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THE DEPTH-KEEPING CONTROL CHARACTERISTICS OF MORAY TV-1A

By

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PREFACE

The following paper escapes editorial classification only by virtue of the eventual inclusion of some estimated control force curves for MORAY TV-1A. It seemed timely, however, in view of the pending manned sea trials of the vehicle to discuss its control characteristics as they are presently understood, based on simulator experience, analysis, and considerable conjecture, to provide a focal point on the matter for those persons representing both technical and administrative functions who are to pass on the vehicle's readiness for sea. If it serves this purpose well, sufficient usefulness will have been demonstrated to satisfy the writer.

L. W. SEELEY

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ABSTRACT

Separate displays of vehicle attitude and rates, such as standard aircraft instrumentation presentations, have been found through simulation to be incompatible with torpedo-like submersibles when the human operator is in the primary control loop; their use results in an unstable operator-machine combination. Quickening the display, however, provides the necessary stability by tightening the control loop, and thus resolves many control problems. The theory of quickening is briefly described and the basic control problem of torpedo-like submersibles is discussed. These submersible control arguments point to the conceptual control advantage of winged submersibles. Finally, estimated control forces for various trim conditions are set forth for MORAY TV-1A and certain control system modifications are recommended which will, it is believed, further augment the operator-vehicle stability.

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LIST OF SYMBOLS

α	Angle of attack on body
α_{RP}	Angle of attack on pitch rudders
A	Area of maximum vehicle cross section = 22.34 ft^2
B	Vehicle buoyancy, including internal water
B'	$B/\frac{1}{2}\rho V^2 A$
$\Delta\gamma$	Flight path inclination from horizontal, positive up
CB	Center of buoyancy
CG	Center of gravity
C_T	Rudder axle torque coefficient; C_T = Torque/$\frac{1}{2}$ V^2
δ_{RP}	Pitch rudder deflection, positive trailing edges down
$\Delta\delta_{RP}$	Pitch rudder deflection from trim value
F_{CP}	Pitch control force required of operator; a pull is negative
ζ	Damping ratio
θ	Body angle from horizontal, negative nose down
$\dot{\theta}$	Body angular velocity
$\ddot{\theta}$	Body angular acceleration
k_i	Weighting factor in quickening equation
ℓ	Vehicle overall length = 33 feet
M	Hydrodynamic pitching moment, positive nose up
M_α	$\partial M/\partial \alpha$
M'_α	$M_\alpha/\frac{1}{2}\rho V^2 A \ell$
M_δ	$\partial M/\partial \delta_{RP}$
M'_δ	$M_\delta/\frac{1}{2}\rho V^2 A \ell$

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M'_θ	Metacentric moment coefficient; $M'_\theta = B z_B / \frac{1}{2}\rho V^2 A \ell$
o	Subscript denoting steady-state trim values
ρ	Water density; 2 slugs per cubic foot
ϕ	Arbitrary function
σ_i	Roots of characteristic stability equation
t	Time
V	Velocity
ω_n	Undamped natural frequency, radians per second
W	Vehicle weight, including internal water
$(W-B)'$	$(W-B)/\frac{1}{2}\rho V^2 A$
x_B	Longitudinal position of CG from CB, negative aft
x'_B	x_B/ℓ
z	Depth, positive down
$\dot{z}$	Vertical velocity
$\ddot{z}$	Vertical acceleration
z_B	Metacentric height; approximately distance CG is below CB
Z	Hydrodynamic normal force, positive down.
Z_α	$\partial Z/\partial \alpha$
Z'_α	$Z_\alpha/\frac{1}{2}\rho V^2 A$
Z_δ	$\partial Z/\partial \delta_{RP}$
Z'_δ	$Z_\delta/\frac{1}{2}\rho V^2 A$
$\left(\frac{dC_m}{dC_L}\right)_{FREE}$	Slope of aircraft pitching moment coefficient versus lift coefficient, with elevators free

INTRODUCTION

The purpose of this note is to summarize the present MORAY TV-1A control situation, and to recommend certain control system modifications to improve the control forces and the apparent vehicle control characteristics as seen by the operator. These recommendations stem from a simulator-demonstrated need to upgrade, in all ways practical, the basic stability of the MORAY TV-1A-operator combination. They are based on the well established art in aircraft design of intentionally arranging the control system dynamics to complement objectionable airframe dynamics, and thus yield good flying qualities from the pilot's point of view.

In these discussions, arguments are made on the basis that MORAY TV-1A's dynamic flight problem is in some respects the mirror image of the aircraft flight problem by virtue of the downward hydrodynamic force constantly required to offset the everpresent, net upward buoyancy force; a situation analagous to aircraft aerodynamic lift and gravity force equilibrium. It is recognized, however, that for the most part submersible and dirigible flight dynamics offer better comparison.

The organization of this note is impromptu. As a beginning the control history on the MORAY TV-1A flight simulator is reviewed, and it is observed that control of torpedo-like submersibles with basic aircraft flight instrument displays seems to be measurably more difficult than aircraft control, as an unstable operator-submersible combination results. It develops, however, that notwithstanding the above real difficulty the introduction of the simple but powerful technique of "quickening" the aircraft instrument displays to the operator effectively helps a number of control problems, and the theory of quickening is briefly described.

An attempt is then made to explain the poor pre-quickening simulator results by comparison of the aircraft and submersible control problem, and it is pointed out that a number of factors mitigate against the aircraft instrument display in a submersible, the chief one being the poor dynamic characteristics of submersibles, even stable submersibles, compared with aircraft.

Later in the report, estimated control forces at the stick produced by various level flight trim cases are presented for the current MORAY TV-1A configuration. Finally, desirable stick force characteristics are discussed and a means of providing them artificially in a direct, reversible mechanical control system, such as is employed by MORAY TV-1A, is described. These control system changes would improve the force "feel" characteristics of the controls and would artificially

provide "stick-free" stability. They would also reduce the requirement on the mercury system to one of providing emergency buoyancy only.

SIMULATOR RESULTS

Although the high degree of hydrodynamic stability of MORAY TV-1A is well known (references 1, 2, and 3), early flight simulator results demonstrated a pronounced operator-vehicle instability, when standard, basic aircraft flight instruments were used as the display to the operator. These results, reported in references 4, 5, and 6, show that the MORAY TV-1A vehicle could not adequately be controlled in level flight thereby, although steady state glides, climbs, turns, and spiral ascents were executed well by an experienced instrument pilot (reference 5). These latter results were obtainable, however, only by fixing the controls and accepting that forward velocity and climb or turn rate that resulted. Since MORAY TV-1A is hydrodynamically stable, this maneuvering control technique is workable.

In level flight, however, or depth-keeping as submariners call it, approximate rates will not do--the vertical velocity is required to be zero, and the depth deviation around the desired depth is reasonably expected to be no more than $\pm$ 1 foot as a maximum. Indeed, submarine operating personnel are very specific in requiring depth-keeping to as little as $\pm$ 6 inches for periscope operations (reference 7). Depth-keeping (and course-keeping) ability have, then, come to be primary measures of a submarine's controllability, although the recent advent of high speed, high performance fleet submersibles has introduced serious maneuvering control problems also. MORAY TV-1A's simulation history indicates, however, that its major control problems are depth-keeping (and secondarily course-keeping) as the results reported in references 4, 5, and 6 show depth-keeping error oscillations with amplitudes as high as two to three times the length of the vehicle. Therefore the depth-keeping problem is considered almost exclusively in this report, as in its solution we find and can examine the maximum number of control parameters.

In an attempt to improve depth-keeping a depth-error meter was provided but alone it was not particularly effective. Later a partially "quickened" display for depth-keeping, known locally as the target-meter display, was made available on the simulator and moderate improvements in depth-keeping were observed. In February 1963 Allyn Berryman and Roger Wickenden of the MORAY project group (Code 4064) introduced a fully quickened display which produced remarkable improvement in depth-keeping performance regardless of operator skill. A comparison summary of the relative effectiveness of the depth-error, target-meter and fully quickened displays on depth-keeping is made in reference 6, which the interested reader is earnestly urged to review. Reference 6 reports results which show that by use of a fully quickened display MORAY TV-1A

can continuously be controlled in depth to within ± 1 foot. Figure 1 demonstrates qualitatively the relative effect of the three displays not only on depth-keeping but on the work output required of the operator. The depth-error bias apparent in the target follower and quickened display traces of Figure 1 are due to the manner in which the displays were quickened, which is explained in the following section.

THE QUICKENED DISPLAY

Quickening seems to be a generic term coined by H. P. Birmingham and F. V. Taylor of the Naval Research Laboratory to describe their extremely useful control technique (reference 8) wherein position, rate, and other necessary weighted derived terms, depending upon the complexity of the system under control, are summed and the sum displayed to the human operator. The ameliorating effect of the technique on the control of difficult high order systems can be explained in various ways. It increases operator-machine stability by tightening the feed-back loop around the operator (reference 8). It eliminates the time delay usually observed by an operator between a control input and the system response, which is particularly advantageous with high-control-order* and long-time-constant systems such as are characterized by submersibles. Most important, quickening reduces the complexity of the submarine control task to one where simple motor skills predominate, i.e., simple position-tracking. It does this by reducing the requirement for perceptual skill on the part of the operator by relieving him of the necessity of mentally estimating rates, that is, differentiating. Moreover, it provides the operator with information showing him how to position his controls correctly. A pertinent example of the application of this technique is to the depth-keeping control of MORAY TV-1A.

For depth-keeping, the MORAY TV-1A operator desires to proceed at a constant depth z, and therefore he desires that the deviation Δz from the desired depth be zero. He will have much less trouble in attaining this goal if, throughout the time of interest, he can hold the vertical velocity $\dot{z}$ and the vertical acceleration $\ddot{z}$ to zero also. By quickening the operators display of Δz, i.e., adding $k_1\ddot{z} + k_2\dot{z} + \Delta z$ and presenting the sum to him, he need only position his control to hold all of the parts of the sum to zero, and the correct control motion is indicated by the deviation, if any, of the sum from zero. If a vertical acceleration develops, the operator can instantly take corrective action rather than acquire knowledge of the acceleration perturbation only after a time delay due to the two integrations to Δz. He is thus forewarned--the display is quickened---and from his standpoint the number of control orders of the system he is operating is effectively reduced by two.

* The number of integrations required of the operator in closing the control loop.

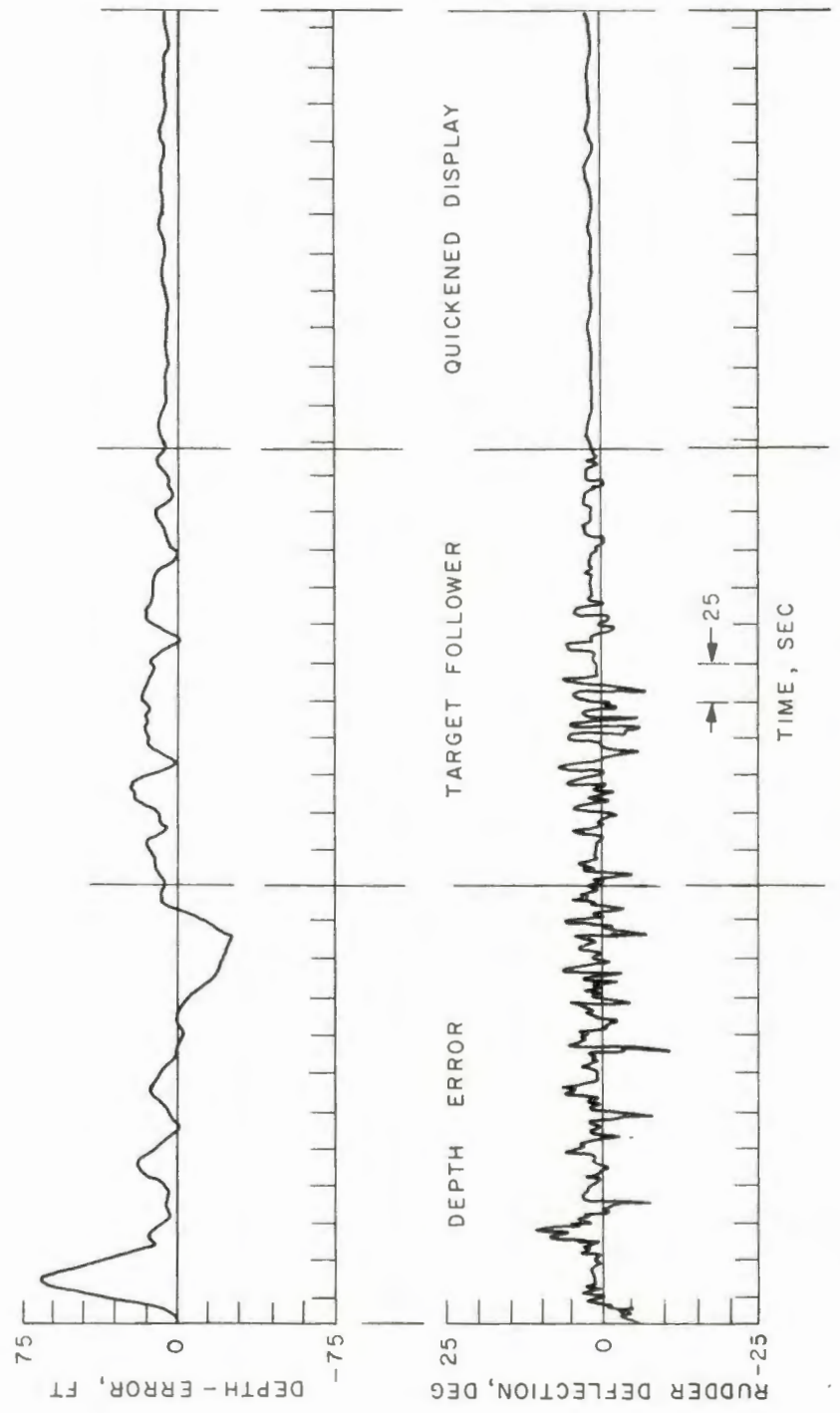

FIG. 1. REPRESENTATIVE SIMULATOR TRACES

Here is the power of the quickening technique. It is known to investigators in control theory (reference 7) that the results an operator wishes to achieve and the results he does achieve are not meaningfully related if three or more control orders are involved and if their time constants are long compared with the operator's time constant. Since four integrations are involved in the control of torpedo-like submersibles (Figure 2) and since their time constants are long compared with the operator's, the simulator-demonstrated inadequacy of the unquickened aircraft instrument display in the MORAY TV-1A vehicle can readily be understood. With the quickening scheme described above, the MORAY TV-1A operator can act on information only two control orders away from that which he actually controls, which is pitch angular acceleration $\ddot{\theta}$ caused by a deflection of the pitch rudder ($\Delta\delta_{PR}$).

Figure 2 is a block diagram representing the integrations that take place upon a step deflection of a submersible's pitch rudder. It is seen that perfect quickening would require the feedback of $\dddot{\theta}$, $\ddot{\theta}$, $\ddot{z}$, $\dot{z}$ and summing with Δz. The first quickening scheme described in this section employs only feedback of $\ddot{z}$ and $\dot{z}$. The "target meter" system described in the previous section fed back only $\Delta\theta$ (or θ as it was actually done). Berryman's and Wickenden's method, following a suggestion by Dr. Richard Pepler and Mr. J. C. Wohl of Dunlap and Associates adds, in addition, only $\Delta\delta_{RP}$ (actually δ_{RP}) thereby achieving full quickening and eliminating the necessity of measuring $\dddot{\theta}$, $\ddot{\theta}$, $\ddot{z}$ and $\dot{z}$ (Figure 3). That is, in addition to the body angle (θ) signal already available from the artifical horizon gyro, the method requires only the introduction of a signal proportional to pitch rudder deflection (δ_{RP}) which is readily at hand. One drawback to this scheme is that the use of signals proportional to the total angles θ and δ_{RP} instead of signals proportional to $\Delta\theta$ and $\Delta\delta_{RP}$ measured from level flight equilibrium values θ_o and δ_{RP_o} cause the depth bias seen in Figure 1. It is shown in Appendix B, however, that the vehicle can be trimmed with the mercury trim system so that θ and δ_{RP} are in the correct ratio to cancel bias errors. This display quickening simplification seems most desirable, judging from the simulator results.

Moreover, Berryman has demonstrated with operating breadboard hardware in conjunction with the simulator that these simple quickening signals can also be utilized for autopilot operation in lieu of the outputs of conventional rate sensors. Any future MORAY autopilot development should exploit this approach; not only is it in the basic NOTS tradition of accomplishing a difficult job simply, hence reportedly more reliably and economically, but an accomplished technical development here might well model innumerable future applications.

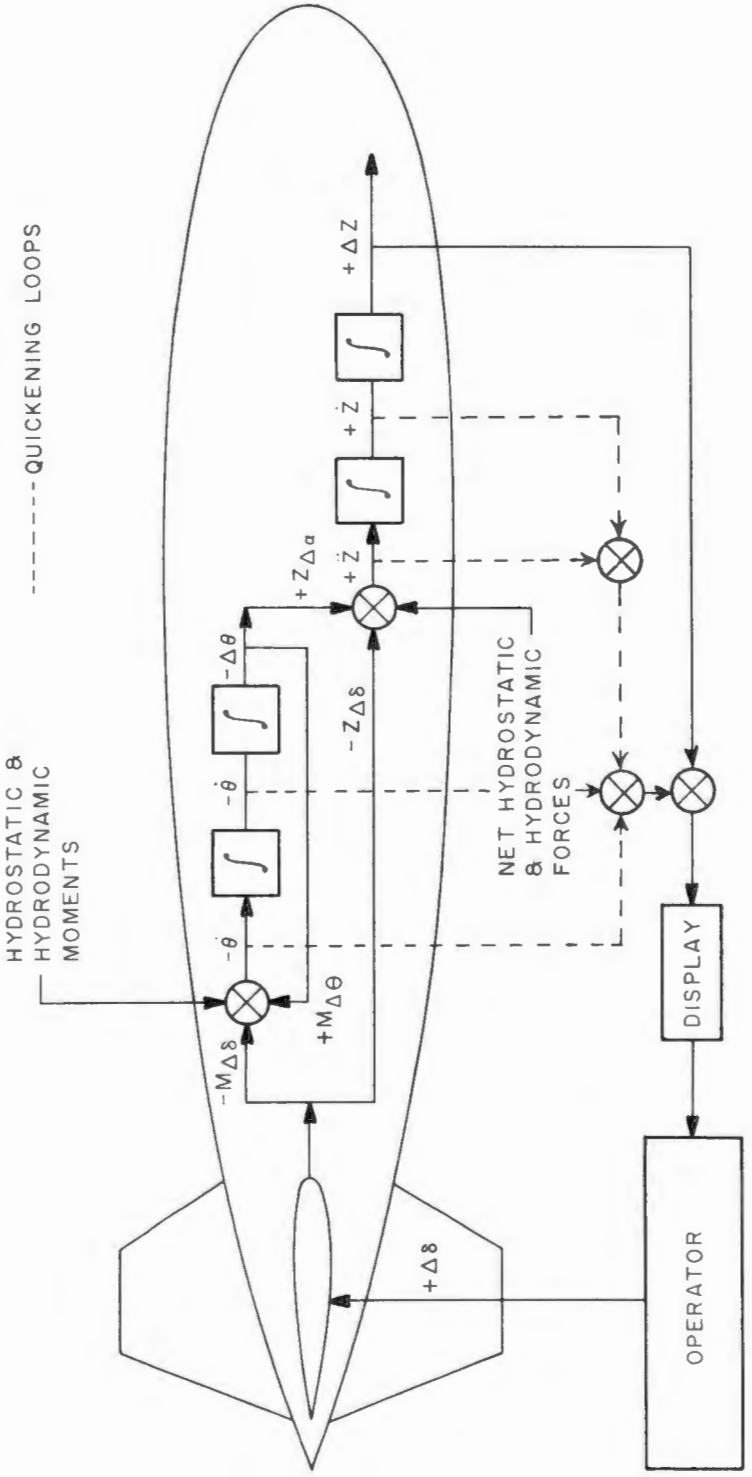

FIG. 2. BLOCK DIAGRAM OF DEPTH CONTROL WITH PERFECT QUICKENING

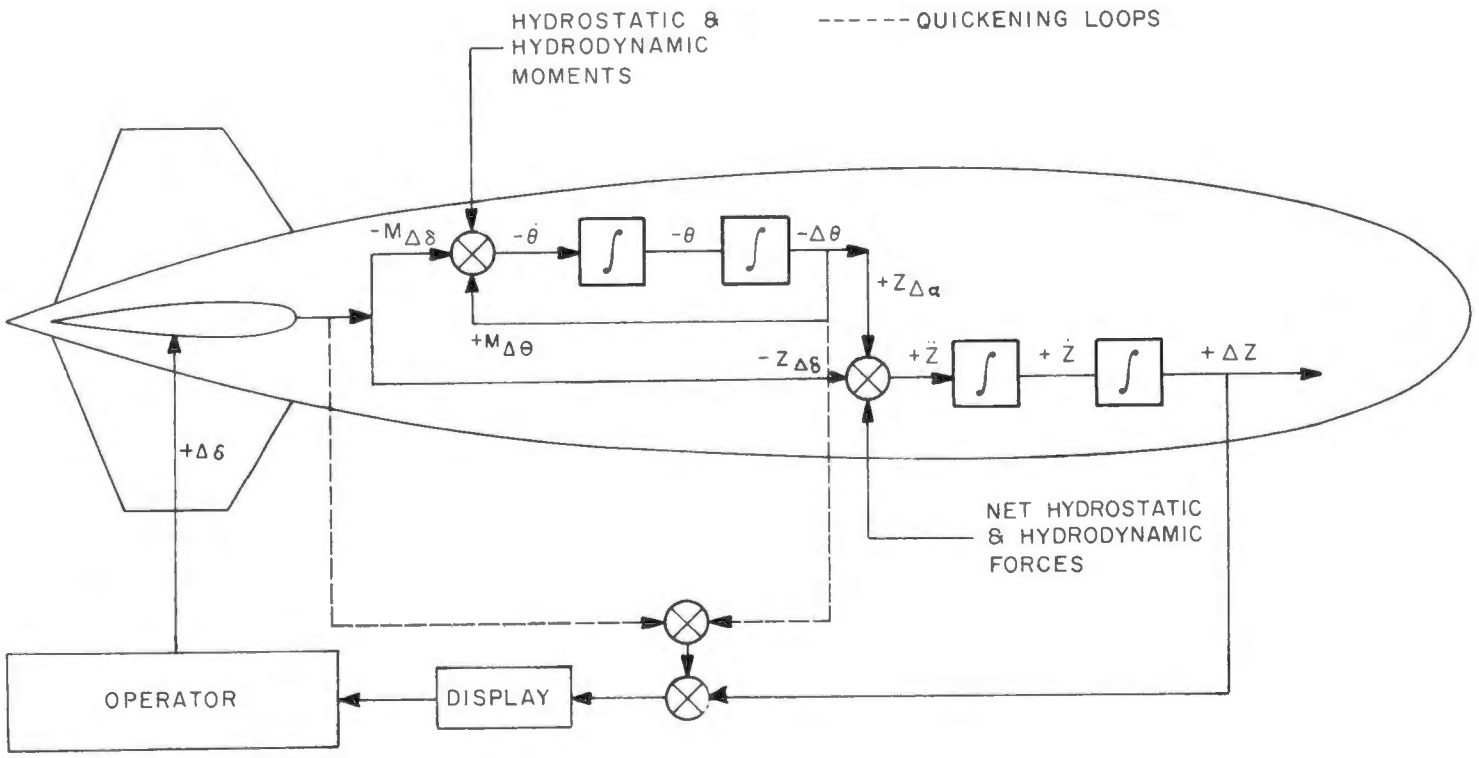

FIG. 3. BLOCK DIAGRAM OF DEPTH CONTROL WITH SIMPLIFIED FULL QUICKENING

THE CONTROL PROBLEM

The problem of display, however, arises only by virtue of the basic problem which is the poor dynamic characteristics of conventional submersibles for manual control. Bogden, et al, of the Cornell Aeronautical Laboratory say the following on this point in reference 7:

> "In the case of the submarine, its large degree of mass and inertia coupled with small hydrodynamic stiffness results in lags between input and output that are extremely large. It is primarily this result, namely that there are large differences in the response times of the operator and the submarine, that accounts for the inability of the operator to close the loop in a manner that produces fast, well-damped maneuvers. To compensate for the long time lag of the submarine, the operator attempts to speed up the submarine response by applying large initial control displacements. Because the time for the submarine to reach steady-state is so long, the maneuver is generally effected before a condition of steady-state equilibrium is attained. The operator has difficulty in ascertaining at what stage in the maneuver a pull-out or recovery should be initiated to quickly stabilize at the desired final conditions. In essence, attitude control and path control become completely intermingled, resulting in increased complexity of the control task."

Moreover, in a torpedo-like configuration sans bow planes such as MORAY TV-1A, a simple nose-down pitch rudder signal first puts a force on the vehicle in exactly the wrong direction, namely up. This is not an insignificant force as the pitch rudder force rate is on the order of the body side force rate for MORAY TV-1A (reference 2). The situation is salvageable only because, with time, as pitch angular rates develop, the angle of attack on the body increases as the angle of attack on the pitch rudders decreases and eventually the net down force becomes of sufficient magnitude to make its effect known to the operator. This mix-up in force direction further increases the time lag between input and vehicle response. The same effect appears, of course, in the yaw plane.

It is interesting to compare TV-1A's frequency response characteristics in pitch, then, with the pitch frequency response characteristics of aircraft, by virtue of the MORAY project's heavy initial reliance on aircraft instrument flying technology. Although the aircraft and the submersible have different solutions to their differential equations of motion, a revealing direct comparison can be made in the following way.

Figure 4 maps general areas of pilot opinion regarding desirable and undesirable flying qualities of aircraft (reference 10). The abcissa and ordinate employed are the frequency response parameters $2\zeta\omega_n$ and ω_n^2 respectively, where ζ is the dimensionless damping ratio and ω_n is the undamped natural frequency in radians per second, both of the aircraft's second order short period mode of pitch oscillation (see reference 11). Now although TV-1A's characteristic pitch stability equation is a cubic (12) with roots σ_1, σ_2, and σ_3 (Figure 5), the large, negative, stable root σ_2 can be disregarded* and a second order system with characteristic stability equation roots σ_1 and σ_3 assumed. If this is done to approximate MORAY TV-1A's frequency response characteristics, they can be computed directly from the roots σ_1 and σ_3 of Figure 5 since it can be shown that in the stable, unforced second order system

$$\ddot{\phi} + 2\zeta\omega_n\dot{\phi} + \omega_n^2\phi = 0 \qquad (1)$$

which has the solution

$$\phi = \phi_1 e^{\sigma_1 t} + \phi_2 e^{\sigma_2 t} \qquad (2)$$

and the characteristic stability equation

$$\sigma_i^2 + 2\zeta\omega_n\sigma_i + \omega_n^2 = 0 \qquad (3)$$

the following relations hold for all values of ζ :

$$-(\sigma_1 + \sigma_2) = 2\zeta\omega_n \qquad (4)$$

and

$$(\sigma_1\sigma_2) = \omega_n^2 \qquad (5)$$

Thus the sums and products of σ_1 and σ_3 taken from Figure 5 at various velocities are plotted for TV-1A in Figure 4, and it is seen that only at very low speeds, where the metacentric moment prevails

*This is often done, as in reference 13 for example. It is the effect of the longer-time-constant roots σ_1 and σ_3 which create the troublesome long response times characteristic of submersibles.

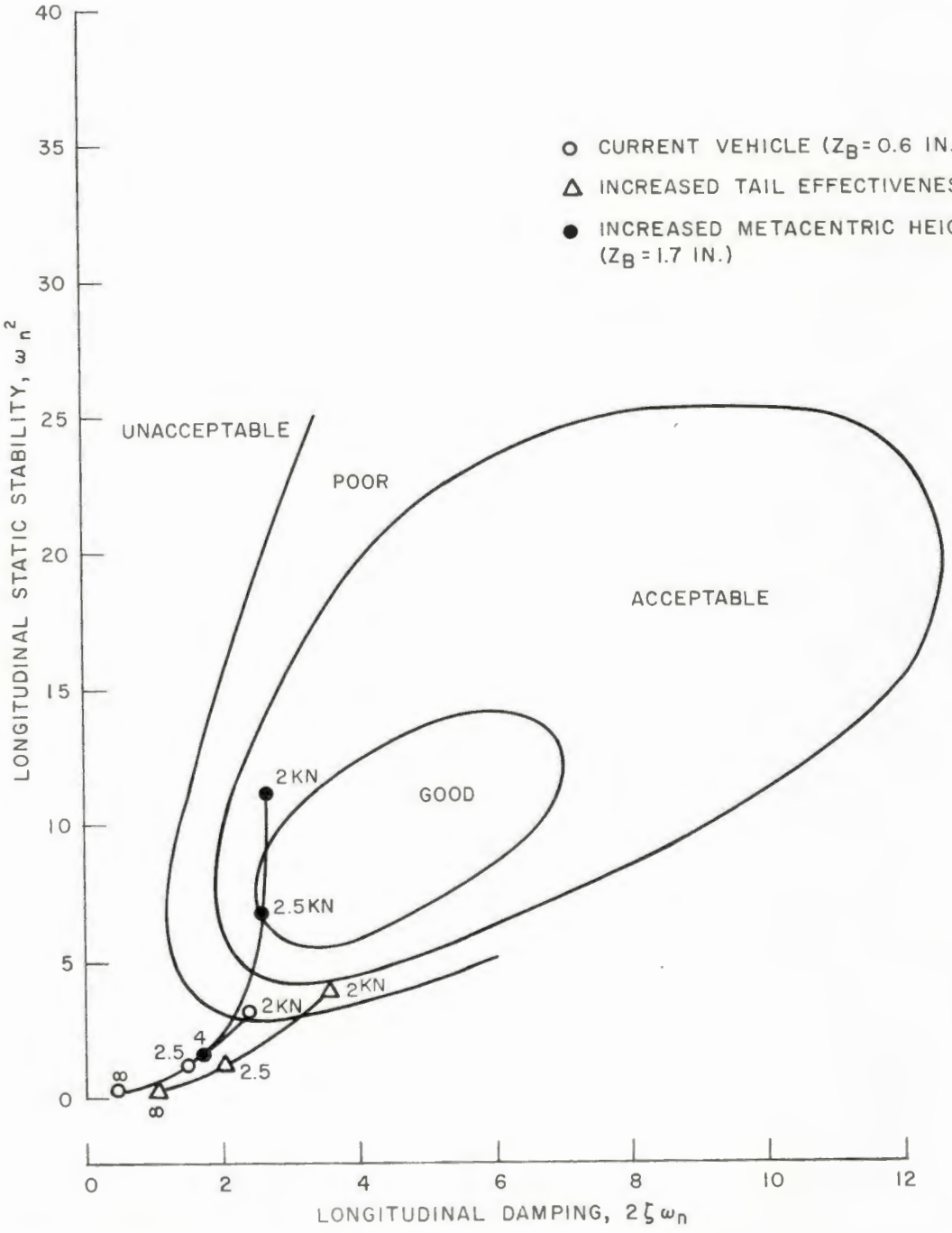

FIG. 4 MORAY TV-1A PITCH FREQUENCY RESPONSE CHARACTERISTICS PLOTTED ON MAP OF AIRCRAFT FREQUENCY RESPONSE CHARACTERISTICS DEFINED BY PILOT OPINION

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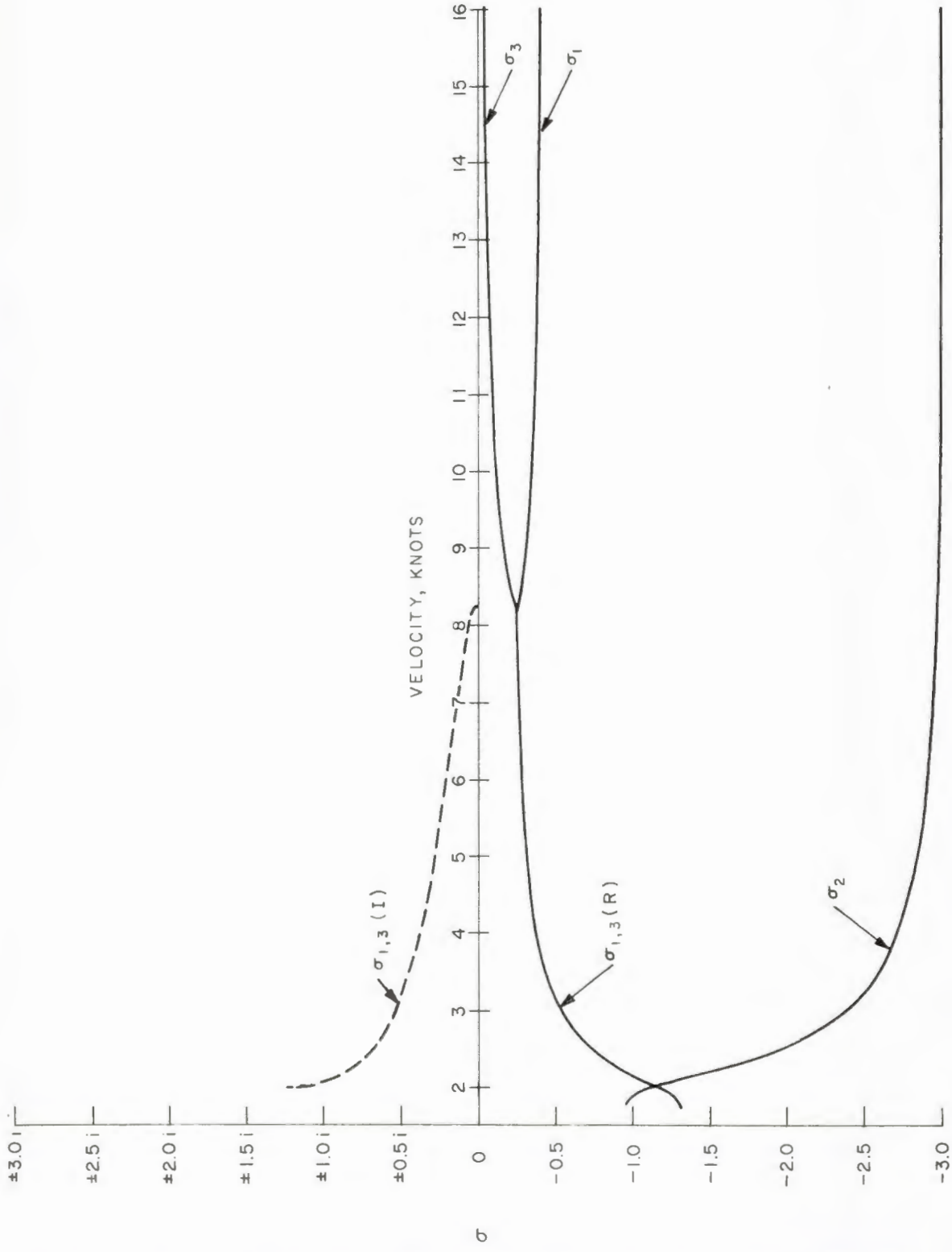

FIG. 5. VARIATION OF MORAY TV-1A PITCH STABILITY ROOTS WITH VELOCITY

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(12), does TV-1A even approach acceptable frequency response characteristics by aircraft standards. At the higher speed where the vehicle actually operates, the hydrodynamic moments prevail and the pitch motion is overdamped. By aircraft standards this is an unacceptable frequency response regime.

Another factor which further strains the capability of the aircraft display is the stringent, by comparison, requirement for depth keeping in submersibles. Although the block diagram of Figure 2 could serve for aircraft as well, since four control orders are also involved in the altitude control of aircraft, the writer understands that the actual technique is to first off control the horizon position (actual or artificial) which essentially represents the body angle θ, with only occasional, relatively casual references to the actual altitude. If this is the case, then the operator attempts to control θ primarily, which is only <u>two</u> control orders away from $\ddot{\theta}$. These integrations have sufficiently short time constants such that the operator has no other opinion but that he is effectively controlling θ (hence $\ddot{z}$) directly. This control technique is not possible in a submersible because it will not provide sufficient accuracy in depth-keeping. Moreover, in an aircraft the tail lift rate is small compared with the wing lift rate so the reversed tail force problem is minimal.

Still another tax upon the aircraft control scheme is the nature of the submersible's stability in equilibrium level flight. Although a mathematical demonstration can be made of this stability (reference 12, for example), the equilibrium is sufficiently tenuous and of such a character as to be not markedly apparent to the operator. For example, if a hydrodynamically stable submersible of conventional configuration was in fact in equilibrium level flight and then perturbed in pitch, it would undergo a slow, damped, transient at the end of which it would take up equilibrium level flight <u>but with a depth change</u>. Even were the operator sufficiently patient to wait out the long transient, he might then not be willing to accept the resulting depth change, which would require control action on his part after all. MORAY TV-1A has an enhanced problem in this regard as its metacentric height is quite small and it is only the metacentric moment which provides directional stability in pitch. Without it, a perturbation would result in the vehicle taking up and holding an inclined flight path.

Thus it appears that MORAY TV-1A can not, in practice, attain equilibrium (trimmed) level flight as easily as it is done with aircraft. An aircraft under the same assumed initial conditions would undergo a rapidly damped oscillation around its original flight path and attain equilibrium again at essentially its original altitude. This is due to the aircraft's high degree of static stability (aerodynamic stiffness). Were MORAY TV-1A to be made statically as well as hydrodynamically stable, the depth change problem described above would disappear but the vehicle's frequency response characteristics and time constants would not

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be markedly helped, as shown previously (Figure 4), and fins in excess of 90 inches in span would be required, resulting in a considerable drag penalty. This is not now recommended as the quickening technique seems to help alleviate this problem.

All of the above problems are compounded as the velocity increases. In addition, velocity contributes another problem which is still with us even after quickening. This, quoting reference 7, "is a consequence of the proportionalities of the hydrodynamic forces to the square of the velocity. Thus, whereas large control surface deflections are in order at low speeds, minute and precise plane positioning is vital to accurate control at the higher speeds". To explore this point the writer assumed incremental errors ($\Delta\delta_{RP}$) in the positioning of the pitch rudder, measured from the mathematically correct value δ_{RP_0} for equilibrium level flight, and computed the resulting flight path inclination $\Delta\gamma$, or rather the ratio ($\Delta\gamma/\Delta\delta_{RP}$). The resulting expression turned out to be

$$(\Delta\gamma/\Delta\delta_{RP}) = + \frac{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta}{Z'_\alpha M'_\theta} \qquad (6)$$

from the Davidson-Schiff theory (reference 16) employed in the following section of this report. Here Z'_δ and M'_δ are the force and moment coefficients with respect to pitch rudder deflection and Z'_α and M'_α are the force and moment coefficients with respect to body angle of attack. M'_θ is the metacentric moment coefficient which varies with velocity.

Equation (6) is plotted in Figure 6, and it is seen that at 3 knots, a one-degree error in position of the pitch rudder ($\Delta\delta_{RP}$) will produce an inclination of approximately 4 degrees in the flight path inclination. But at 15 knots, a pitch rudder error of as little as 0.1 degree will produce a flight path inclination of approximately 10 degrees. Obviously, at speed, the pitch rudder effectiveness needs to be reduced for depth keeping and a control system modification of the MORAY TV-1A vehicle is currently being made to provide vernier positioning of the control yoke, hence pitch rudder, at the operator's option.

It thus appears that the concept of direct aircraft displays in submersibles can be assessed, in retrospect, by saying that it is a case of installing a control scheme in a vehicle of unacceptable dynamic characteristics by the control scheme's standards, and then requiring the operator thereof to produce a trajectory of undue precision by the control scheme's standards. Again in retrospect, we would not expect good results. However, despite the negative evidence set forth above, the powerful quickening technique seems to make feasible the direct manual control of MORAY TV-1A.

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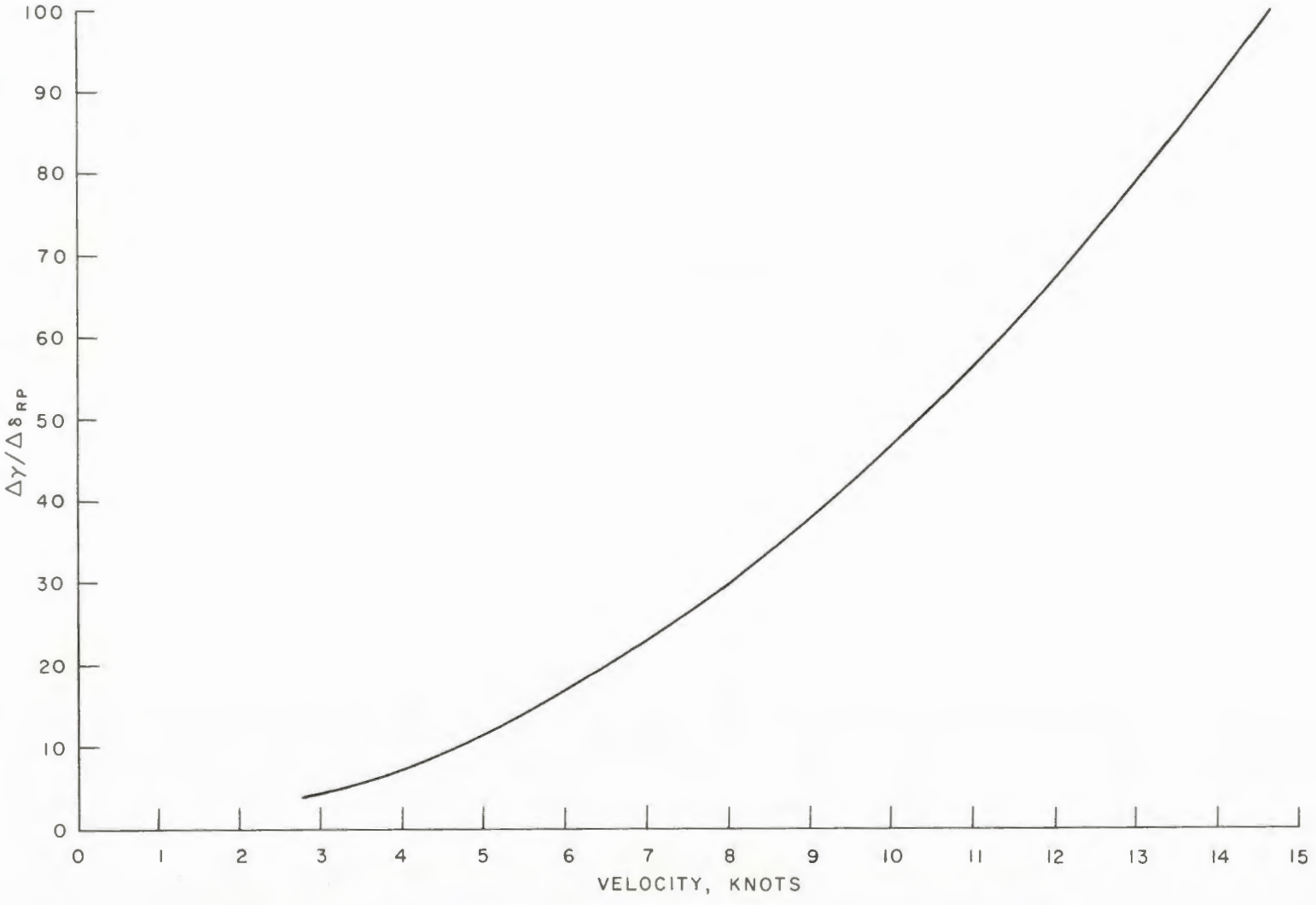

FIG. 6. RATIO OF RESULTING FLIGHT PATH INCLINATION ($\Delta\gamma$) TO PITCH RUDDER TRIM POSITION ERROR ($\Delta\delta_{RP}$) VERSUS VELOCITY (Small Angles Only)

At this point the writer desires to report a long-held conviction: that although little can be done to adequately improve the frequency response of submersibles by upping their hydrodynamic stiffness, the control orders (thus essentially the time constants) can be halved by letting the operator operate directly on $\ddot{z}$ of Figure 2, by giving him a SHRIKE-like configuration to control. This would also obviate the rudder force reversal problem mentioned earlier. It seems to the writer that from an ease-of-control standpoint the ultimate vehicle configuration one could contrive for use in a Newtonian sea would be a two-control-order vehicle; for example, a SHRIKE-like submersible. On this point, the stability-maneuverability advantages of winged submersibles are well delineated by Strumpf in reference 9. From the separate control standpoint this view needs simulator verification, and an experiment is scheduled for the near future. If the view is verified it means that submersibles (including torpedoes and MORAY TV-1A) have been configured incorrectly for the last century. It is entirely possible that in a two-control-order vehicle conventional unquickened displays of position, attitude, and rates might be completely adequate.

CONTROL FORCES

Because of the accent on depth-keeping control problems in this report, steady-state level-flight trim control forces seen by the operator will be examined for four level-flight trim cases of more than academic interest. Since the mercury trim system provides a wide range of possible center of gravity positions in the longitudinal direction (approximately $\pm$ 2 inches around the center of buoyancy), the following four cases of level flight trim can be considered:

Case 1: $\theta_o = 0$. Here the body is level, and the assumed net upward buoyancy of 350 lbs is offset by an equal down load on the pitch rudders. The resulting nose-up hydrodynamic moment is held in equilibrium by a buoyancy-gravity couple which requires that the center of gravity be ahead of the center of buoyancy. This mode of operation is considered potentially useful for leaving the surface with net upward buoyancy.

Case 2: $x_g = 0$. This trim mode has the center of gravity under the center of buoyancy where it normally would be with the vehicle at rest on the surface. It reflects an inoperative or non-existant mercury trim system, the latter desirable from a systems standpoint.

Case 3: $\delta_{PR} = 0$. This trim mode positions the center of gravity to provide trim with the control yoke, hence pitch rudders, in mid-position, i.e., zero deflection. It is conceptually useful, as it allows full pitch rudder throw for emergency maneuvering, if required, and also allows a spring centering device on the control yoke.

Case 4: $F_{CP} = 0$. Finally, a mode which results in no load at the control yoke (trailing rudders) is treated, as prior to the introduction of the control force bias scheme to be described in the next section, it was the only way the MORAY TV-1A operator could trim out control yoke loads.

Two tail configurations are considered. One, the current 78-inch span tail with its 13-inch span rudders oriented in an X configuration, and two, the same tail and rudder rotated 45° to the + orientation. This was done as several control and control system advantages accrue if pitch control and yaw control are physically separated, as they can be with the + configuration. For example, the pitch control system friction, inertia, viscous resistance and hydraulic system rubberiness would be halved. In addition, the yaw control force cross-talk through the current differential at the bottom of the yoke would be eliminated. Finally, the maneuvering capability of the vehicle in pitch and yaw could be set separately. On this point, the MORAY TV-1A vehicle is currently capable of doing outside loops in 3 lengths and this pitch agility does not seem completely necessary.

Until such time, however, as the surface running and submerging characteristics of the MORAY TV-1A vehicle are well understood, the X tail configuration should be retained as it will provide higher tail effectiveness in the pitch plane while underway on the surface. This is important, as it is known from model surface running tests (reference 15) that if tail pitch effectiveness is lost or reduced sufficiently, the vehicle will nose down abruptly to body angles exceeding 30 degrees and will submerge at high rates of descent. The submergence, in essence, is not controlled.

To come to the calculations, finally, all the control wheel and yoke couples and forces set forth here are based on the torque coefficient (C_T) versus angle of attack on the rudders (α_{RP}) curve shown in Figure 7. In the absence of model test data, this curve was estimated based on the pitching moment data for low-aspect-ratio wings set forth in reference 14. These data, although wind-tunnel data, were conveniently taken in a Reynolds number range appropriate to MORAY TV-1A's underwater velocity capability. The axle torques, then, resulting from specified trim conditions, are transposed directly to control yoke forces,

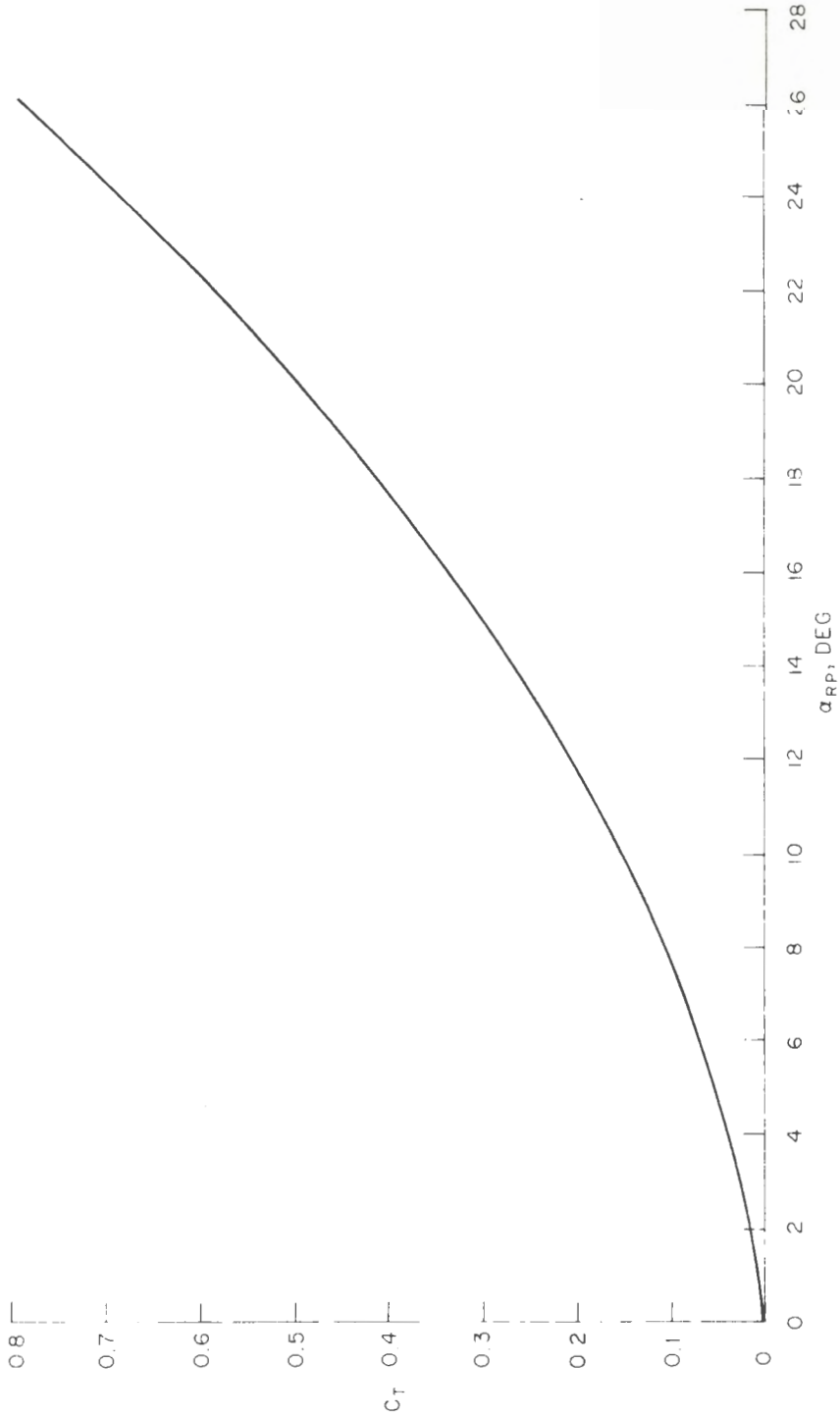

FIG. 7. CURVE OF ESTIMATED TORQUE COEFFICIENT VERSUS ANGLE OF ATTACK ON RUDDERS (FOR 4 RUDDERS)

employing the existing 1:1 gear ratio between yoke and rudder axles and employing the yoke lever arm of 1.36 feet. In the transposition, a frictionless and 100% efficient control system was assumed. This was done because the control system is currently undergoing a required major upgrading in this regard, and the final values of efficiency and friction are unknown at this time. This is not conservative, and these factors must be considered as soon as available.

From the steady state relationships for the neutral angles Θ_o and δ_{RP_o} (i.e., level flight trim angles)

$$\Theta_o = + \frac{(W-B)' M'_\delta - Z'_\delta B' x'_B}{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta} \qquad (7)$$

and

$$\delta_{RP_o} = - \frac{(W-B)' (M'_\alpha + M'_\theta) - Z'_\alpha B' x'_B}{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta} \qquad (8)$$

obtained in reference 12 in the solution of MORAY TV-1A's pitch plane equations of motion, the required body angle Θ_o, the pitch rudder deflection δ_{RP_o}, the center of gravity location x_B, and the resulting angle of attack α_{PR} on the pitch rudders were each calculated, as pertinent, for the four trim cases described above. The necessary relationships, derived from equations (7) and (8) are set forth in the Appendix, and, as before, values for the hydrodynamic stability derivatives obtained by the David Taylor Model Basin (reference 2) were employed. A net upward buoyancy (W - B) of -350 pounds was assumed, as was a metacentric height (z_B) of 0.6 inches. A water density of 64.4 pounds per cubic foot was used in the calculations.

The body angles required for level flight are shown in Figure 8. They turn out to be directly proportional to the net buoyancy, and independent of the tail configuration. Strangely enough, one way of decreasing the body angle in trim is to move the center of gravity forward of the center of buoyancy which is a nose down gravity-buoyancy couple. This requires, then, more down load on the pitch rudder, for trim, which reduces the hydrodynamic lift (hence body angle) the body must develop to offset the net upward buoyancy.

Figures 9 through 12 show the center of gravity location and the pitch rudder deflection required for level flight in the four trim cases described previously. Also shown are the resulting pitch rudder axle torques transposed to control yoke forces (F_{CP}) in the manner previously described. It is noted that the trim control forces (pull forces) decrease steadily as the center of gravity moves aft, becoming push forces

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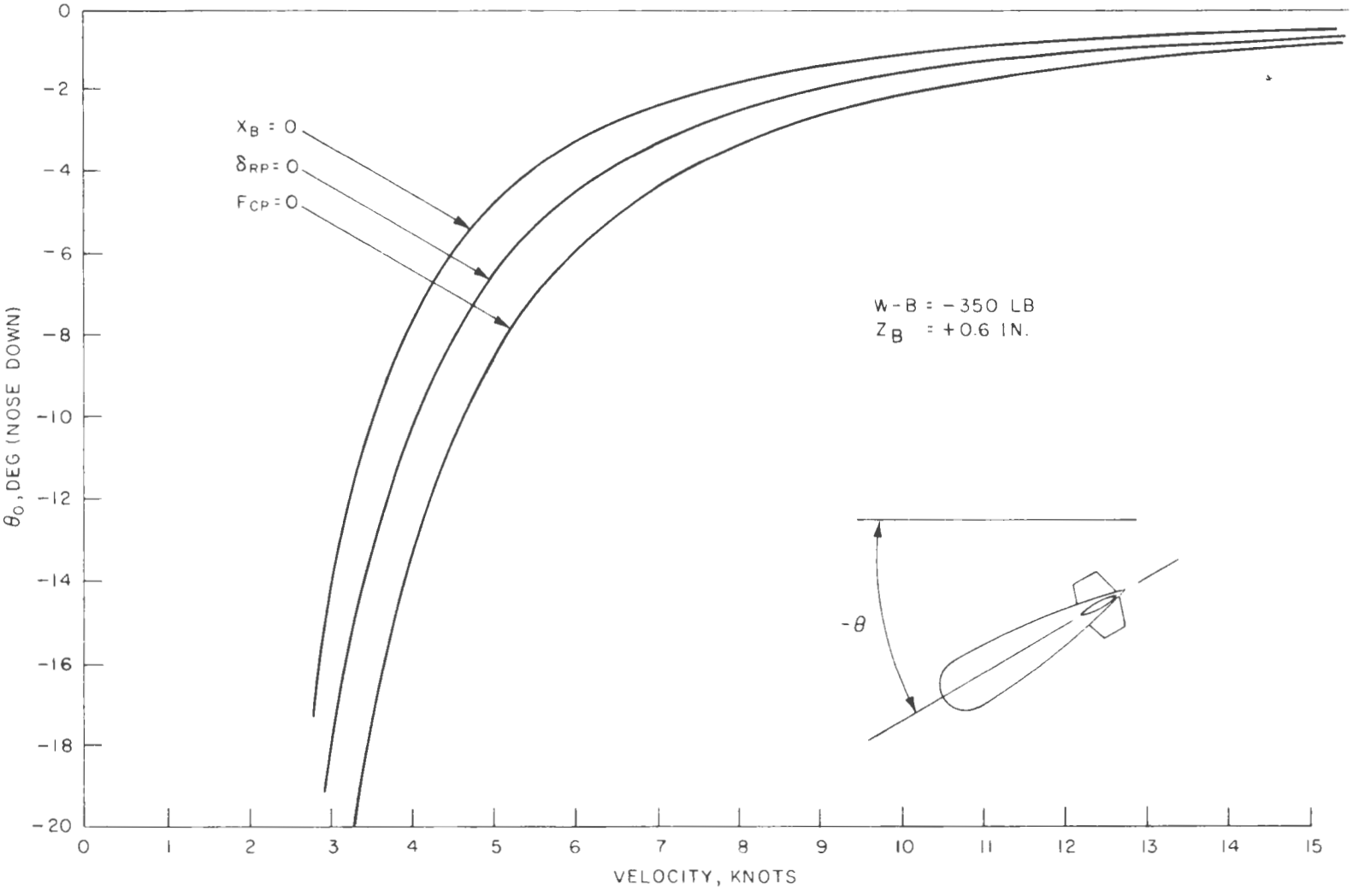

FIG. 8. CURVES OF BODY INCLINATION Θ_o VERSUS VELOCITY FOR FOUR TRIM CASES

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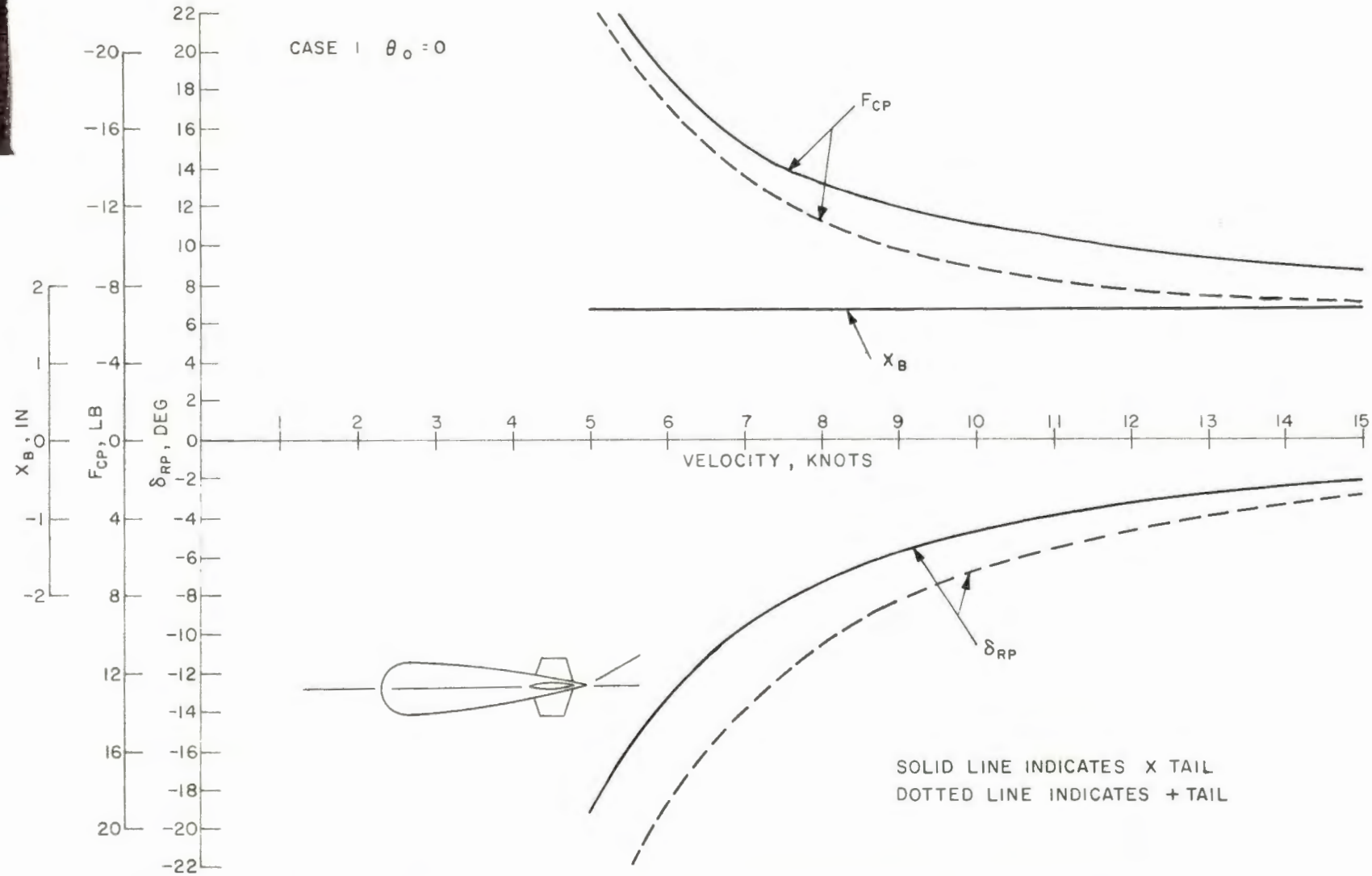

FIG. 9. CURVES OF REQUIRED PITCH RUDDER DEFLECTION, CG LOCATION AND PITCH CONTROL FORCES VERSUS VELOCITY FOR TRIM AT ZERO BODY ANGLE

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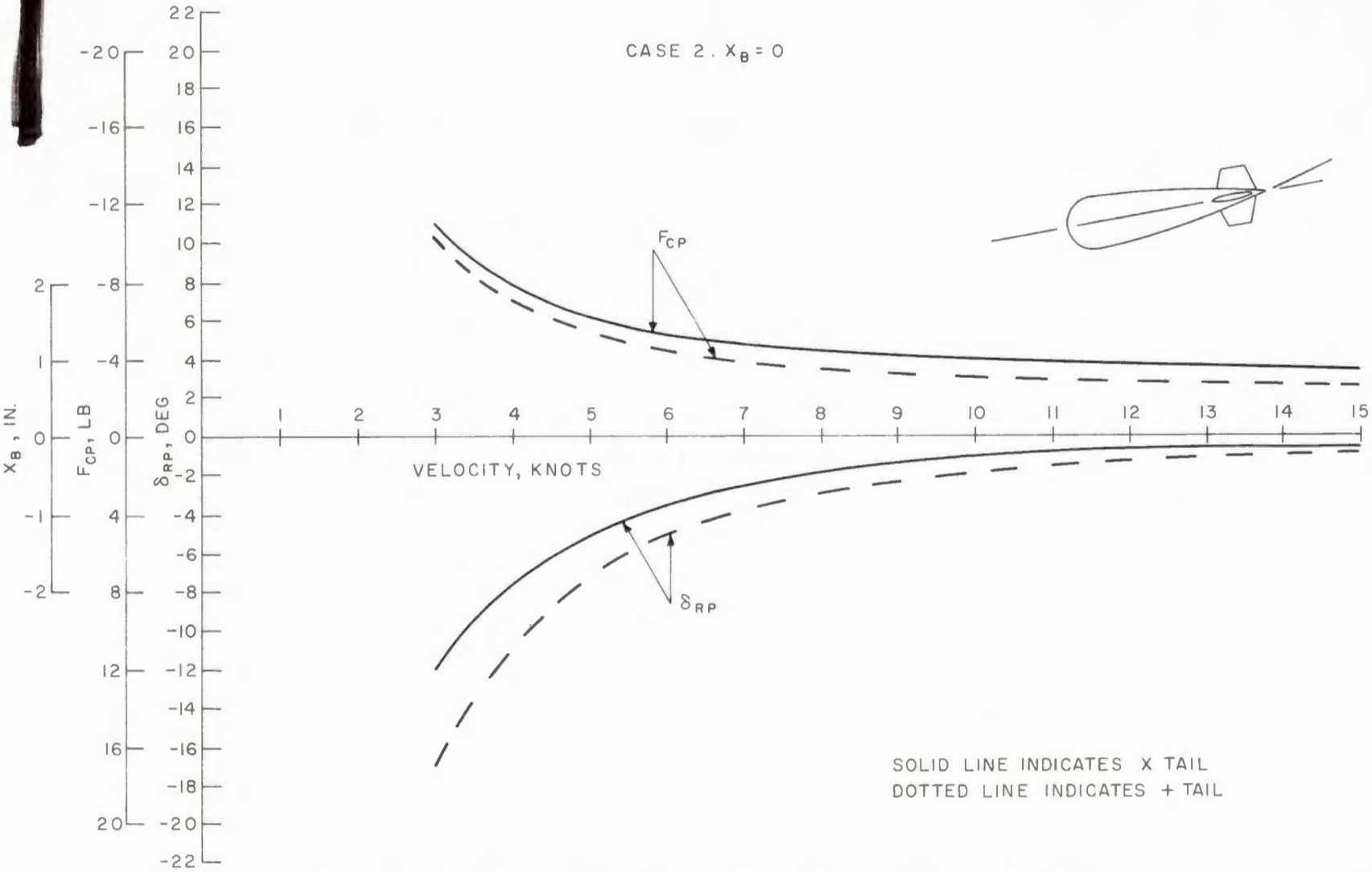

FIG. 10. CURVES OF REQUIRED PITCH RUDDER DEFLECTION AND PITCH CONTROL FORCES VERSUS VELOCITY FOR TRIM AT ZERO CG DISPLACEMENT

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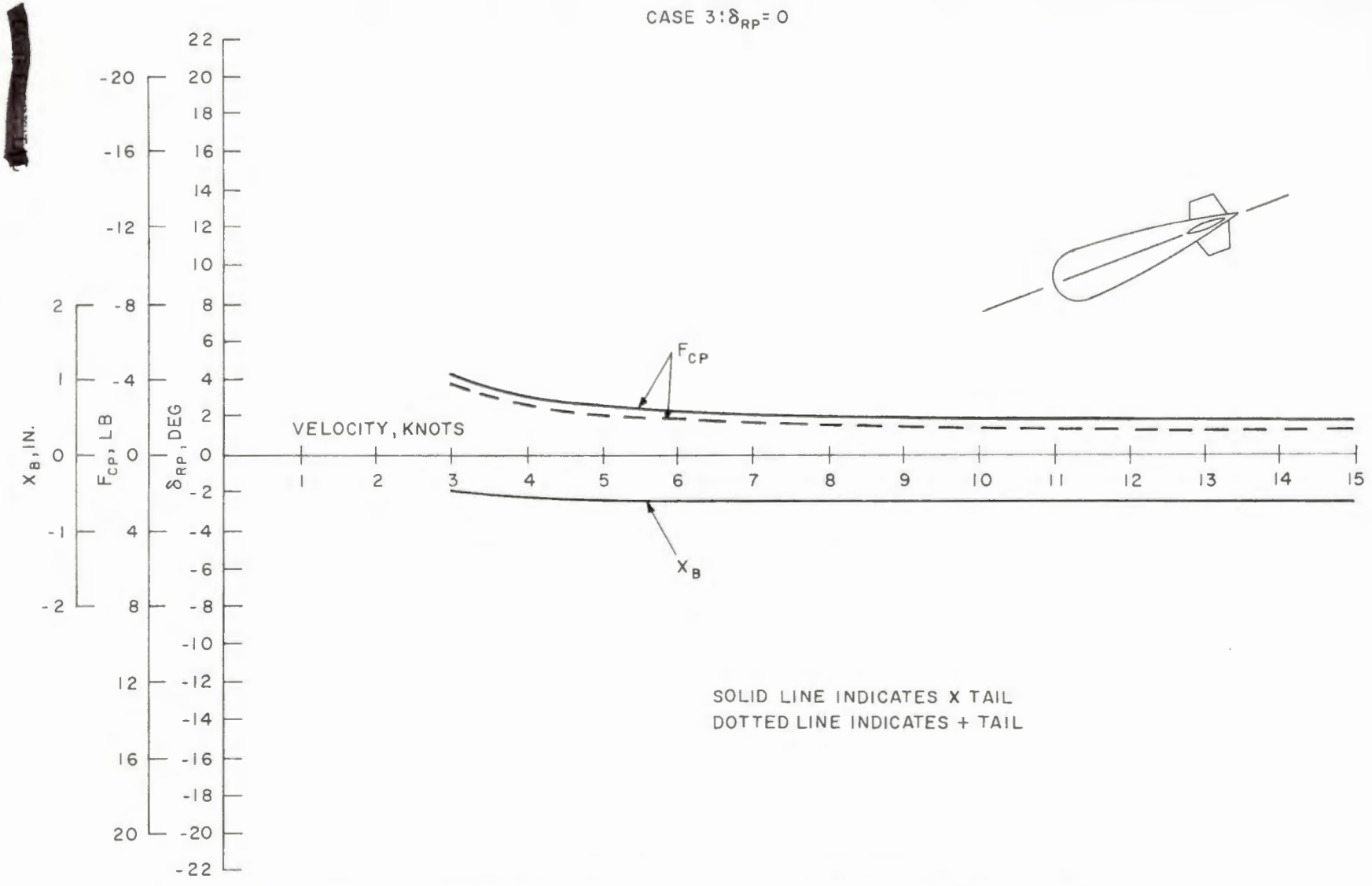

FIG. 11. CURVES OF REQUIRED CG LOCATION AND PITCH CONTROL FORCES VERSUS VELOCITY FOR TRIM WITH ZERO TRIM RUDDER DEFLECTION

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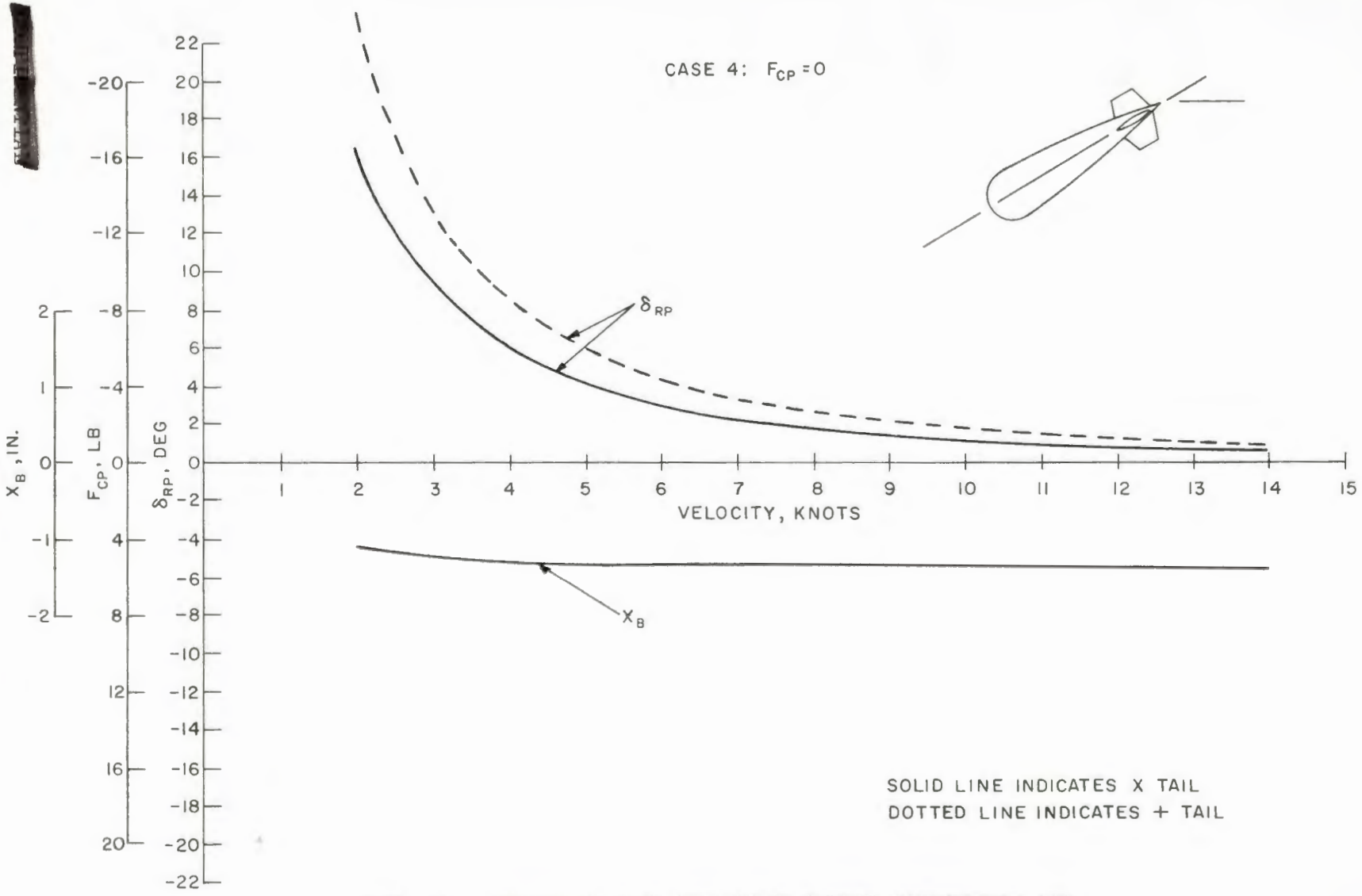

FIG. 12. CURVES OF REQUIRED PITCH RUDDER DEFLECTION AND CG LOCATION VERSUS VELOCITY FOR TRIM WITH ZERO PITCH CONTROL FORCES

if the center of gravity is moved more than 1.4 inches aft of the center of buoyancy. This trim mode, however, probably requires excessive nose down body angles, particularly at the lower speeds, and is not recommended.

Finally, although the center of gravity location for trim is mathematically a function of velocity, it appears that for all practical purposes, once a trim mode is selected, the center of gravity can be adjusted to one nominal position and held there. This means that the mercury system need be operated only twice per mission--once upon leaving the surface, and again upon returning to the surface.

CONTROL FORCE GRADIENTS

We have seen that the techique of quickening the display to an operator of a submersible is a very effective way of up-grading the stability of the operator-machine combination. Another way that needs exploring and hopefully exploiting for MORAY TV-1A is an adaptation of the well established aircraft control system design art in which reversible control system dynamics are intentionally coordinated with the airframe dynamics to negate instabilities otherwise present. The control system is used to redeem aerodynamic shortcomings by being made to serve as a simple auxilliary stability-augmentation system, by automatically providing control system corrections upon perturbations of the airframe from equilibrium level flight. The discussion that follows is, in the main, restricted to equilibrium level flight, or depth-keeping at constant power settings.

The simple, direct, manually-operated reversible control system used in many aircraft provides level flight control forces of the character shown by curve A of Figure 13. These are characterized by pull forces at the lower speeds and push forces at high speeds. Separately operated trim tabs* provide the capability of adjusting the curve to zero at any desired trim velocity, as shown by curves B and C. Now it is well known in aircraft control system design circles that pilots base their opinion of aircraft flying qualities upon these very control system force characteristics. For example, pilots subjectively measure an aircraft's stability by "feeling" the slope of the stick- or control-force-with-velocity curve at a trim point (trim point A, for example). This is only natural, because if the stick force gradient is stable at the trim point as shown, the pilot can release the control and velocity perturbations from equilibrium trim velocity will automatically be corrected by the control system. For example, if velocity increases from trim velocity due to a slight glide angle, the pilot would feel pressure on the stick tending to move the stick back.

* Legislated out of MORAY TV-1A in its preliminary design because of the additional personnel compartment pass-throughs required.

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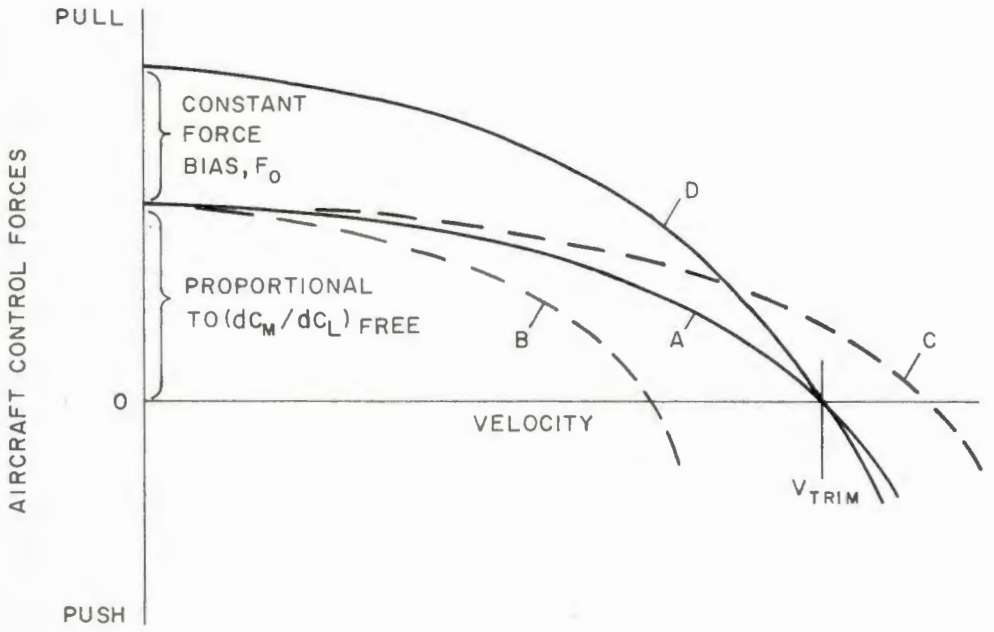

FIG. 13. CHARACTERISTIC AIRCRAFT LEVEL FLIGHT, PITCH CONTROL, FORCE-VELOCITY CURVES

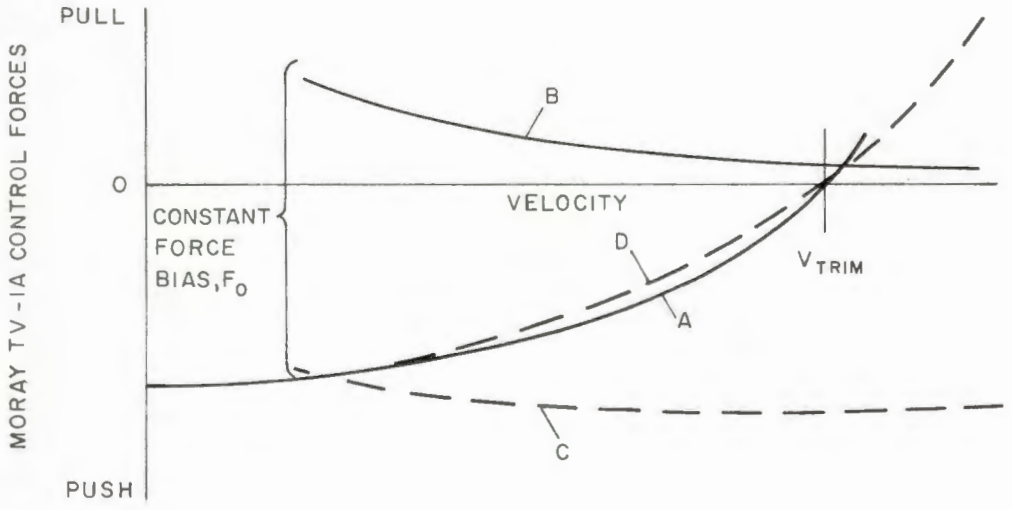

FIG. 14. MORAY TV-1A LEVEL FLIGHT, PITCH CONTROL FORCE-VELOCITY CURVES

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Were he to free the control stick, it would then move back resulting in a nose up correction until the trim speed was reattained. Said another way, to increase the speed from trim speed, the pilot must push the nose down, and to decrease it (climb) he must pull the stick back. If he leaves the stick alone, the airplane will fly level.

This, then, is the pilot's definition of aircraft "stability" and it turns out that he is on sound ground. It is shown in many standard texts on aircraft design (reference 11, for example) that both the fixed part at zero velocity and the slope at the trim point of curve A are directly proportional to the airplane analytical stick-free stability parameter $(dC_M/dC_L)_{FREE}$. A strong gradient at the trim point is so greatly desired that in the case of many aircraft with marginal-to-inadequate stick-free stability, designers have devised a number of control system tricks to provide, for the pilot's benefit, ersatz stick-free stability by artifically increasing the slope at the trim point as shown by curve D of Figure 13.

Most of these control system gadgets work by adding a constant nose down force bias to the control system. These are the well known "downspring", "bobweight", or "blowdown tab" devices. They require that the trim tab work harder to pull the resulting curve to zero at any desired velocity but a stiffer gradient results as can be seen at the trim point of curve D. Thus we see that in the case of aircraft, contrived tailoring of the control system force characteristics results in augmented aircraft stability from the pilot's point of view which, in the long run, is the only valid one. Note carefully that the basic stability of the aircraft is unchanged.

It occurred to the writer that the technique might be useful in MORAY TV-1A; not only useful, but undoubtedly desirable in view of the demonstrated vehicle-operator basic instability. And it turns out that simple pitch control force characteristics modifications in the MORAY TV-1A vehicle will, in all probability, considerably augment, in like manner, the overall vehicle-operator stability.* The arguments are as follows.

If one applies all the reasons, set forth in aircraft control system design literature on the subject, which point to the desirability of the aircraft control system trim force characteristics shown in curve A of Figure 13 to the mirror image flight dynamics of MORAY TV-1A, one arrives at a desired force characteristic curve of the general shape shown by curve A of Figure 14. Thus, in the case of MORAY TV-1A, trim velocity perturbations resulting from flight path inclination perturbations will

* It remains for the vehicle's pitch plane equations of motion and the pitch control system's equations of motion to be solved simultaneously to provide rigorous proof of stick free stability.

be corrected automatically by the control system. A flight path inclination downward will result in a velocity decrease and a back pressure on the stick which, if unresisted by the operator, will lift the nose to increase the speed to the trim speed. But the characteristic trim force curve currently existing for MORAY TV-1A is of the general shape shown by curve B of Figure 14, as can be seen by re-inspection of Figures 9 through 12. The shallow force gradients that do exist are perversely in the wrong direction. The problem then is to tailor curve B to approximate curve A, and to provide trim capability (zero force) at the stick without recourse to pilot controlled trim tabs. One way to do this is as follows.

A simple force bias obtained from a constant force spring will put curve B on the right side of the abscissa, as shown by curve C. This spring is now an "upspring"; that is, it provides a constant nose up force, against which the MORAY TV-1A operator must push. This bias could also be provided by a "blowdown" tab which has the advantage that it does not introduce large control forces at low speeds or at rest on the surface. The addition, then, of a conventional q-bellows will provide a force proportional to V^2, opposing the upspring, and curve C will become curve D which can be made to exhibit the desired force characteristics with velocity. Or a tab, fixed at a constant deflection with respect to the rudder, will also provide opposing forces proportional to V^2. The trim problem then becomes one of providing the operator with mechanical means of changing the magnitude of the constant force bias F_o as shown in Figure 15, which in effect merely moves curve D of Figure 13 up or down.

We now need to examine the magnitude of the force gradients we would want to develop by this scheme. Our source of information on desirable force gradients is general aircraft practice, and here reference 17 gives an examples of a 4 # stick force producing a 30 mph speed change from a 500 mph trim velocity. This identifies a force-velocity gradient of 0.09 #/fps. Mr. Douglas Drake, Stability and Control Engineer of the Douglas Aircraft Company, advises that pilots of fast maneuverable aircraft such as the F6A or the A4 consider a stick force gradient of 10 # per 50 knot speed change very stable and 5 # per 50 knot speed change a little on the light side at, say, 300 knots trim speed. These numbers reduce to 0.12 #/fps and 0.06 #/fps, respectively. We will select 0.1 #/fps as representing a reasonably stiff stick force-velocity gradient for aircraft and will use it, suitably transformed, as a design criteria at MORAY TV-1A's maximum speed of approximately 25 fps.

The transformation needs to be made by way of dynamic pressure effects, as it is the change in dynamic pressure rather than velocity per se that produces the stick force change. This means that we are really interested in $(\partial F/\partial q)$ rather than $(\partial F/\partial V)$, which are related as follows:

$$(\partial F/\partial q) = (\partial F/\partial V)/(\partial q/\partial V) \qquad (9)$$

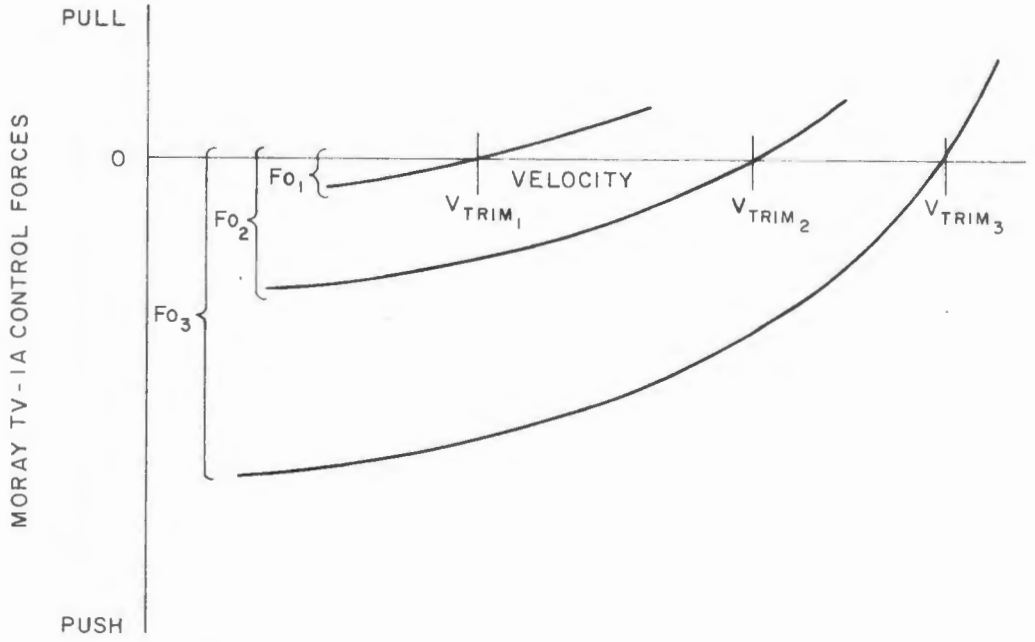

FIG. 15. A PITCH CONTROL-FORCE TRIM SCHEME FOR MORAY TV-1A

and $$(\partial q/\partial V) = \rho V \qquad (10)$$

from $$q = \tfrac{1}{2}\rho V^2 \qquad (11)$$

Alternately $$(\partial F/\partial V) = (\partial F/\partial q)(\partial q/\partial V) \qquad (12)$$

As stated above, the force gradients derive primarily from rates of change of dynamic pressure q, and the scheme here is to hold $(\partial F/\partial q)$ for MORAY TV-1A at that level corresponding to a stiff airplane gradient of $(\partial F/\partial V)$ = 0.1 #/fps. For the airplane at a density altitude of, say, ρ = 0.002 and a velocity of 300 knots ($\approx$ 500 fps) this is

$$(\partial F/\partial q) = (0.1)/(0.002)(500) = .1 \text{ \#/fps} \qquad (13)$$

from equation (9). Then the force-velocity gradient we would need for MORAY TV-1A at 25 fps is

$$(\partial F/\partial V) = (0.1)(2 \times 25) = 5\ \#/fps \qquad (14)$$

from equation (12). Since our desired force curve D of Figure 14 is of the form $F = F_{o\ max} - cV^2$, $\partial F/\partial V = -2cV = 5\ \#/fps$ whence $c = -0.1$ and $F_{o\ max} = 62.5\ \#$. Then q-bellows and force bias systems of a maximum of 62.5 # capacity each would serve, which would require a q-bellows of little more than 4 inches in diameter.

Now all of the arguments set forth above with regard to reversible control system "feel" presume an efficient, mechanical design of the control system which specifically prohibits excessive friction, backlash, and elasticity. Friction will mask the force gradients, and the force feedback or "feel" will be lost. If one can look at this from the standpoint of quickening, precise "feel" of the forces acting at the control surfaces is the ultimate in control derivatives that can be acted upon by the operator, as it is two derivatives ahead of control surface deflection, according to Newton. Thus it is so that all who are knowledgeable in direct, manual control system design are unanimous in asserting that friction must go. Since this is patently impossible, a compromise has been reached and aircraft design specifications now set upper limits of 3 pounds break-out force for pitch control systems in highly maneuverable aircraft. It is important that this limit be met or bettered for MORAY TV-1A.

In summary, several conceptual advantages accrue to this control system modification, if reasonable friction values are not exceeded. Besides providing apparent stick-free stability to the operator, the trim force curve slope at trim increases with velocity, where the vehicle's stability most needs augmentation, as described previously. In addition, the manual trim device provides not only the capability of reducing stick forces to zero for long term operations, but provides the operator with vernier pitch control, a sorely needed capability at speed. Thirdly, the system will work equally well with the X tail, if the V^2 force bias from the q-bellows is applied equally through appropriate linkage to the two rudder jack shafts in the tail of the vehicle, as the bias torques are then self-cancelling at the control yoke differential and will not be felt by the operator at the wheel in a turn. With the + tail configuration, a simple fixed tab would suffice. Speaking of turns, the normal velocity loss in a turn will be felt by the operator as back pressure on the stick which will require him to push MORAY TV-1A around in a turn, as opposed to the mirror image aircraft, which is pulled around in a turn. This seems consistent to the writer. Moreover, mild transient pitch maneuvering control loads at a particular trim speed will not be affected by the balance between tab and spring or q-bellows forces.

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CONCLUSIONS AND RECOMMENDATIONS

It is concluded that conventional submersibles are basically difficult to control by direct manual means; first, by virtue of their poor dynamic characteristics, and second by virtue of their traditional configuration. It is recommended that the control ease of winged submersibles be explored.

It is also concluded that separate operator displays of position, attitude, and rates, such as aircraft displays, are incompatible with conventional submersible configurations, when the operator is directly in the control loop, and operating a simple, direct, reversible control system; but that display quickening is one effective way of affording increased operator-submersible stability.

It is further concluded that an adaptation of aircraft control system design techniques, wherein stabilizing control system force gradients are artificially provided, may well afford another way of providing adequate operator-submersible stability. It is recommended that an analytical demonstration of stability be attempted through the simultaneous solution of MORAY TV-1A's pitch control system equations of motion and the vehicle's pitch plane equations of motion.

It is finally recommended that the MORAY TV-1A pitch control system modifications described herein be accomplished, and the stability experiment made full scale in the forthcoming sea trials. If it is determined therein that surface effects are no problem, it is recommended that the tail casting be rotated to the + tail configuration.

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APPENDIX A
LEVEL FLIGHT TRIM RELATIONSHIPS

CASE 1: $\theta_o = 0$

$$\delta_{RP} = - \frac{(W - B)'}{Z'_\delta}$$ ← FOR X TAIL

$$\delta_{RP} = - \frac{\sqrt{2}^{*}(W - B)'}{Z'_\delta}$$ ← FOR + TAIL

$$X'_B = + \frac{(W - B)'}{B'} \cdot \frac{M'_\delta}{Z'_\delta}$$ ← BOTH TAILS

$$\alpha_{RP} = \delta_{RP}$$ ← BOTH TAILS

CASE 2: $X_B = 0$

$$\theta_o = + \frac{M'_\delta (W - B)'}{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta}$$ ← BOTH TAILS

$$\delta_{RP} = - \frac{(W - B)' (M'_\alpha + M'_\theta)}{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta}$$ ← FOR X TAIL

$$\delta_{RP} = - \frac{\sqrt{2}^{*}(W - B)' (M'_\alpha + M'_\theta)}{Z'_\delta (M'_\alpha + M'_\theta) - Z'_\alpha M'_\delta}$$ ← FOR + TAIL

* WHERE Z'_δ AND M'_δ ARE DETERMINED WITH TAIL IN X CONFIGURATION

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$$\alpha_{RP} = \frac{\theta}{\sqrt{2}} + \delta_{RP} \quad \leftarrow \text{X TAIL}$$

$$\alpha_{RP} = \theta + \delta_{RP} \quad \leftarrow \text{+ TAIL}$$

CASE 3: $\delta_{RP} = 0$

$$\theta = -\frac{(W - B)'}{Z'_\alpha} \quad \leftarrow \text{BOTH TAILS}$$

$$X'_B = \frac{(W - B)}{B} \cdot \frac{(M'_\alpha + M'_\theta)}{Z'_\alpha} \quad \leftarrow \text{BOTH TAILS}$$

$$\alpha_{RP} = \frac{\theta}{\sqrt{2}} \quad \leftarrow \text{X TAIL}$$

$$\alpha_{RP} = \theta \quad \leftarrow \text{+ TAIL}$$

CASE 4: $F_{CP} = 0$

$$\theta = -\frac{(W - B)'}{\left(Z'_\alpha - \frac{Z'_\delta}{\sqrt{2}^*}\right)} \quad \leftarrow \text{BOTH TAILS}$$

$$\delta_{RP} = -\frac{\theta}{\sqrt{2}} \quad \leftarrow \text{X TAIL}$$

$$\delta_{RP} = -\theta \quad \leftarrow \text{+ TAIL}$$

$$X'_B = \frac{(W - B)}{B} \cdot \frac{(M'_\alpha + M'_\theta) - \frac{M'_\delta}{\sqrt{2}^*}}{(Z'_\alpha - \frac{Z'_\delta}{\sqrt{2}^*})} \quad \leftarrow \text{BOTH TAILS}$$

$$\alpha_{RP} = 0 \quad \leftarrow \text{BOTH TAILS}$$

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APPENDIX B

ZERO DEPTH BIAS RELATIONSHIPS

It is possible to trim MORAY TV-1A to eliminate any depth error bias due to quickening, as follows. The quickening relationship set forth in reference 6, for small angles, is:

$$k_3 \delta_{RP} - k_4 \theta_o + \Delta z = 0 \qquad (1)$$

For Δz to actually be zero, finite values of δ_{RP} and θ_o must have the relationship

$$\delta_{RP} = \frac{k_4}{k_3} \theta_o = k_5 \theta_o \qquad (2)$$

In reference 12, the following level flight relationships are found:

$$\alpha_o = \theta_o = - \frac{(W-B)' + Z'_\delta (\delta_{RP})}{Z'_\alpha} \qquad (3)$$

$$\theta_o = \frac{M'_\alpha (W-B)' - Z'_\alpha B' x'_B + (M'_\alpha Z'_\delta - Z'_\alpha M'_\delta)\delta_{RP}}{Z'_\alpha M'_\theta} \qquad (4)$$

If equation (2) is substituted into equation (3) the desired relationship for the body angle (θ_o) is determined:

$$\theta_o = - \frac{(W-B)'}{(Z'_\alpha + k_5 Z'_\delta)} \qquad (5)$$

and the required pitch rudder deflection is then calculated from equation (2).

* In reference 6, k_3 and k_4 are given the values 8 feet/degree and $\frac{10}{9}\pi$ /degree, respectively.

Finally, the substitution of equations (2) and (5) into equation (4) yields the required center of gravity position or trim condition for zero depth bias:

$$X'_B = \left(\frac{W-B}{B}\right) \cdot \frac{(M'_\theta + M'_\alpha + k_5 M'_\delta)}{(Z'_\alpha + k_5 Z'_\delta)} \qquad (6)$$

or X_B, in inches, is

$$X_B = 12\ell \left(\frac{W-B}{B}\right) \cdot \frac{(M'_\theta + M'_\alpha + k_5 M'_\delta)}{(Z'_\alpha + k_5 Z'_\delta)} \qquad (7)$$

Equations (2), (5), and (7) are plotted in Figure 1 versus velocity.

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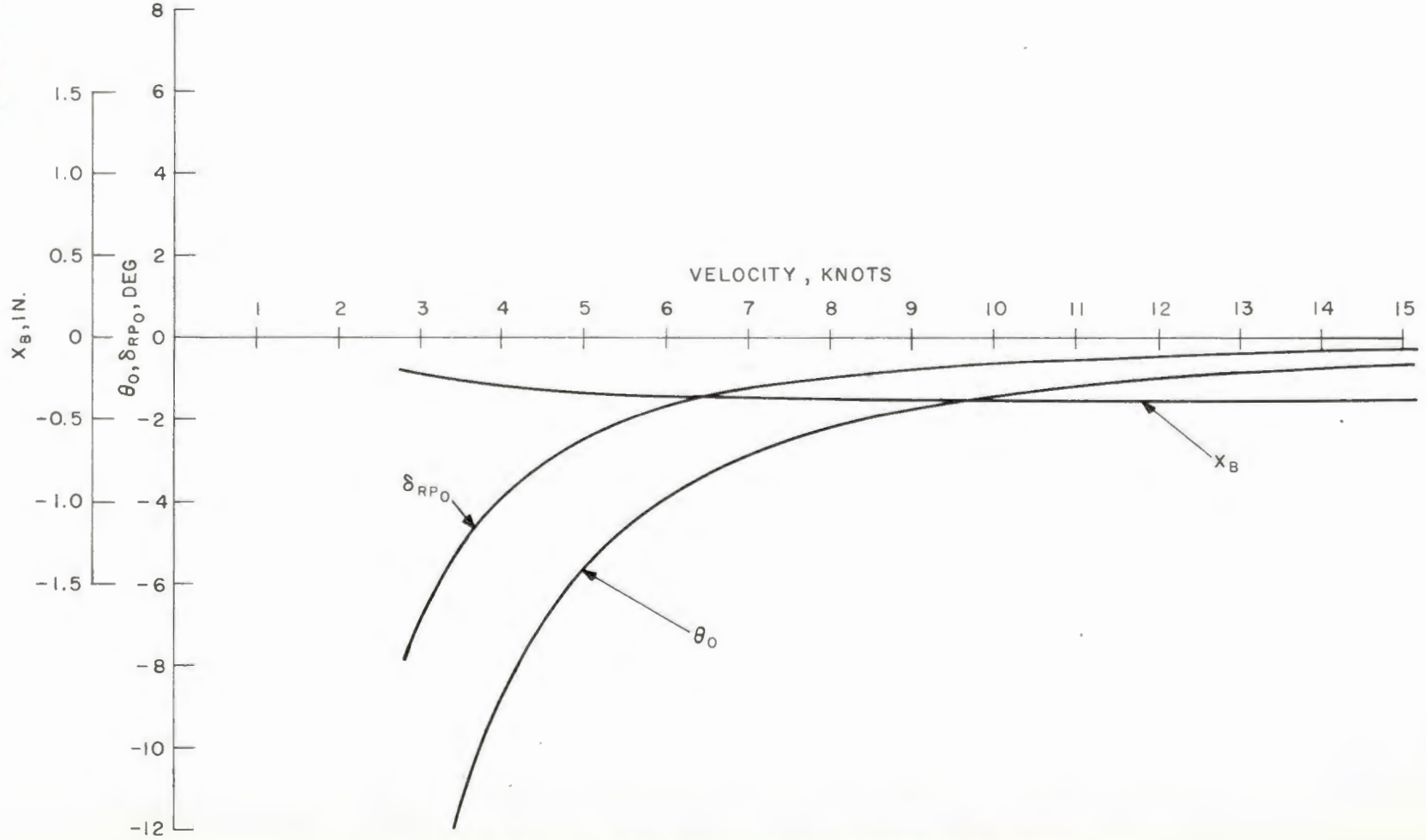

FIG. 1. CURVES OF BODY ANGLE, PITCH RUDDER DEFLECTION, AND REQUIRED CG LOCATION FOR TRIM WITH ZERO DEPTH BIAS

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