frequency could be effected. At this writing it is felt that the significant fault may be in the strength of material approximation to wing stiffness. This type analysis implicitly assumes, as is usual in swept wing analysis, that a lateral force to the elastic axis produces no twisting. Since frequency appears to be the variable which has an undesirable trend, it is felt that the effect of fluid and inertial forces on wing twist should be considered for nonrectangular plan forms.

Conclusions

The theory presented appears to provide a reasonably consistent divergence speed up to sweep angles of 20°. However flutter frequency appears to have a trend which indicates further refinement is still necessary to completely describe the behavior of the foil. It is suggested in the text that it is felt that the strength of material approximation may be the cause of the flutter frequency variation determined, and the incorporation of wing twist due to lateral loads at the elastic axis of a foil, with a large sweep angle, may improve this frequency characteristic of this solution.

References

[1] Dugundjii, J. and Ghareeb, N., "Pure Bending Flutter of a Swept Wing in a High Density, Low Speed Flow," Fluid Dynamics Research Group Rept. 64-1, March 1964, MIT, Cambridge, Mass.

[2] Yates, E. C., Jr., "Flutter Prediction at Low Mass Density Ratios with Application to the Finite-Span Subcavitating Hydrofoil," AIAA Paper 68-472, San Diego, Calif., 1968.

[3] Rowe, W. S., "Collocation Method for Calculating the Aerodynamic Pressure Distributions on a Lifting Surface Oscillating in Subsonic Compressible Flow," *AIAA Symposium on Structural Dynamics and Aeroelasticity,* AIAA, New York, 1965.

[4] Chu, W. and Abramson, N., "Further Calculations of the Flutter Speed of a Fully Submerged Subcavitating Hydrofoil," *Journal of Hydronautics,* Vol. 3, No. 4, Oct. 1969, pp. 168–174.

[5] Mahig, J., "Theory for the Determination of the Flutter Speed of a Class of Hydrofoils," *Journal of Engineering for Industry,* Vol. 94, Ser. B, No. 1, Feb. 1972, pp. 76–80.

[6] Huang, T. T., "Experimental Study of a Low Modulus Flutter Strut for a Hydrofoil System," *Journal of Hydronautics,* Vol. 2, No. 4, Oct. 1968, p. 198.

[7] Kemp, N. H. and Sears, W. R., "The Unsteady Forces Due to Viscous Wakes in Turbomachines," *Journal of Aeronautical Sciences,* Vol. 22, 1955, pp. 478–483.

[8] Baird, E. F., Squires, C. E., Jr., et al., "Investigation of Hydrofoil Flutter," Final Rept. DA10-480-3, Feb. 1962, Grumman Aircraft Engineering Corp, Bethpage, N.Y.

[9] Baird, E. F., Squires, C. E., Jr., and Caporali, R. L., "An Experimental and Theoretical Investigation of Hydrofoil Flutter," *Aerospace Engineering,* Vol. 21, No. 2, Feb. 1962, pp. 34–41.

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Impressed-Current Cathodic Protection of Aluminum-Hulled Craft

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Overprotection is a major problem accompanying cathodic protection of aluminum-hulled craft. Investigations were conducted concerning the protection and overprotection of aluminum under various conditions of galvanic coupling, seawater velocities and dilutions, dielectric shield materials, lengths of exposure and influence of seawater location. Overprotection was found to occur above −1500 mv, the exact value depending on seawater velocity and other conditions. The corrosion resulting from overprotection was severe, making imperative a protection system design which eliminates the possibility of accidental overprotection. Data is presented which can aid in the design of a reliable protection system.

ALUMINUM alloys of the 5000-series are used for the hulls of hydrofoils, surface effect ships, and other weight-critical craft. While these alloys have good inherent resistance to corrosion in seawater, they are subject to accelerated attack if electrically connected to other structural alloys. The galvanic effect of coupling dissimilar metals in this electrolyte results in accelerated attack of the anodic member of the couple. Aluminum alloys are anodic to copper, nickel, and titanium alloys, steels, and any other common structural materials used for propellers, hydrofoil struts and foils, and seawater systems. In addition, metal barges or docks which might be accidentally coupled to an aluminum-hulled craft through a gangway or wire rope may also be constructed of these materials.

Use of a "protective" coating on the anodic alloy is likely to be more harmful than beneficial. Since some flaws or breaks in the coating are probable, the coating only serves to reduce the effective anodic area of the imperfections, leading to rapid attack in localized areas. Although coating of the cathodic materials is the recommended approach to reduce the galvanic current acting on the anodic material, this is not practical on aluminum craft where many of the other alloys encountered are in parts not suitable for coatings. Also, the aluminum hull should be coated for fouling resistance. For these reasons a cathodic protection system is required.

Several types of cathodic protection systems have been used on aluminum ships including zinc anodes, magnesium anodes, sprayed zinc coatings, and impressed-current systems. This note concerns the use of impressed-current systems such as illustrated in Fig. 1. A varying potential is applied between the hull and hull-mounted anodes in order to keep the hull at a constant potential relative to a Ag-AgCl reference cell. Two cells, several inches across, are usually located in the hull, well away

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Received July 10, 1972; also presented as Paper 72-593 at the AIAA/SNAME/USN Advanced Marine Vehicles Meeting, Annapolis, Md., July 17-19, 1972; revision received March 22, 1973.

Index categories: Marine Surface Vessel Systems; Corrosion/Erosion of Marine Materials.

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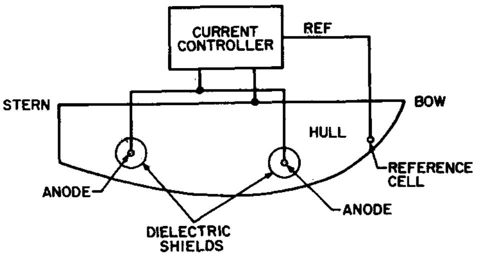

Fig. 1 Impressed current cathodic protection system.

from the anodes. One may be used as a spare or as a check on proper operation of the reference cell controlling the system. Depending on the craft, 2-6 anodes, about 1 ft in diameter can be used. They are generally lead-silver, platinum-coated titanium, or platinum-coated tantalum. Surrounding the anodes for 2-4 ft is a thick, waterproof, nonconductive material called the dielectric shield. In the absence of this shield the current would follow the path of least resistance to the hull and, therefore, be concentrated in the area surrounding the anodes. The shield increases the distance and voltage drop through the water, thereby lowering the apparent anode potentials at the hull beyond.

Impressed-current cathodic protection systems have been used effectively on aluminum-hulled craft. There have, however, been some problems related to electrical design faults, inadequate failsafe devices and dielectric shield failures. The major problem which can result from improper control on aluminum craft is overprotection. This condition occurs when the potential of the protected metal is too cathodic, creating hydroxyl ions and a condition of alkalinity at the cathode-seawater interface. Aluminum, being amphoteric in nature, may be rapidly corroded by a high pH environment; steel, however, is not affected. Therefore, overprotection corrosion is a problem which exists only on aluminum and not steel, craft.

Review of Service Problems

Adherence failure or mechanical damage of the dielectric shield material may cause localized corrosion near the anodes where voltages may exceed −1.5 v. This is shown in the anode potential scan in Fig. 2. Shield failure may also be caused by an electrical malfunction in a controller which has no failsafe features. This malfunction could cause excessive anode voltages which blister the shield. The corrosion resulting from overprotection at failed shields has been known to completely penetrate a ¼ in. thick hull approximately one month after shield failure. The potential applied to the anode in this failure was believed to be much greater than those illustrated in Fig. 2.

Table 1 Corrosion of 5456-H117 aluminum galvanically coupled to various alloys

Alloy coupled to 5456	Rate (mil/year) 8 fps 40 days	Rate (mil/year) 13 fps 30 days
Monel 400	76.7	62.3
70-30 Cu-Ni	75.3	72.7
AISI 1040	67.9	100
Ni-Al bronze	65.7	90.3
HY-80 steel	51.7	70.7
IN625	51.6	66.1
Hast C	42.1	68.3
3045.5.	38	58
Ti-6Al-4V	35.5	59.1
Zinc	2.3	6.4
5086 Al	2.1	—
Uncoupled	2.4	5

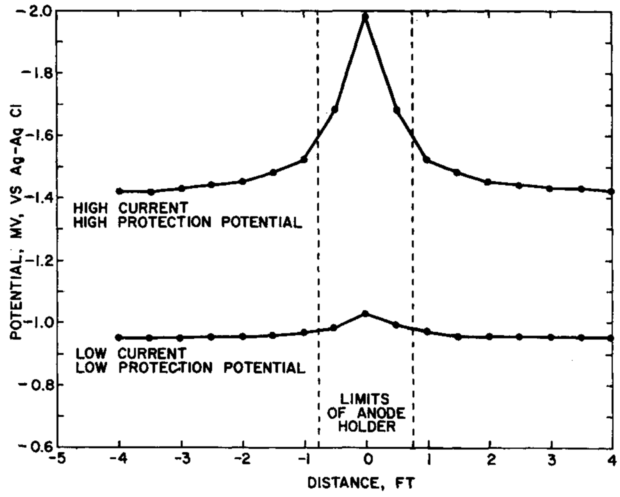

Fig. 2 Potential across a dielectric shield.

Such electrical failures may also be due to either shorts or breaks in the reference cell connection, a faulty or erratic reference cell, or improper selection of maximum and minimum currents. If the minimum current output of the controller is too high it may cause overprotection of aluminum craft with freshly coated appendages. The newly coated appendages have little exposed area to absorb the anode current. One vessel has had its unit made operational by bypassing a portion of the excessive controller output current through an external resistance.

Even properly designed units without an appropriate maximum potential limit may cause overprotection if the craft is accidentally coupled to a steel barge or dock, demanding additional current and overdriving the system. Large negative potentials in the range where aluminum experiences overprotection may also have deleterious effects on certain materials coupled to the aluminum hull. For instance 17-4PH stainless steel presently used in come hydrofoil struts and foils may be embrittled by the hydrogen evolved at the more negative potentials.

Laboratory Investigation

Tests were performed on unprotected 5456-H117 aluminum specimens to determine the current and potential demands on the protection system under various conditions of galvanic coupling.

Open Circuit Potentials

Open circuit potentials of aluminum indicate the minimum potentials to which a hull can be protected. Unprotected specimens of aluminum alloy 5456-H117 were immersed in fresh seawater at Harbor Island, N.C. and

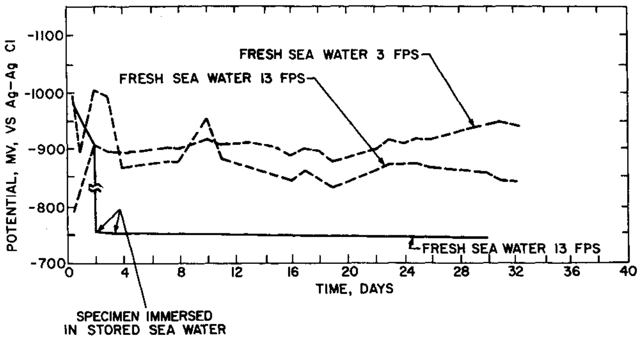

Fig. 3 Open-circuit potentials of 5456-H117 aluminum in Harbor Island seawater.

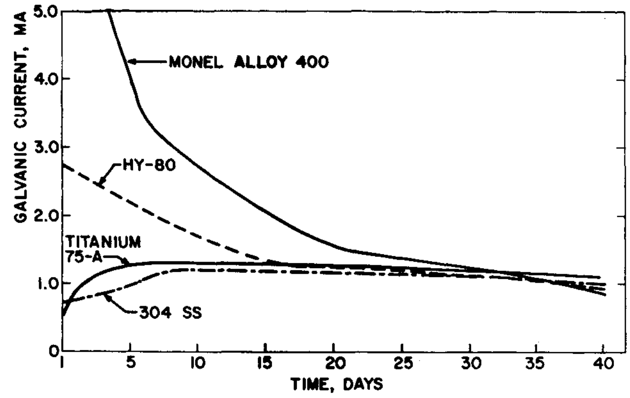

Fig. 4 Stabilization of galvanic current in the 8 fps test.

Puget Sound, Wash. Specimens were also exposed at Annapolis in seawater shipped from Harbor Island. Open-circuit potentials vs an Ag-AgCl half-cell were monitored and recorded over a 40-day period. Figure 3 illustrates the variety of potentials displayed under the various conditions of immersion in Harbor Island seawater. In Puget Sound seawater, the potentials all fell between −730 and −770mv. This may be related to a difference in seawater chemistry at the two locations. Brief immersion in stored seawater at Harbor Island was found to stabilize the potential at less negative values.

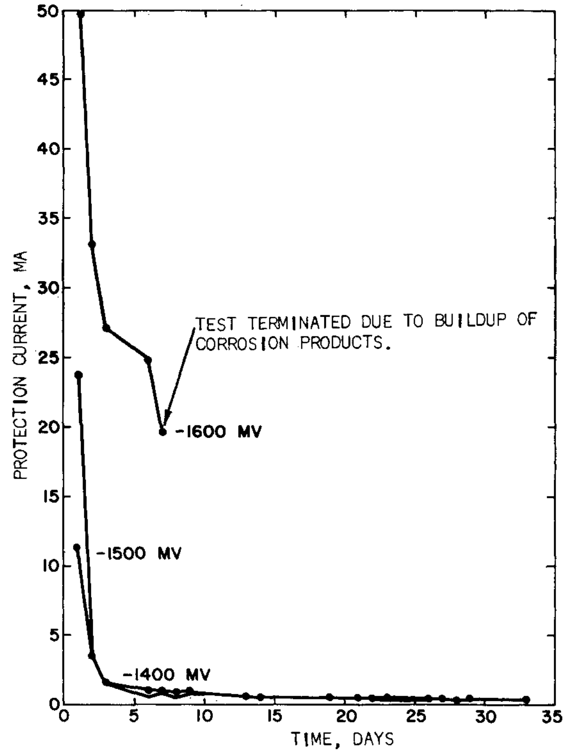

Fig. 6 Current variations of cathodically protected 5456-H117 Aluminum, 8 fps.

Galvanic Coupling

Galvanic couples were created by affixing plates, $1\frac{3}{16} \times 2\frac{7}{8} \times \frac{1}{4}$ in., of 5456-H117 aluminum and of the material to be coupled, in a flowing seawater test cell at Harbor Island. Specimens were positioned facing each other, $\frac{1}{4}$ in. apart, secured and electrically coupled from the outside of the cell. Wetted area of each plate was 2.8 in.^{2}. Natural seawater was pumped between the plates at two velocities, 8 and 13 fps. The weight loss was measured after 30–40 days and corrosion rates were calculated.

Table 1 shows that acceleration of corrosion due to the coupling is large for all materials tested except zinc; from 2–5 mils/year for uncoupled aluminum to 35–100 mils/year when coupled. Representative current-time curves in Fig. 4 show that the galvanic current stabilized within 3 weeks to approximately the same value for all materials, 1.0 ma. The Monel and HY-80 curves are representative of most of the materials tested. The only two exceptions, titanium and 304 stainless steel, showed an initial current increase instead of a decrease.

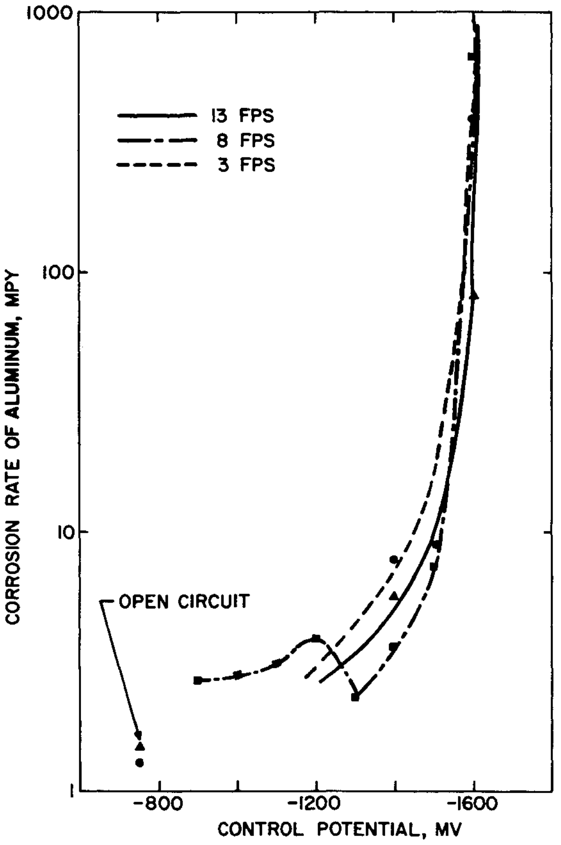

Fig. 5 Corrosion rate of cathodically protected aluminum.

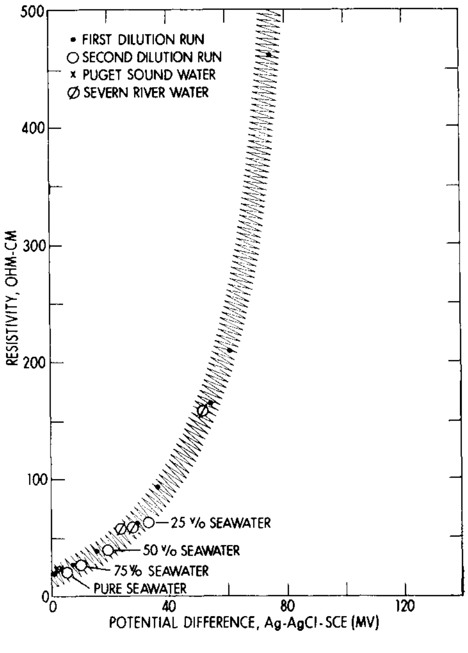

Fig. 7 Ag-AgCl potential shift with seawater dilution.

Constant-Potential Studies

Figure 5 shows corrosion rates of 5456-H117 aluminum vs control potential at seawater velocities of 3, 8, and 13 fps. In these tests, potentiostats were employed to maintain constant control potentials ± 10 mv. The anodes used were platinum-coated titanium and the reference cells were Ag-AgCl. Test lengths were 30–35 days.

Between −1300 and −1500 mv the total amount of corrosion increases slightly. This probably is due to higher initial corrosion rates, as can be seen in Fig. 6 which presents protection current vs time.

Curves at the more negative potentials up to −1500 mv start with initially higher current, but the differences disappear with time. Overprotection begins to occur between −1500 and −1600 mv at all velocities. At −1600 mv the curve does not level off rapidly, indicating that the initial corrosion continues. The drop in current with time may be due to the buildup of calcareous deposits on the cathodic aluminum surface. Therefore, −1500 mv should be the maximum protection potential permitted on uncoated aluminum using a cathodic protection system.

Dielectric Shield Studies

Resistance of two dielectric shield materials to imposed voltages was studied. Both materials, an epoxy mastic and a cold tar epoxy are in use on cathodically protected aluminum or steel vessels. Several of the 5456-H117 aluminum specimens were coated with these materials, and a pinhole was drilled through the coating on each to simulate a break. These plates were immersed at Harbor Island and a 6.0 v potential applied between the specimen and a platinized titanium electrode. The specimen was cathodic. Test duration was 6 months. The epoxy mastic material proved superior, showing no signs of blistering or deterioration.

Seawater Dilution Effects

Diluted seawater would be encountered if the craft were to cruise into fresh-water bodies. The potential of Ag-AgCl reference cells varies with chloride content, whereas that of saturated calomel electrodes (SCE) does not. It is not practical however to use SCE on an operating vessel due to dilution of fluid in the cell with seawater. The magnitude of the potential drift of the Ag-AgCl cell in fresh water relative to SCE is therefore important in determining the operation of the cathodic protection system in rivers or lakes.

Water taken from Harbor Island, Puget Sound, and the Severn River in Maryland was used in these tests. The Harbor Island seawater was used in the dilution runs. The magnitude of the potential shift was less than 80 mv, even in highly diluted seawater (Fig. 7). The direction of the shift was positive, away from the lower overprotection limits. Therefore, the net effect of reference cell shift on the system should be small, without danger of overprotection. However, for hull potential to remain constant as seawater resistivity increases, higher anode voltages are necessary due to the greater voltage drop through the seawater adjacent to the dielectric shield. This increases the possibility of overprotection near the dielectric shield.

Conclusions

Severe corrosion due to overprotection will occur on aluminum in seawater where the potential is more negative than −1500 mv. This can be avoided on craft with impressed current cathodic protection systems by using a suitable shield material, properly applied, and by preventing the current controller from overdriving the anodes.

The controller design should include features to suppress the current if the reference cell is either disconnected or shorted to the hull. A second reference cell might be placed adjacent to the shield to detect protection voltages more negative than −1.5 v and either suppress the current automatically, or sound a warning. This would automatically detect accidental coupling to steel barges or docks. The same warning device could be used to signal reference cell shorts or disconnection. Finally, the controller unit should be designed to deliver minimum currents lower than those delivered by impressed current systems designed for use on steel-hulled vessels.

The results of this investigation indicate that with proper attention to selection of equipment and with special emphasis on quality of dielectric shield materials, aluminum-hulled craft may be satisfactorily protected from galvanic corrosion effects.

References

[1] Deltombe, E. and Pourbaix, M., "The Electrochemical Behavior of Aluminum," *Corrosion,* Vol. 14, No. 11, Nov. 1958, pp. 496–500t.

[2] Draley, J. W and Ruther, W. E., "Aqueous Corrosion of Aluminum," *Corrosion,* Vol. 12, Sept. 1956, pp. 441t–448t.

[3] Ailor, W. H., "Flowing Sea Water Corrosion Potentials of Aluminum Alloys," Paper 36, NACE 26th Annual Conference, Philadelphia, Pa., March 2–6, 1970.

[4] Niederberger, R. B., Basil, J. L., and Bedford, G. T., "Corrosion and Stress Corrosion of 5000-Series Al Alloys in Marine Environments," *Corrosion,* Vol. 22, No. 3, March 1966, pp. 68–73.