the additional constraint of cavitation-number scaling for missile oblique water-entry modeling[4,5] have been demonstrated experimentally. The need for gas-density scaling in water-entry cavity modeling has been shown[6] and, hence, the possibility of its need for undercavity scaling inferred. However, no experimental studies have been made to assess the adequacy of these scaling parameters for modeling the water-entry pitch behavior of missiles over the first missile length of water penetration, a very involved regime during which flow is established and forces due to fluid inertia, gas pressure, and gas density act on the missile and interact with each other in complex ways.

The purpose of the studies described here is to develop a technique for modeling pitch behavior of full-scale missiles entering water obliquely under conditions of cavity flow, over approximately one missile length of penetration. Spatial limitations on the model launching tank precluded modeling of the underwater trajectory. However, theory indicates that scaling conditions for which water-entry pitch may obtain also model the water-entry cavity, and, therefore, missile underwater trajectory in cavity behavior as well.

Modeling Technique

Froude-number, cavitation-number, and gas-density scaling are designated by the symbols F, σ, and ρ, respectively. For

† In this report the Froude scaling technique is defined as the launching of geometrically and dynamically similar models with model water-contact velocity scaled in accordance with the Froude law.

‡ G. Birkhoff first pointed out that air density causes cavity surface seal and must be scaled for cavity modeling.[1,2]

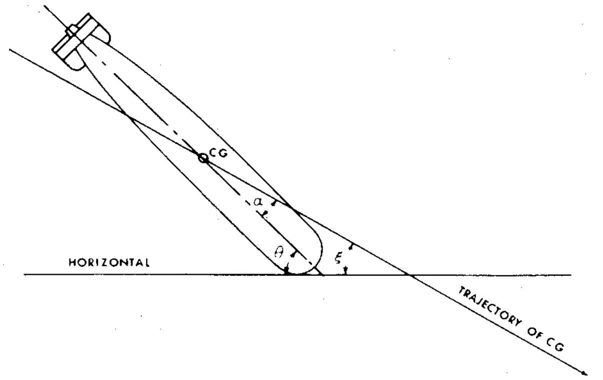


Fig. 1 Diagram of missile showing attack, pitch, and trajectory angles. All angles negative.

F, σ, and ρ scaling using water in both prototype and model systems,[1,2] model scaling constraints are $l_m = \lambda l_p$, $m_m = \lambda^3 m_p$, and $I_m = \lambda^5 I_p$. The atmospheric scaling constraint is $p_{am} = \lambda p_{ap}$ and the gas-density constraint is $\rho_m = \rho_p$. For trajectory similitude, $s_m = \lambda s_p$ and $t_m = \lambda^{1/2} t_p$. Other model-prototype relationships (also model launching constraints) are $v_m = \lambda^{1/2} v_p$, $\xi_m = \xi_p$, $\theta_m = \theta_p$, and $\lambda^{1/2}\dot{\theta}_m = \dot{\theta}_p$ for corresponding model and prototype positions and times. It is assumed that missile yaw angles are sufficiently small that their effect is negligible. Attack, pitch, and trajectory angles are illustrated in Fig. 1.

Full-scale missile water-entry data obtained in other studies were used as prototype data for modeling. Using the model launcher that was available, it was not always possible to scale prototype water-contact velocity and pitch velocity accurately, and corrections for scaling discrepancies were made in order to compare model and prototype data. These corrections were made to assess the modeling technique and not to overcome the limitations of the equipment.

It is evident that over one missile length of water penetration, small water-contact pitch velocities produce small changes in water-entry pitch, only slightly affecting the water-entry forces; the pitch due to water-entry forces should not be appreciably affected. Hence, the effect of water-contact pitch velocity would be additive and both prototype and model water-entry pitch may be corrected to zero water-contact pitch velocity as follows:

$$\theta_m(t_m) = \theta_{me}(t_m) - \dot{\theta}_{me}(0)t_m \tag{1}$$

$$\theta_p(t_p) = \theta_{pe}(t_p) - \dot{\theta}_{pe}(0)t_p \tag{2}$$

where the subscript e denotes experimentally obtained water-entry pitch and water-contact pitch velocity data.§

For some head configurations, it was necessary to correct the prototype water-entry pitch data to the nominal water-contact velocity. It was observed for these configurations that nearly all of the change in pitch velocity takes place soon after water contact. Therefore, the change in pitch velocity is very nearly impulsive and is closely connected with the change in the transverse velocity of the nose in the flow-forming stage. Now, for forces on the head which may be assumed proportional to $v_p{}^2(0)$, the time during which the forces are unbalanced (acting on the lower side of the head and not the upper side) varies as $1/v_p(0)$ so that the impulse will vary as $v_p(0)$. Therefore, the change in pitch velocity[7] is proportional to $v_p(0)$. Then for missile data that have been corrected to zero water-contact pitch velocity, we have very nearly

$$\theta_p(t_p) = cv_p(0)t_p \tag{3}$$

where c is a constant. Now let $v_p(0)$ be the nominal water-contact velocity and $v_{pe}(0)$ an experimental water-contact velocity, where $v_{pe}(0)$ differs slightly from $v_p(0)$ so that the character of the flow-forming stage and hence c remain unchanged. Then

$$\theta_{pe}(t_{pe}) = cv_{pe}(0)t_{pe} \tag{4}$$

and from Eqs. (3) and (4) corresponding times after water contact for which the change in pitch is the same as given by

$$t_p = [v_{pe}(0)/v_p(0)]t_{pe} \tag{5}$$

The pitch-vs-time data for the nominal water-contact velocity are determined from the experimental data by

$$\theta_p(t_p) = \theta_{pe}(t_{pe}) \tag{6}$$

where the relation between t_p and t_{pe} is given by Eq. (5).

Experimental Program

Prototypes

A series of prototype missiles with ogive and disk-ogive head configurations for which water-entry data were available[8] was selected for modeling. The head configurations (Fig. 2) range from the fine-nosed 3.5-caliber ogive to the blunt disk-cylinder, and include the hemisphere and disk 0.25-caliber ogive heads that have been used in practical application. The heads were attached to a dummy Mk 25 aircraft torpedo afterbody (Fig. 3a) 101.4 in. long. The head lengths ranged from 42.2–51.7 in., giving missile lengths of 143.6–153.1 in. (6.4–6.8 calibers). Missile parameters for the hemisphere head which are typical of all head shapes tested are shown in Table 1.¶ Missile diameters were all 22.42 in. and the centers of gravity were within 0.01 in. of the longitudinal axis of symmetry.

Launchings were made into fresh water and at atmospheric pressure from the fixed-angle launcher at the Morris Dam

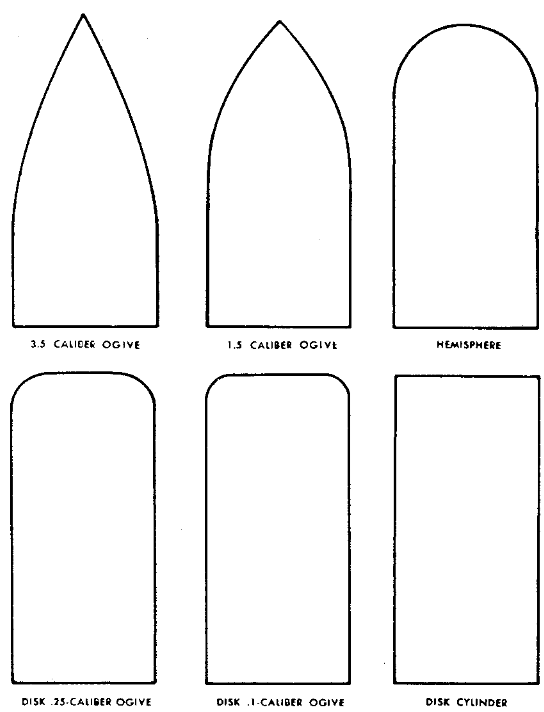


Fig. 2 Head configurations used in water-entry pitch modeling studies.

§ Times at which pitch, and both pitch and linear velocities obtain are given in parentheses.

¶ Prototype and model missile parameters and experimental data for all studies reported are available from the author.

Torpedo Range, San Gabriel Canyon, Azusa, Calif.[9] This launcher's angle of inclination is 19 deg with the horizontal. Launchings were made at a nominal water-contact velocity of 400 fps. Because of changes in the lake level and variations of the air trajectory due to variations in missile velocity, the actual trajectory water-contact angles ranged from −20.5 to −20.9 deg. Missile water-contact angles of attack (range: −1.6 to 1.4 deg) and yaw (range: ±2.3 deg) were small. Since model angles of attack and yaw were also small, the effect of these parameters was not considered in the modeling studies.

Calculation indicated that the cavitation number over one missile length of water penetration for all head configurations studied would be less than 0.05. Comparison of this low value with results from other studies[10–13] indicated that water entry would take place under conditions of cavity flow.

Water-entry pitch and velocity data were obtained by means of a flare camera. This camera and the methods for reduction and evaluation of the data are described in Refs. 7 and 9. Data were obtained for 2-msec intervals and the estimated instants of water contact are accurate to within ±1 msec.

Models

Two-in.-diam models of the prototype head configurations (Fig. 2) were used. Since the modeling studies were restricted to about one missile length of water penetration under conditions of cavity flow where the tail did not contact the cavity wall, it is reasonable to assume that the configuration of the afterbody and tail would have little or no effect on the water-entry pitch. Therefore, a cylindrical afterbody with a tail of simple design was used (Fig. 3b). The length of each head was 3.6 in. and the over-all length of each missile was 12 in. (6 calibers). The models were made of 24 ST Dural and had internal adjustable weights to achieve dynamical similarity to the corresponding prototypes.

The scale factor $\lambda = 1/11.21$. Typical scaled mode parameters and experimental data are given in Table 1. The center of gravity for all models was situated on the longitudinal axis of symmetry. Since the prototypes were launched at atmospheric pressure, the scaled model air pressure is 1/11.21 atm. The nominal prototype water-contact velocity is 400 fps, and the scaled model water-contact velocity 119.6 fps. Prototype and model nominal trajectory water-contact angle and angle of attack are −20.5 and 0 deg, respectively.

Model launchings were made into fresh water at a nominal water-contact velocity of 119.6 fps and $\frac{1}{11}$-atm abs air or gas pressure in the variable-angle variable-pressure launching tank[14] in the Hydroballistics Laboratory, Naval Ordnance Test Station, Pasadena, Calif. Water-contact yaws were small, lying within the range ±0.5 deg. The trajectory water-contact angle was −20.5 deg and the water-contact angles of attack were small, lying within the range −0.20–0.55 deg. Water-entry pitch and yaw data were obtained with the optical whip recorder[7,14] at intervals of 0.8 msec if the change in water-entry pitch was low, and 0.4 msec if the change was high. Simultaneous side-view camera data[14] were also obtained, permitting correlated analysis of the missile water-entry pitch and water penetration as well as water-entry cavity growth and development.

Table 1 Model and prototype parameters hemisphere head (Fig. 4c)

		Model, 2-in. diam	
Parameter	Prototype, 22.42-in. diam	Required by Froude scaling	Model used
Diameter, in.	22.42 + 0.020 − 0.010	2.0000	2.0000 ± 0.0002
Length, in.	154 ± $\frac{1}{8}$	...	12.0
Mass, lb	1526 ± $\frac{1}{2}$	1.083	1.084 ± 0.005
Distance from nose to c.g., in.	69.5 ± $\frac{1}{4}$	6.200	6.20 ± 0.01
Moment of inertia about transverse axis through c.g.	771 ± 5 slug ft^2	20.19 lb in.^{2}	20.12 ± 0.15 lb in.^{2}
Contour tolerance, in. on radius	0.040	...	+0.000 − 0.001

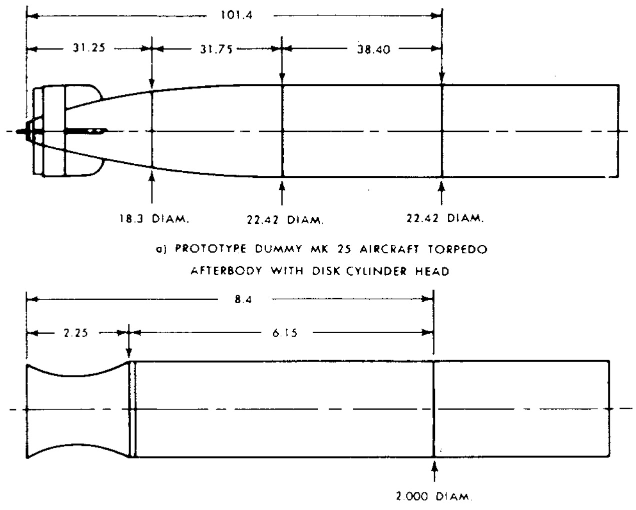


Fig. 3 Prototype and model afterbody configurations used in modeling studies. Dimensions in inches.

For F and σ scaling, the models were launched with $\frac{1}{11}$-atm abs air pressure over the water surface, and when ρ scaling was added a heavy gas was used at the same pressure. The lack of a sufficiently heavy gas precluded scaling the gas density completely, but the results of the partial scaling that was achieved may be of value in assessing the merit of F and σ scaling where the gas density is completely scaled. This is discussed later.

Since average ambient conditions of temperature and pressure at the Morris Dam Torpedo Range (where prototype tests were conducted) and the Hydroballistics Laboratory approximated 20°C and 740 mm of mercury, it was convenient to define 1 atm as 740 mm of mercury. Gas densities are described in terms of a gas-density coefficient ρ', which is the ratio of the density of the gas to that of air at 20°C and 740 mm pressure.

The partial gas-density scaling was obtained with the heavy gas Freon 114B2 (dibromotetrafluoroethane),[15] which has a density nine times greater than air under the same conditions of temperature and pressure. However, dilution of the gas with water vapor decreased the gas-density coefficient. The gas-density coefficient for equilibrium gas-water-vapor mixtures at $\frac{1}{11}$ atm in the presence of water is 0.69 at 20°C and 0.79 at 10°C. Therefore, there would be an appreciable gain in partial scaling by chilling the water to 10°C. The increase in water density at 10°C over that at 20°C is only 0.15%, which could be ignored. For these reasons, the tank water was chilled to 10°C for the launchings that involved gas-density scaling.

The variable-angle variable-pressure launching tank was evacuated to the vapor pressure of the water and the residual air "washed out" with Freon, after which the tank pressure was brought to $\frac{1}{11}$ atm. In order to insure homogeneity, the gas was stirred by a small fan in the dome of the tank. Immediately before launching, the fan was stopped and a gas sample withdrawn. The gas sample, taken at tank pressure, was drawn into a calibrated gas-density balloon and the gas density determined gravimetrically.

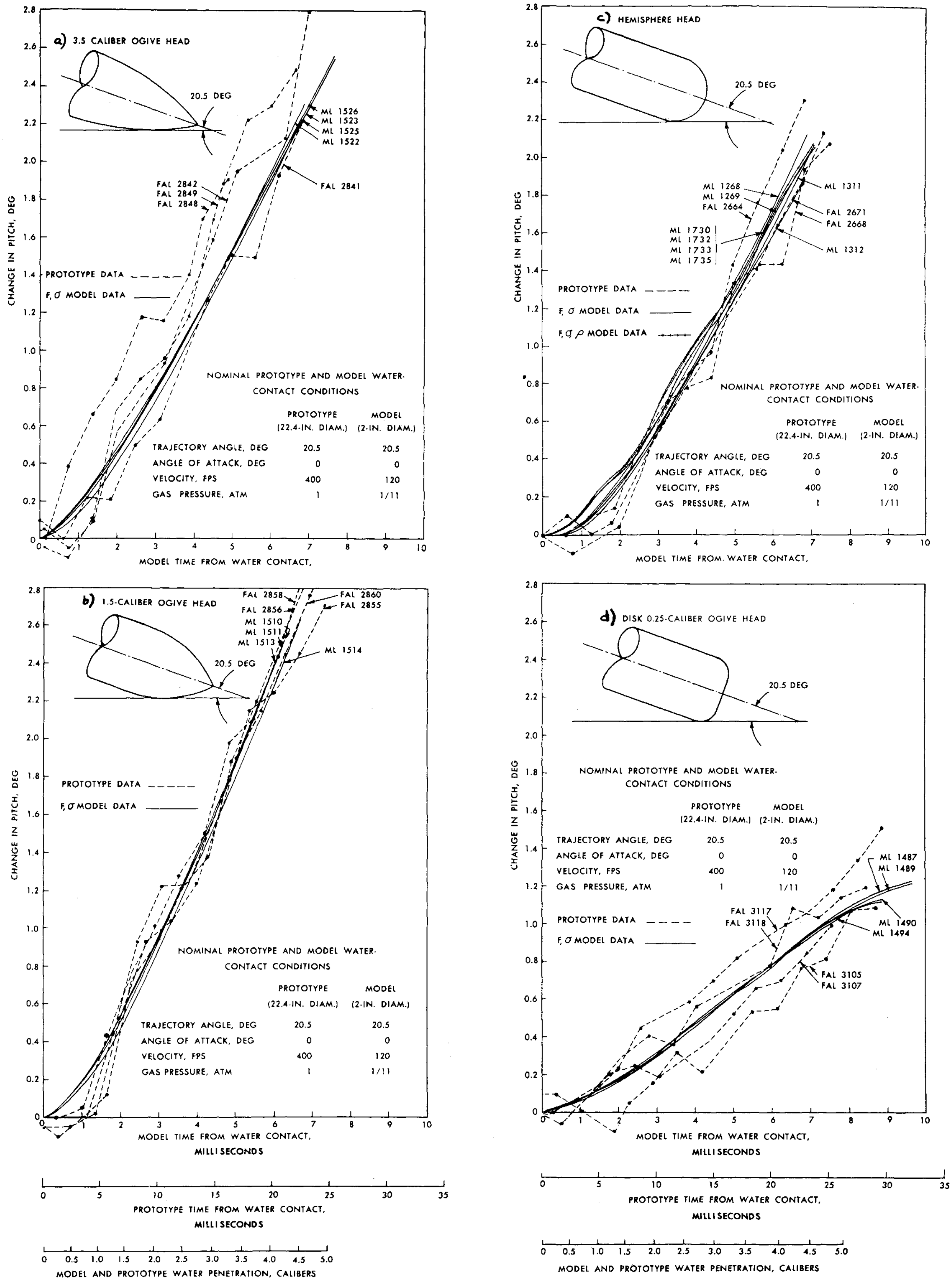
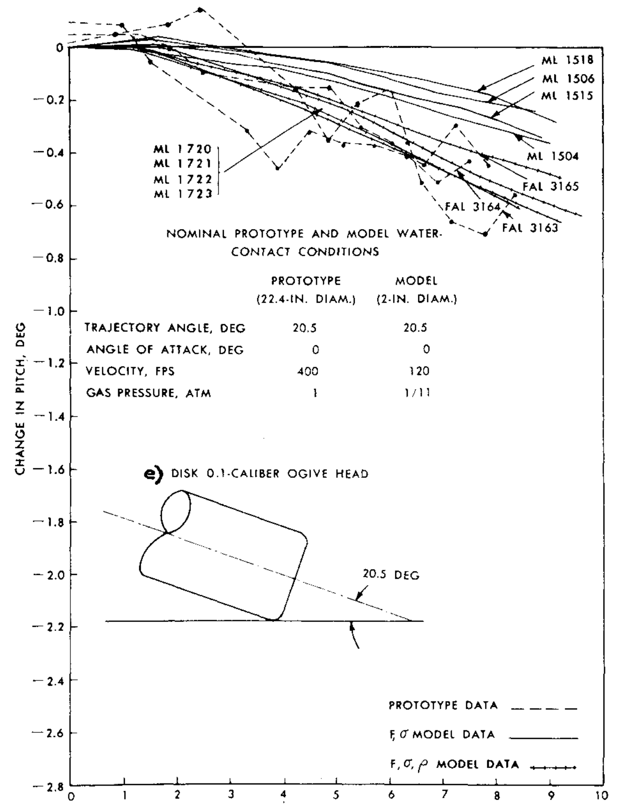
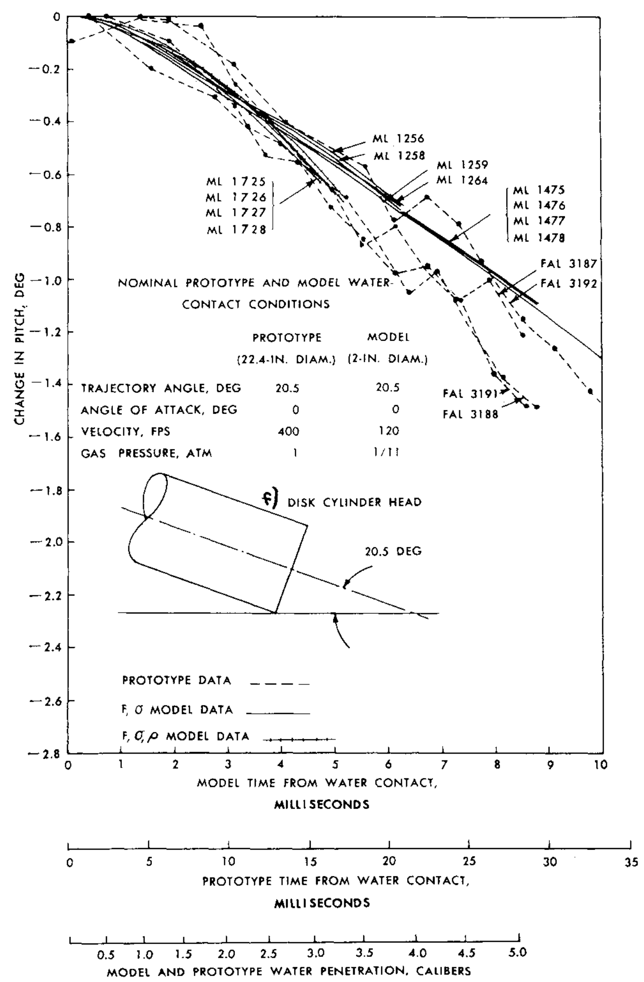


Fig. 4 Prototype and model water-entry pitch data; Figs. 4e and 4f on next page.





Figs. 4e and 4f (caption on preceding page).

Results

F and *σ* Scaling

Modeling studies with F and σ scaling were made with all head configurations. With four head configurations, the prototype water-contact velocities were as much as 11% above the nominal water-contact velocity of 400 fps. No attempt was made to Froude-scale these higher velocities since the model launcher was operating at its extreme upper range. It was considered better to launch the models at 119.6-fps nominal water-contact velocity and correct the prototype data to 400-fps nominal water-contact velocity. Since the prototype velocity correction was, at most, 11%, it was felt that this correction would not modify the validity of the data for the modeling studies. No correction was made for the small deviations in model water-contact velocities.

The model and prototype water-entry pitch data are shown in Figs. 4a–4f.** Model data are denoted in the figure legends as "F, σ Model Data." Both model and prototype water-entry pitch data have been corrected to zero water-contact pitch velocity and are shown as the change in pitch after water contact. The model and prototype time scales are in the ratio $1:(11.2)^{1/2}$, which should obtain for modeling. In addition, the model and prototype water penetration was measured. The penetration, expressed in calibers, was plotted to the respective model and prototype time scales and compared. The agreement was good. In no case did the model and prototype penetration data for corresponding scaled times deviate more than 7% over a penetration range of 5 calibers, which was the actual limit of comparison.

A third scale was constructed by plotting the averages of the model and prototype penetration expressed in calibers for corresponding scaled times. This scale is also given in Figs. 4a–4f. The deviation of experimental data from this scale is at most 3.5%.

For the disk-cylinder head the modeling equipment did not yield data beyond about 4 calibers of missile motion. To extend the range of penetration, the equipment was programmed to obtain data over a later range, extending the total to 5 calibers. Water-contact pitch and pitch velocity data could not be obtained for these launchings, but since these were nearly constant for successive launchings, the values from previous launchings were used for data correction. The data for the extended-range launchings (ML 1475 to 1478 inclusive) are shown in Fig. 4f for a range of 4 to about 5.5 calibers of water penetration.

F, *σ*, and *ρ* Scaling

Modeling studies with F, σ, and ρ scaling were made for the hemisphere, disk 0.1-caliber ogive, and disk-cylinder head configurations. The model and prototype water-entry pitch data are shown in Figs. 4c, 4e, and 4f. The data were corrected to zero pitch velocity and are shown as the change in pitch after water contact. The data are denoted in the figure legends as "F, σ, ρ Model Data."

Discussion of Results

F and *σ* Scaling

From Figs. 4a–4f it is seen that water-entry pitch modeling to within the accuracy of the prototype data was obtained for five head configurations. For the disk 0.1-caliber ogive head, the change in nosedown pitch was about half that of the prototype, and modeling was not obtained. From its position in the series it is not immediately apparent why this head was not modeled. However, the change in water-entry pitch for this head was smaller than that of the other heads tested, and consequently the pitch-inducing force, which is the resultant of hydrodynamic and underpressure forces, was also small. The configuration of this head indicates that the

** FAL (prototype launching) and ML (model launching) numbers are in-house designations.

hydrodynamic component of the pitch-inducing force is small and in the same direction as the underpressure force. Therefore, it would be expected to be more sensitive to nonmodeling of the underpressure force due to nonscaling of the gas density than heads such as the hemisphere or disk-cylinder, whose configurations indicate that the hydrodynamic component of the pitch-inducing force is appreciable. The dispersion of the model data curves is also indicative of the sensitivity of the disk 0.1-caliber ogive head and the preceding conclusion seems to be substantiated by further studies on the heads with the added condition of gas-density scaling. This will be discussed later.

In summary, the results indicate that while water-entry pitch modeling with F and σ scaling may be adequate for head configurations that show decided change in water-entry pitch, the technique is questionable for heads that show small pitch change.

F, σ, and ρ Scaling

Since the results of modeling tests using F and σ scaling indicated that this technique is not completely adequate for water-entry pitch modeling, it was decided to extend the tests to include gas-density scaling. Tests were restricted to three head configurations, the hemisphere, disk 0.1-caliber ogive (for which modeling was not previously obtained), and disk-cylinder. Complete gas-density scaling could not be obtained, as previously stated. However, it is believed that the results obtained with 0.7–0.8 complete scaling can be used to assess the feasibility of this technique where the gas density is completely scaled since other studies[16,17] indicate that there is very little change in the water-entry cavity using F and σ scaling when the gas density scaling is varied from 0.8 to 1.

From Figs. 4c, 4e, and 4f it is seen that water-entry pitch modeling to within the accuracy of the prototype data was obtained with F, σ, and ρ scaling where the gas density is at least 0.7 scaled. Modeling of the disk 0.1-caliber head configuration was obtained without any reduction in modeling agreement for the other two configurations with F and σ scaling. For the hemisphere head, the modeling agreement remained unchanged, while the disk-cylinder head showed increased nose-down change in pitch and the agreement appears to be better. Evidently, the inclusion of gas-density scaling results in proper scaling of the underpressure effect and water-entry pitch modeling is obtained.

The disk 0.1-caliber ogive head was very sensitive to gas-density scaling, the disk-cylinder was less sensitive, and the hemisphere head showed little or no sensitivity, indicating (as previously surmised) that heads that show small change in water-entry pitch are more sensitive to gas-density scaling.

The model water-entry cavity data for both scaling conditions were not sufficiently resolved to permit further investigation of this point. Although the complete set of head configurations was not tested and complete gas-density scaling was not achieved, the results indicate that water-entry pitch modeling within the accuracy of the prototype data will be obtained with F, σ, and ρ scaling. Since other studies[16,17] indicate that this technique models water-entry cavities for at least 20 calibers of missile underwater travel, it seems feasible that F, σ, and ρ scaling can be used to model simultaneously missile water-entry and underwater trajectory in cavity behavior.

Conclusions

With F and σ scaling, modeling to within the accuracy of the prototype data was obtained for all head configurations except the disk 0.1-caliber ogive. This head showed the least change in pitch at water entry and the discrepancy may arise from nonmodeling of the underpressure effect due to the absence of gas-density scaling. The F and σ scaling may be adequate for head configurations that show decided change in water-entry pitch, but the technique is questionable for heads that show small change.

With F, σ, and partial ρ scaling, modeling was obtained to within the accuracy of the prototype data for studies restricted to the disk 0.1-caliber ogive, hemisphere, and disk-cylinder heads. The results indicate that water-entry pitch modeling to within the accuracy of the prototype data will be obtained with F, σ, and ρ scaling.

The F, σ, and ρ scaling satisfies some of the scaling conditions for modeling the subsequent underwater trajectory. Since other studies indicate that this technique models water-entry cavities for at least 20 calibers of missile underwater travel, it seems feasible that F, σ, and ρ scaling can be used to model missile water entry and underwater trajectory in cavity behavior simultaneously.

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