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Hydrodynamics Technology for an Advanced Expendable Mobile Target (AEMT)

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ABSTRACT

This report summarizes work on hydrodynamics technology conducted in support of the Advanced Expendable Mobile Target, a NAVSEA exploratory development program directed toward demonstrating the application of low-drag vehicle technology to a small, expendable acoustic training target. The summary includes descriptions of the analyses used to support the design effort in the areas of laminar and turbulent boundary layer flow, potential flow, propeller performance, fin design, and hull contour tolerances. Also included are descriptions of a trim and balance problem and a speed and power problem, both discovered during instrumented field trials, and the ensuing investigations that led to their resolution. These investigations encompassed two wind-tunnel test programs which included powered-model testing. The adequacy of the hydrodynamics technology base to support similar designs is assessed on the basis of field-trial experience and the resolution of all outstanding hydrodynamic problems. Finally, supplementary studies offering future design options are described and recommendations made for future development programs.

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1. SUMMARY

Using a low-drag hydrodynamic body shape defined by the Westinghouse Electric Corporation, the Applied Physics Laboratory at the University of Washington designed and built an experimental vehicle for an Advanced Expendable Mobile Target (AEMT). The purpose of this development was to demonstrate the concept, and to expose the design problems associated with adapting low-drag technology to a small, expendable acoustic training target within the context of an exploratory development effort. The forebody of the vehicle is characterized by laminar flow which is achieved by shaping the hull so that the longitudinal static-pressure gradient is uniformly favorable (negative). Turbulent transition is initiated by an abrupt reversal of the pressure gradient which produces laminar separation followed by turbulent reattachment on the afterbody. Turbulent drag is minimized by the short streamwise extent of the turbulent flow over the abruptly closed off afterbody. The tail fins feature an unconventional, variable-camber control scheme that avoids the usual hinge fabrication difficulties encountered with a simple flap. A conventional propeller is used for propulsion.

Because of severe restrictions on manpower and funding, it was decided to dispense with the usual subsystem developmental testing, and proceed directly to an open-water demonstration of the concept. To minimize the technical risks associated with this constraint, a series of analyses was performed to support the design study. Boundary layer analyses were conducted to estimate the hull drag, and propeller analyses provided an estimate of the propulsive coefficient. A fin analysis was used to select the fin planform, sized for neutral static stability, as well as to introduce a unique variable-camber concept. In addition, tolerances for the radius, waviness, surface discontinuities, and finish of the shell were developed using boundary layer theory as well as potential flow analyses. Hydrodynamic stability derivatives were developed for the vehicle dynamics studies used to select the design for the automatic control system.

The design speed of 15 kn was obtained routinely in early field trials. However, the addition of a small on-board data-acquisition system revealed two technical problems that demanded solution. First, it was noted that straightaway operation of the vehicle was characterized by abnormal elevator and rudder deflection angles. Second, the vehicle was found to require propulsive power significantly in excess of design expectations.

Analysis of field-trial data in conjunction with a careful survey of the fin profile revealed that the fins had excessive camber due to a combination of fabrication deficiencies in the fin proper and asymmetry in the bell crank mechanism used to vary the camber. The investigation also revealed that the fin's trailing edge was subject to permanent deformation during handling owing to improper heat treatment of the flat spring forming the core of the trailing edge.

Initial efforts to solve the speed/power problem focused on the fact that the propeller's advance ratio was much higher than design predictions. This suggested that the propeller was operating in a highly retarded flow field, such as would be produced by poorly attached turbulent flow on the tail boom. However, a wind-tunnel test confirmed that the hull flow was in good agreement with design predictions, due consideration being given to the fact that the hull was operated well below its design Reynolds number during most field trials and therefore carried a sizable laminar bubble on the afterbody. The test did reveal, however, that fin drag was abnormally high, a situation identified with the presence of separated laminar flow over the aft 30-40% of the fin chord.

A second wind-tunnel test series was conducted in which a variety of candidate propellers were operated in the wake of the hull during powered-model tests. The tunnel was fitted with a honeycomb to control turbulence and allow flow visualization tests. The tests verified that hull flow conditions were normal, and indicated that the best candidate for improving propulsion performance was an Octura model-hydroplane propeller. In addition to the powered-model tests, tests also were conducted on a redesigned fin incorporating a thinner section. The new fin reduced the fin profile drag 50% while maintaining attached flow to 83% of chord.

Field trials with the new propeller showed that the propulsion performance was improved, but it still fell short of expectations based on the wind-tunnel results. An independent propeller analysis was therefore performed using a diagnostic technique especially developed to accommodate the possibility of laminar separation on the propeller blades. The analysis revealed that the hydroplane propeller was operating normally, but not at maximum efficiency because the limited wind-tunnel data had been smoothed incorrectly. Most importantly, the analysis revealed that the poor performance exhibited in the earlier trials with the original model-ship propeller was due to laminar separation on the blades, both aft of midchord on the suction surface and from the leading edge on the pressure surface. It was concluded that the original propeller had been too highly cambered for low Reynolds number operation and too lightly loaded for the application. The apparently abnormally high advance ratio that had served as the earliest clue was determined to be an artifact introduced by an inappropriate correction for flow curvature used in the original propeller analysis.

This experience has led us to the following conclusions about the adequacy of the hydrodynamics technology base to support new designs involving low-drag technology in a small expendable target. First, it should be possible to proceed with confidence on new designs based on the AEMT hull form, provided that due consideration is given to the fact that operation well below the design Reynolds number will lead to a laminar bubble on the afterbody. Further, it is judged that the variable camber fin is a valid concept, although additional structural/hydrodynamic analysis would be appropriate in support of new designs. The choice of a propeller for the AEMT demonstration vehicle was constrained to the use of stock propellers only. To realize the full potential of the low-drag hull form, however, the design must incorporate a wake-adapted propeller. Finally, the value of wind-tunnel testing, especially testing of powered models, and of using a fully instrumented prototype for field trials has been clearly demonstrated.

2. INTRODUCTION

2.1 Background

The success of the Mobile Target Mk 38 proved the technical and economic feasibility of a small, expendable acoustic training target. In fact, the introduction of the Mk 38 into the Fleet stimulated interest in a target with increased speed, endurance and acoustic capability. In late 1974, the Applied Physics Laboratory at the University of Washington (APL-UW) began to investigate the feasibility of adapting the evolving low-drag vehicle technology to small, expendable target vehicles.

Initially, the Laboratory hired a consultant to perform a feasibility study[1] and conduct a series of informal tutorial sessions on boundary layer theory for selected staff members. The feasibility study indicated that available analysis methods were adequate to support the vehicle design process, and the consultant recommended that concept design efforts be pursued. Recommended for study were forebody flow laminarization through shaping, afterbody pressure recovery at incipient turbulent separations, and integrated propulsion and boundary-layer control in which the turbulent boundary layer on the afterbody was ingested by a ducted propeller. The latter concept features pressure recovery to ambient pressure at the inlet of a ducted, relatively large diameter, slow turning propeller.

The feasibility study also suggested modifying one of the existing Mk 38 targets by molding a plastic body with a new contour over the cylindrical aluminum shell. Fitted with a new propeller, this modified vehicle could then be used to demonstrate in open water the potential of hull shaping alone for improving vehicle performance. It was recommended that water-tunnel testing of new hull designs be conducted with self-propelled vehicles prior to open-water testing.

In early 1975, motivated by the desire to demonstrate the concept of an advanced miniature mobile target at a minimum expenditure of program funds, APL-UW decided to defer water-tunnel testing and go directly to an open-water demonstration of a new vehicle with an advanced hull form that utilized conventional propeller propulsion. Because of the experience of the Westinghouse Electric Corporation (WECO) with low-drag technology, the table of offsets for the shell was procured from WECO who utilized the hull form design technique of Reference 2. Also procured from WECO was a wake-adapted propeller design characterized by a very small expanded area ratio.[3]

The hydrodynamics technology effort required to demonstrate the concept successfully within the described constraints is the subject of the present report.

2.2 Purpose and Scope

The primary purpose of this report is to retain the experience gained during the program. Problem solving being the best source of experience, the contents are predominantly problem oriented.

This is not intended to be a "how to do it" handbook. The absence of extensive subsystem developmental testing seriously limits the design options from which to draw future designs. Nevertheless, items such as the wind-tunnel testing performed in support of problem diagnosis should provide a useful basis for innovation in future designs.

The report provides convenient access to the hydrodynamic bases for the design of the AEMT, an assessment of the adequacy of the design based on interpretation of field trial results, and recommendations for future designs based on the experience gained. To help in future studies, previously unpublished internal APL design memoranda and reports on this project have been assembled under separate cover in a limited supplement entitled "Selected Reference Material for APL-UW 8013," dtd October 1980.

2.3 Hydrodynamic Description of Vehicle

2.3.1 Hull Form

The form used for the AEMT hull is one of a large family of low-drag shapes computed by WECO using the eight-parameter polynomial functions of Parsons et al.[2] The axisymmetric hull (Fig. 1) is characterized by a fine forebody over which laminar flow is maintained by virtue of a favorable pressure gradient (Fig. 2). The afterbody closes off rather abruptly to a tail boom to produce a relatively steep gradient in the pressure recovery and a sharp negative pressure peak. Laminar separation followed by turbulent reattachment occurs immediately downstream of the negative pressure peak such that at design speed the afterbody is characterized by fully turbulent flow. Low drag is achieved by maximizing the regime of laminar flow while minimizing the regime of turbulent flow. The latter is achieved by properly shaping the afterbody so as to minimize turbulent skin friction drag while avoiding turbulent separation on the afterbody.

The hull offsets are given by three polynomial equations:

For $0 \le X/L \le 0.610$,

$$\frac{R}{L} = (0.004513889\ x^4 - 0.018750000\ x^3 + 0.017013889\ x^2 + 0.004166667\ x)^{1/2},$$

where $x = (X/L)/0.610$.

For $0.610 \le X/L \le 0.750$,

$$\frac{R}{L} = (0.010659187\, x^5 - 0.006818373\, x^4 - 0.023174147\, x^3 + 0.043500000\, x + 0.059166667)\ ,$$

where $x = (0.750 - X/L)/0.140$.

For $0.750 \le X/L \le 1.00$,

$$\frac{R}{L} = (0.031964286\, x^5 - 0.118750000\, x^4 + 0.130952381\, x^3 + 0.015000000)\ ,$$

where $x = (1 - X/L)/0.25$.

In these equations, R is the local radius of the hull, X is the distance from the nose along the axis of symmetry, and L is the overall length, 3.01335 ft.

2.3.2 Fins

The tail boom of the hull is fitted with four fins of rectangular planform having a nominal planform area of 6.42 square inches per semi-span. Each fin is molded in a semirigid urethane to the NACA-16-006 section over an internal structure consisting of a rigid aluminum spine up to 0.6 chord and spring bronze aft of 0.6 chord. The trailing edge adjacent to the hull is deflected by a bell crank assembly to produce "variable-camber" control. The internal spring is slotted so that it is stiff in bending but torsionally soft; however, the trailing edge deflection reduces to zero as the tip of the fin is approached.

2.3.3 Propeller

In the current configuration, the vehicle is fitted with a stock Octura 2.0 two-bladed model-hydroplane propeller molded in rigid plastic. The propeller is installed aft of the 30° tail cone that closes off the tail boom of the hull. Although the propeller blades have a blunt-based section designed for base-vented operation, in this application the propeller is operated deeply submerged. The propeller turns at a nominal speed of 5000 rpm for 10 kn operation.

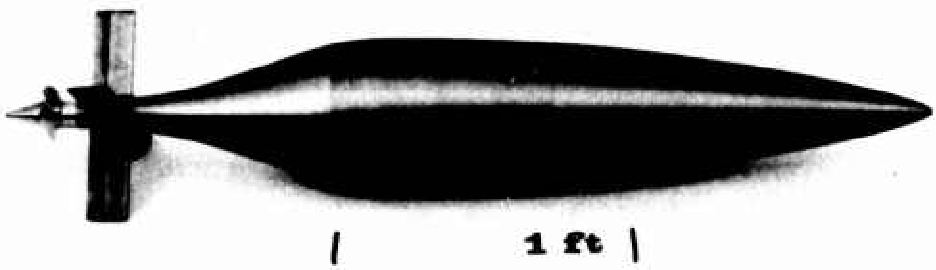

Figure 1. The AEMT vehicle.

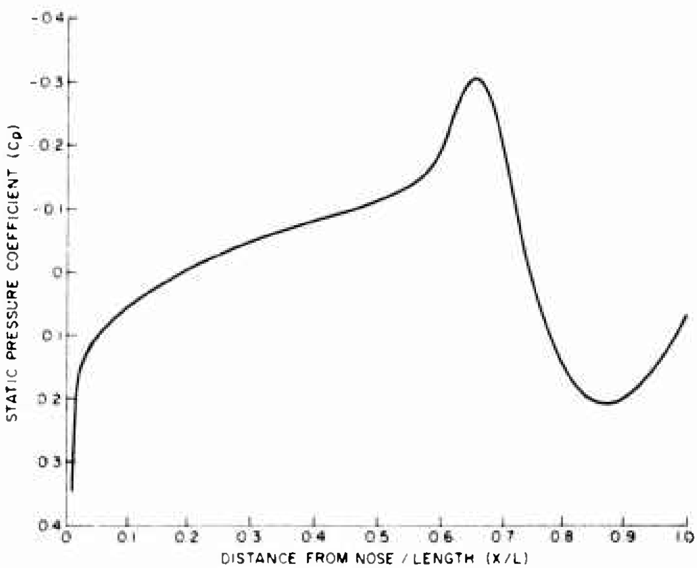

Figure 2. Theoretic static pressure coefficient for AEMT hull form.

3. HYDRODYNAMIC ANALYSES PERFORMED IN SUPPORT OF THE DESIGN EFFORT

The decision to proceed directly with the detailed design and fabrication of a concept-demonstration vehicle, without the benefit of the usual subsystem developmental testing, dictated that every effort be made to confirm the adequacy of the design through theoretical analyses. These analyses ranged from validations of WECO designs by outside consultants to original design analyses performed at APL-UW.

3.1 Review of Westinghouse Shell Profile

Using an original, piecewise similar-flow analysis technique, an APL consultant performed a boundary layer analysis[4] on the basis of only the hull table of offsets and the static pressure distribution in potential flow. Boundary layer momentum thickness, turbulent transition point, flow separation, and total profile drag were computed at a free-stream velocity of 28 ft per second. The effects of free stream turbulence and of a modification to the inviscid flow pressure profile on the hull were also examined.

The turbulent pressure recovery on the afterbody was determined to be close to optimum, departing only slightly[5] from Stratford's zero skin friction condition. The increase in the favorable pressure gradient immediately upstream of the negative pressure peak was found to improve resistance to premature turbulent transition due to free-stream turbulence to the extent that the transition point was insensitive to turbulence levels below 0.2%.

The profile drag coefficient was computed to be 0.009, based on enclosed volume to the 2/3 power, although it was noted that the assumption of a thin boundary layer could not be justified aft of $X/L = 0.87$.

The use of laminar separation to initiate turbulent transition opened up the possibility that the laminar separation would create a bubble on the afterbody, and thus increase the drag. In Reference 6 I elaborate further on this possibility, noting that off-design operation at reduced speed (less than about 8 kn) could be expected to produce a substantial laminar bubble.

3.2 Review of Westinghouse Propeller Concept

Design calculations by the WECO Oceanic Division for a three-bladed wake-adapted propeller were checked independently.[7] This design was judged to be a good choice because the disk loading was relatively light, thereby promoting high Froude efficiency, whereas the blade loading on blades of high aspect ratio was relatively high, thereby promoting low induced drag and profile drag. The surprisingly high values (0.94 to 0.95) calculated for the propulsive coefficient, or power ratio in Westinghouse terminology, were found to be due primarily to the omission of viscous drag in the calculation of the torque coefficient. That is, the thrust coefficient and torque coefficient were based solely on the results of the lifting line analysis for inviscid flow. The addition of a viscous drag estimate reduced the propulsive coefficient to values of 0.85 to 0.86. Other practical considerations would be expected to reduce the propulsive coefficent further, but a value of 0.80 was judged to be achievable.

It was found that a comfortable margin against cavitation existed at depths below 3 ft.

3.3 Fin Design Concept

One valuable result of the review of the Westinghouse hull design was an awareness of the necessity for tailoring the fin to the unique properties of the low-drag hull. A static stability and control analysis that included trim and balance revealed strongly conflicting requirements between the minimum control effectiveness needed for low-speed trim/balance and the maximum tolerable control sensitivity consistent with practical fabrication tolerances on flap hinges, bearings, and linkages. Fin sizing and control effectiveness requirements were based on these findings and on an analysis of the effects of the body boundary layer on fin effectiveness. Fin section and planform were based on achieving low drag and avoiding separated flow.

From the study evolved a variable-camber control concept designed to achieve a compromise control effectiveness factor ($\Delta\alpha/\Delta\delta$) of 0.25. This value permitted balancing a center of gravity offset of ±0.025 ft at 5 kn, with margin for control, while limiting the control sensitivity at 15 kn to a maneuver rate of 4°/sec per degree of control deflection.

To minimize fabrication costs, four identical fin semispans of constant chord were selected. The induced-drag penalty associated with the choice of an untapered fin was negligible because of the very low lift coefficient at 15 kn. A planform area of 0.044 ft^2 per semispan with an effective aspect ratio of 4.0 was chosen. Initially, an NACA-0009 fin section was selected because of its resistance to laminar separation and adequate thickness for the structural concept chosen. This fin was designed to achieve neutral "weathercock stability" while incurring a total fin drag of 0.50 lb at 15 kn. Fin size was adjusted to compensate for "shading" by the boundary layer.

The structural/mechanical concept was based on the use of molded semirigid plastic to achieve the airfoil shape, with the addition of two internal metal stiffeners that provided structural rigidity but allowed sufficient torsional flexibility aft of midchord to permit variable-camber control. Control deflection was limited to ±5° to achieve the best resolution and mechanical advantage with the available rotary actuator.

It was recommended that a structural analysis be per.ormed and a structural model of the fin be fabricated to verify fin deflection and hinge moment characteristics.

3.4 Contour Tolerance Rationale

The approach used to establish the hull contour tolerances was a mixture of boundary layer theory, empirical data, and engineering judgment.[6] Tolerances were established independently on radius, waviness, surface finish, and surface discontinuities although such tolerances also were determined by WECO in conjunction with their shell design.

Radius tolerances were selected by computing the effect of small changes in hull shape on the pressure profile of the hull in inviscid flow. These changes were introduced without introducing waviness or slope discontinuities by modifying selected parameters in the eight-parameter polynomial functions that defined hull form.

The roughness or discontinuity heights required to avoid laminar instability were established on the basis of the empirical relationship:

$$\frac{U_\tau \, k_t}{\nu} \leq 15 \quad ,$$

where U_τ is the friction velocity, k_t is the roughness or discontinuity height, and ν is the kinematic viscosity.

The waviness tolerance was defined by computing a critical wavelength for laminar instability on the basis of the Tollmien-Schlicting theory which relates the critical wavelength to the displacement thickness of the laminar boundary layer.

Substantial safety margins and liberal applications of engineering judgment were applied to the results of the preceding analyses in arriving at the following tolerances:

Station	Radius	Waviness	Finish	Discontinuities
0-17	±0.001 in.	0.001 in./1.0 in.	32 μin.	0.0005 in.
17-38	±0.005 in.	0.001 in./1.0 in.	32 μin.	0.0005 in.
38-69	±0.005 in.	0.0005 in./1.0 in.	32 μin.	0.0005 in.
69-99	±0.005 in.	0.002 in./1.0 in.	32 μin.	0.0005 in.

3.5 Independent Potential Flow and Boundary Layer Analyses

Analytical Methods, Inc., of Bellevue, Washington, was retained to perform a potential flow and boundary layer analysis of the hull form as defined by the offsets discussed in Section 2.3. The following is a description of their tasks and findings:

(1) Compute the pressure distribution for potential flow on the hull at a 0° and at a 2° angle of attack. At 0° the computation agreed exactly with WECO's; variation of the angle had minimal effect.

(2) Compute the hull pressure distribution for two minor variations in shape. These results are described in detail in Reference 6.

(3) Analyze the boundary layer at a 0° angle of attack for the basic hull form and two minor variants. The boundary layer analyses confirmed turbulent transition initiated by laminar separation at the selected speed of 16.6 kn. The volumetric drag coefficient was computed to be 0.0095 and was insensitive to the minor changes in the hull profile.

3.6 Independent Propeller Analysis

The services of Flow Research, Inc., of Kent, Washington, were obtained to analyze the performance of various candidate propellers operating in the design boundary layer of the hull. The propellers analyzed were:

(1) Web three-bladed model-ship propellers, 2.5 in., 2.75 in., and 3.0 in. diameter.

(2) An Octura two-bladed model-hydroplane propeller, 2.8 in. diameter.

(3) A Westinghouse wake-adapted three-bladed design, 2.6 in. diameter.

The results of the analyses[8,9] led to the selection of the Web 2.75 for initial trials. This selection was based on a computed peak propulsive coefficient of 0.91 compared with 0.88 for the Octura 2.8 and 0.85 for the Westinghouse design. The Flow Research computations were for a vehicle speed of 14.8 kn and a 1/7 power boundary layer with a physical thickness of 1.03 in. Their propeller analysis technique, outlined in Reference 10, was based on the method of Glauert, with an empirical relationship added for estimating the induced angle of attack.

3.7 Hydrodynamic Stability Derivatives

Hydrodynamic stability derivatives for the basic hull and for the fully appended hull were computed both by the Westinghouse Oceanic Division and independently by APL-UW in support of a fin design study.[11] The technique utilized by APL-UW treated the hull in terms of an equivalent ellipsoid of the same maximum diameter and displaced volume. This equivalent ellipsoid had an overall length of 2.27 ft compared with an overall length of 3.013 ft for the actual AEMT, including tail boom. The Westinghouse derivatives were transmitted informally and incorporated in the initial vehicle dynamics and control analyses as described in Reference 12. The APL-UW derivatives used in the fin design study are compared with the Westinghouse derivatives in Reference 11. The APL derivatives have since been updated as a result of the University of Washington wind-tunnel tests.[13]

4. HYDRODYNAMIC ASPECTS OF THE FIELD-TRIAL RESULTS

4.1 General

The program goal of demonstrating the concept of an advanced performance mobile target utilizing a low-drag hull form was achieved from the outset. Initial demonstration runs with no on-board data-acquisition capability routinely achieved the 15 kn design speed and demonstrated good course/depth control and adequate maneuvering capability.

These results were gratifying, but fell far short of true design validation. It was only with the installation of an on-board data-acquisition capability that certain design limitations and deficiencies were revealed.

4.2 Vehicle Trim and Balance

The first instrumented trials were conducted on 25 January 1978. A review of data collected on vehicle attitude and control surface deflection during straightaway operation at about 12.5 kn revealed an abnormal list to port and excessive rudder and elevator deflections. Representative values were:

Pitch Angle:	-0.08°	(nose down)
Roll Angle:	-8.87°	(to port)
Rudder Angle:	-1.55°	(trailing edge to starboard)
Elevator Angle:	-3.52°	(trailing edge up)

Because full-scale deflection of the control surfaces is only slightly in excess of 5°, the possibility of running out of elevator trim was a cause of special concern. Also, it is important to note that the AEMT vehicle has no active roll control system or differential deflection capability. Roll moment balance is provided passively by offsetting the center of gravity to port (to compensate for propeller torque) and below the center of buoyancy (to assure an upright attitude). Thus any extraneous rolling moment due to fin asymmetry or abnormal propeller torque, for example, would be expected to result in a non-zero roll attitude.

A review of the design data given in Reference 4 for longitudinal trim and balance revealed that the measured pitch attitude of -0.08° was in excellent agreement with the design expectation of -0.081°, whereas the measured elevator angle of -3.52° disagreed with the expected angle of +0.029°.

4.3 Vehicle Speed and Power

The field trials on 17 May 1978 were the first in which propulsion motor current and voltage were measured. Those trials and the subsequent trials of 2 June 1978 revealed that the electrical power consumed by the motor exceeded design expectations by a significant degree, approaching a factor of two in some cases. To gain further insight into the nature of the speed/power problem, a simple mathematical model of the propulsion motor was developed on the basis of previous bench tests. This model was used to compute the apparent shaft torque and propeller speed,[14] and with the aid of these data the propeller thrust coefficient, torque coefficient, and advance ratio were estimated. The most startling revelation was that the apparent advance ratio, defined as the ratio of vehicle speed to propeller tip speed, was much higher than design predictions. Specifically, the field-trial data indicated advance ratios well in excess of 0.50, whereas the propeller analysis conducted by Flow Research[8] indicated that the propeller thrust coefficient would be negative for advance ratios in excess of 0.40. That is, at the observed advanced ratios, the propeller theoretically should have been windmilling rather than propelling the vehicle. It also was noted that the abnormally high current drain by the propulsion motor forced it to operate at an efficiency of only 40%.

5. RESOLUTION OF FIELD TRIAL DEFICIENCIES

5.1 Trim and Balance

Because the pitch attitude of the vehicle appeared to be in good agreement with design predictions for the chosen positive buoyancy, it was deduced that the anomalous elevator deflection resulted from an imperfection in the fin itself. A fin survey[15] revealed that, although all the fins were properly aligned with the longitudinal axis of the vehicle, they were characterized by varying amounts of extraneous camber in the flexible aft portion.

The net rolling moment that would be produced by the camber in all four fin semispans was computed and found to be in reasonable agreement with the restoring rolling moment developed by the center of gravity offset at the observed angle of list. The net flap deflection that would be required to correct for the extraneous camber in the elevator fins was found to be in fairly good agreement with the observed anomalous elevator deflection.

The primary source of the anomalous camber was traced to fabrication imperfections in the form of residual curl and to improper heat treatment of the spring material that forms the core of the aft portion of the fins. The improper heat treatment had degraded the material to the point that permanent deformation could be introduced by ordinary stresses encountered during handling. A secondary source of residual camber was found to be a crank arm differential introduced during fabrication of the crank mechanism. This latter source of extraneous camber introduced about 1.5° of elevator differential and 0.9° of rudder differential, both of which would produce moments in the direction of the observed anomalous list.

In the process of investigating the trim and balance problem, the flap effectiveness factor ($\Delta\alpha/\Delta\delta$) was calculated to be 0.125 rather than the design value of 0.250. This estimate included the effect of an apparent ratio of 2.25 between the crank arm deflection required by the variable-camber fin and that required by a simple conventional flap to produce the same control force. The wind-tunnel tests described in Section 6 yielded a revised flap effectiveness factor of 0.150; this value was based on a ratio of 3.33 to achieve equivalence between variable-camber crank deflection and simple-flap deflection.

5.2 Speed and Power

The resolution of the propulsion power problem dominated the exploratory development effort of the AEMT program from July 1978 to July 1979. The analysis effort is fully documented in APL-UW 8009.[16] Copies of the pertinent memoranda referenced in that report are contained in the supplement to the present report.

The most misleading clue to the cause of the excessive propulsion power consumption was the fact that the apparent advance ratio of the propeller greatly exceeded the design value of Reference 8, to the extent that the propeller should have been windmilling rather than producing thrust. This observation led to the theory that the propeller was operating in a retarded flow field such that the true speed of advance was substantially lower than the vehicle's velocity. This, of course, would reduce the true advance ratio to a level more consistent with design expectations. Field trials were conducted on 31 August 1978 to test the theory that the low Reynolds number on the hull permitted a laminar bubble to develop on the afterbody which, in turn, was responsible for a poorly attached, retarded turbulent flow field at the propeller station. The use of annular vortex-generator (trip) strips designed to eliminate any laminar flow aft of maximum diameter produced no significant change in the propeller operating point. The tentative conclusion was that any flow retardation at the propeller was a consequence of basic hull form rather than low Reynolds number operation.

The first meeting of an ad hoc working group[17] led to a wind-tunnel test at the Guggenheim Aeronautical Laboratory of the California Institute of Technology (GALCIT) to resolve the issue of the nature of the hull flow field at the propeller station. The test results[18] revealed that turbulent boundary layer flow at the propeller station was well attached and in good agreement with design expectations. The supposed laminar bubble was found to be present aft of maximum diameter and, although displaying the expected Reynolds number dependence, was quite benign in terms of downstream effects.

The measured drag coefficients (C_{DV}), referenced to 2/3 volume and corrected to 15 kn, are compared with the original design values in the following table:

Configuration	Measured C_{DV}	Design C_{DV}
Bare Hull	0.0116	0.0099
Four Fins	0.0039	0.0018
Appended Hull	0.0155	0.0117

The larger contributor to the drag discrepancy is the fins, which suffer from laminar separation aft of 60% to 70% of chord.

Since the wind-tunnel test revealed that the basic hull was performing in good agreement with design expectations, APL-UW postulated[19] that the advance ratio discrepancy and low propulsive coefficient could be a result of laminar separation on the propeller blades due to their low Reynolds number operation. During the original design process, the possibility of laminar separation on the propeller blades had been dismissed because the propeller would be immersed in the turbulent wake of the hull.

The second meeting of the ad hoc working group[20] on 5 January 1979 led to the recommendations that APL-UW seek a new standard propeller, possibly of the model-airplane type, in an effort to improve propulsive efficiency, and that the fins be redesigned to improve flow attachment. In April and June, a second wind-tunnel test series was conducted, this time at the University of Washington's 3-ft Venturi Tunnel.[21,22] Although intended primarily to evaluate candidate stock propellers through powered-model tests and to validate the selection of an NACA-16-006 section to replace the original NACA-0009 fin section, these tests were actually quite broad in scope, and included static stability tests to assess fin sizing, wake surveys of the self-propelled vehicle, flow visualization on the hull and fins, boundary layer measurements, etc. Unfortunately, it was not possible to test the original Web 2.75 propeller since, being of cast bronze, it could not be safely turned at speeds of 18,000 rpm as required for a test in air.

The results of the University of Washington wind-tunnel tests, presented at a third meeting of the ad hoc working group[23] on 31 July 1979, indicated a 2:1 improvement in the minimum fin profile drag and successful suppression of laminar separation over 83% of chord. The model-airplane propellers were disappointing performers, but the Octura 2.8 model-hydroplane propeller showed good promise.

Field trials on 29 October 1979 showed an improvement in the propulsive coefficient to values of 0.63 to 0.65 when using the Octura 2.8 propeller. However, these values fell short of expectations based on the wind-tunnel results. The Web 2.75 propeller repeated its previous deficient performance, yielding propulsive coefficients of about 0.54.

Resolution of the apparent discrepancy between the wind-tunnel results and the field-trial results for the Octura 2.8 propeller was accomplished by developing a mathematical modeling technique based on the application of thin-wing theory to a geometric definition of the propeller blade. The resultant analysis yielded theoretical thrust and torque characteristics that were in very good agreement with the field trial results, and with the wind-tunnel results after a "wild" data point had been deleted. The analysis showed that the Octura 2.8 propeller was operating with fully attached flow but was too lightly loaded, forcing operation at less than the peak propulsive coefficient of 0.74.

Analysis of the Web 2.75 propeller revealed that the design lift coefficient due to blade camber exceeded the required lift coefficient, forcing the blade to operate at a negative angle of attack. The negative angle of attack on the thin, highly cambered blade produced separation at the leading edge (negative stall). The excessive camber (~10%) resulted in laminar separation aft of midchord (rear stall) even at a negative angle of attack. Surprisingly, the analysis yielded operating point advance ratios that were in good agreement with the field-trial results; all earlier work had treated the apparently abnormal advance ratio as symptomatic of the underlying problem. A comparison of the original analysis by Flow Research with the present analysis led to the conclusion that the former incorporated an excessive correction for the flow curvature due to blade/flow-field interaction and suffered from the absence of a test for flow separation. Deletion of the apparently excessive flow curvature correction placed both analyses in good agreement with respect to advance ratio.

It was concluded that the AEMT speed/power problem resulted from a poor choice of propeller based on an analysis technique with certain deficiencies, and that correction of the problem was to be found in choosing a properly loaded propeller that would maintain attached flow under the design operating conditions. In the latter regard, it was determined that a smaller diameter propeller (Octura 1.8 or 2.0) of the same family as the Octura 2.8 should develop sufficient loading to achieve a peak propulsive coefficient of 0.74.

6. WIND-TUNNEL TEST DATA BASE

6.1 Scope of Tests at GALCIT

In addition to contributing to the resolution of the AEMT speed/power problem, the GALCIT wind-tunnel tests[18] have contributed to the technology data base for low-drag hull forms. The tests involved 38 runs at unit Reynolds numbers ranging from 0.4 to 1.0 million per foot, corresponding to vehicle speeds between 4 and 9 kn, and utilized turbulence management screens to achieve approximately a 0.1% free-stream turbulence level. Force balance data and boundary layer profiles in the tail region were recorded for both normal transition and tripped flow. Flow visualization utilizing a kerosene/talc mixture was accomplished on both the hull and the fins.

6.2 Scope of Tests at University of Washington

The test series in the University of Washington 3-ft Venturi tunnel[24] involved 72 runs without turbulence control and 47 runs with three layers of aircraft honeycomb installed at the entrance of the test chamber to reduce turbulence. In the high-turbulence environment, the unit Reynolds number was approximately 0.88 million per foot whereas in the low-turbulence configuration it was limited to 0.55 million per foot, or equivalent to a speed of 4.6 kn in fresh water. Force balance data, boundary layer profiles, and wake profiles were recorded for the hull with fins. Static stability tests, with and without fins, for both natural transition and for tripped flow were performed in the low-turbulence environment. Propeller screening tests measured the thrust and torque characteristics of a broad range of candidate propellers of both the model-airplane type and the model-hydroplane type while they were operating in the wake of the hull. Wake surveys of the self-powered vehicle yielded both velocity and static pressure profiles for equilibrium thrust as well as for non-equilibrium thrust conditions. Lift and drag data were gathered on both the original NACA-0009 fins and the new NACA-16-006 fins while the fins were mounted in a small ellipsoidal support body. Flow visualization utilizing a kerosene/talc mixture was accomplished both on the hull and on the fins, at various angles of attack.

7. HYDRODYNAMIC DESIGN ASSESSMENT

7.1 Hull Form

The hydrodynamic design used for the AEMT hull results in two distinct Reynolds number regimes. At the design Reynolds number, laminar separation and turbulent reattachment occur at essentially the same streamwise station, immediately downstream of the negative pressure peak (X/L = 0.659). Below the design Reynolds number, what has been termed "bubble transition"[25] occurs. The bubble between the laminar separation point and the turbulent reattachment point consists of a laminar free-shear layer followed by a reattachment zone of transitional flow, and characteristically grows in length with a reduction in Reynolds number. Above the design Reynolds number, natural transition occurs upstream of the previous laminar separation point, and laminar separation per se ceases to exist. All operation of the AEMT vehicle to date, both in the field and in the wind-tunnel tests, has been well below the design Reynolds number, which corresponds to a speed of approximately 18 kn.

The wind-tunnel test results indicate that operation below the design Reynolds number incurs no penalty in terms of flow attachment at the tail; a full turbulent profile occurs in all cases except those involving artificially tripped flow. Such operation does incur a penalty, however, in terms of induced drag; this penalty is most severe at speeds between 4 and 9 kn, where the bubble transition regime is rather extensive. The three independent analyses mentioned in Section 3 estimated an average hull drag coefficient of 0.0093 at 16.6 kn, a speed at which the design Reynolds number is closely approached. Applying a Reynolds number correction of $R_L^{-0.30}$ yields an indicated drag coefficient of 0.0112 at 9 kn when hydrodynamically similar flow conditions are maintained. However, the growth of the bubble transition regime destroys flow similarity and results in a drag coefficient discrepancy of about 20%; this discrepancy is primarily attributed to the presence of the laminar shear layer in the bubble. Noticeable softening of the steep adverse gradient in the pressure recovery region downstream of X/L = 0.75 is seen as constraining the growth of the bubble transition regime at speeds below 9 kn. The turbulent reattachment point at 4 kn, for example, is only slightly downstream of that at 9 kn. Thus the 4.6 kn data from the University of Washington wind-tunnel tests are consistent with the 9 kn data from the GALCIT tests when using the $R_L^{-0.3}$ scaling law.

No experimental data are available for operation of the AEMT hull form above the design Reynolds number. It is worthwhile to note, however, that the design philosophy explicit in Reference 1 provided for a short transition region in which well developed turbulent flow was to be established immediately upstream of an abrupt pressure recovery region. This philosophy was based on an attempt to emulate a Stratford-type pressure recovery[5] for which only well developed turbulent flow could be expected to negotiate the steep pressure gradient In the case of the AEMT hull, calculations indicate that the turbulent drag produced by the adverse gradient downstream of the negative pressure peak would be only 7% greater than that produced by the slightly steeper Stratford-type pressure recovery.[4] Operation of the AEMT hull above the design Reynolds number would produce early onset of turbulent transition and a corresponding increase in turbulent drag for which no offsetting gain would exist in the turbulent pressure recovery region.

The absence of premature turbulent transition that has been confirmed by flow visualization tests is clear evidence of the adequacy of the fabrication tolerances imposed by Reference 6. However, no experimental data have been gathered to assess the actual margins that exist on waviness and discontinuities, for example, compared with the predicted design margins.

In summary, it is judged that the hydrodynamic performance of the experimental AEMT hull involves no significant unknown factors and conforms closely to design expectations when due consideration is given to off-design operation at a reduced Reynolds number.

7.2 Fins

An assessment of the adequacy of the fin design must address the suitability of the variable-camber concept as well as the appropriateness of the choice of section and planform. From a structural/mechanical viewpoint, the variable-camber concept achieves the goals set for ease of contour control, simplification of flap fabrication, and freedom from linkage problems. Choice of materials and quality control measures have been found to be critical in fabricating the flexible portion of the fin, and some tooling difficulties have been experienced in molding the fins; however, these factors are not considered to detract from the basic suitability of the concept.

The concept is also successful from a hydrodynamic viewpoint. Although the demonstration model achieved a flap effectiveness factor ($\Delta\alpha/\Delta\delta$) of 0.15 compared with a design goal of 0.25, this discrepancy can be attributed to deficiencies in the original, simplified analysis of the torsional properties of the fin, which underestimated the flap deflection "washout" caused by the combination of torsional stiffness and hydrodynamic loading of the flexible aft portion of the fin. Fortunately, an increase in the gain of the automatic control system readily compensates for this discrepancy. The potential flap limiting at low speeds due to reduction of the flap effectiveness factor is not a problem in this application because the original requirement for 5 kn operation of the AEMT was later deleted.

The fin drag was improved by a change of section[26] which greatly reduced laminar separation. The lift of the fins was found to be insensitive to separation at low angles of attack. The fin lift effectiveness ($C_{L\alpha}S$) at low angles of attack was 0.34 compared with a design value of 0.30. At angles of attack in excess of about 2°, the lift curve slope for the NACA-16-006 fin was steeper than that for the NACA-0009, which it replaced; this increase is attributed to the appearance on the leading edge of a well defined laminar bubble that was not present on the original fin.

Static stability tests in the University of Washington wind tunnel revealed the fins to be less than 10% oversize with respect to achieving the design goal of neutral static stability.

7.3 Propeller

In view of the extensive coverage of the speed/power problem detailed in Reference 16, comments under the heading of design assessment are somewhat anticlimactic. Nevertheless, it should be noted that, even if the anticipated performance improvements are attained, a net propulsive coefficient of 0.74 is the best that would be achievable with the family of stock propellers (Octura Black Series) recommended for use on the AEMT. Reference 16 reveals that operation of the Octura propeller in the AEMT hull boundary layer is characterized by far from optimum blade loading--the lift coefficient being very high near the root and very low (or negative) near the tip--and that a wake-adapted propeller should produce an improvement. Of course, this comes as no surprise, since only economic factors precluded the procurement of a wake-adapted propeller for the original field trials. The noteworthy surprise is that a propeller like the Octura that is characterized by such non-optimum loading can produce such a relatively high propulsive coefficient. In view of this consideration, a propulsive coefficient of 0.80, the original design goal, should be readily achievable with a wake-adapted propeller.

8. SUPPLEMENTARY STUDIES

Although not utilized directly in support of the design of the AEMT vehicle, two supplementary studies were performed that are potentially applicable to the design of future low-drag vehicles.

8.1 Distributed Suction versus Geometric Shaping for Achieving Low Drag

A concept design study[27] was performed to assess the relative merits of distributed suction, of geometric shaping, and of combinations of the two on the hydrodynamic drag of a body of revolution. The applicability of geometric shaping alone was found to be constrained to maximum-length Reynolds numbers of 15 to 20 million, whereas the applicability of distributed suction apparently had no upper limit regarding Reynolds number. Computations using the torpedo-like shape of the Mk 38 as a reference revealed that distributed suction alone offered the potential for a 4.5:1 increase in the ratio of propulsive coefficient to vehicle drag coefficient; geometric shaping alone offered a 3.3:1 improvement. The combination of a shaped forebody and a suction afterbody offered a 6.1:1 improvement.

8.2 Cost Effectiveness

A study[28] of the relative cost effectiveness of vehicles with low-drag shapes and those with conventional torpedo shapes was made to assess the true "payoff" potential of low-drag technology. Cost effectiveness was measured in terms of weight of payload carried on a given mission per unit cost. The cost included only those systems that are affected by hull shaping; i.e., the hull structure and outfitting, the propulsion system, and the propulsion battery. It was found that a clear line of demarcation exists between the performance regime in which a conventional vehicle has superior cost effectiveness and that in which a low-drag vehicle is superior. The low-drag vehicle is superior for relatively small payloads on missions that demand high performance, whereas the conventional vehicle is superior for very large payloads on low performance missions.

9. RECOMMENDATIONS FOR FUTURE DESIGNS

As a consequence of the experience gained in the exploratory development effort of the AEMT vehicle, the following recommendations can be made relevant to the hydrodynamic design and development of future low drag vehicles.

(1) The fluid dynamic design philosophy inherent in the AEMT hull form should be retained.

(2) The variable-camber fin concept should be retained, but a structural/hydrodynamic analysis should be performed to optimize control effectiveness in the presence of hydrodynamic loading on the flexible structure.

(3) A wake-adapted propeller should be designed with special consideration given to a choice of section that will be free of laminar separation.

(4) A self-powered model wind tunnel test should be performed to confirm the hull and fin flow conditions and to evaluate the vehicle drag and propeller propulsive coefficient in the wake of the hull.

(5) Wind-tunnel tests should be performed to assess the margins available in the selected contour tolerances and to assess the impact of off-design operation of the vehicle.

(6) A prototype field-trial vehicle outfitted with an on-board data-acquisition system should be utilized to validate hull flow conditions and propulsion parameters.

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This report summarizes work on hydrodynamics technology conducted in support of the Advanced Expendable Mobile Target, a NAVSEA exploratory development program directed toward demonstrating the application of low-drag vehicle technology to a small, expendable acoustic training target. The summary includes descriptions of the analyses used to support the design effort in the areas of laminar and turbulent boundary

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layer flow, potential flow, propeller performance, fin design, and hull contour tolerances. Also included are descriptions of a trim and balance problem and a speed and power problem, both discovered during instrumented field trials, and the ensuing investigations that led to their resolution. These investigations encompassed two wind-tunnel test programs which included powered-model testing. The adequacy of the hydrodynamics technology base to support similar designs is assessed on the basis of field-trial experience and the resolution of all outstanding hydrodynamic problems. Finally, supplementary studies offering future design options are described and recommendations made for future development programs.