Journal of Applied Electrochemistry 31: 105–113, 2001.

Dynamic characteristics of ship impressed current cathodic protection systems

D.J. TIGHE-FORD[1,2], P. KHAMBHAITA[2], S.D.H. TAYLOR[2] and A. RAYNER[2]
[1]*Cathodic Protection Unit, Royal Military College of Science, Shrivenham, Great Britain*
[2]*Formerly at the Royal Naval Engineering College, Manadon, Plymouth, Great Britain*

Received 28 April 2000; accepted in revised form 20 July 2000

Key words: control system, impressed current cathodic protection, modelling, switch-on, underway conditions

Abstract

Physical scale modelling was employed to identify the characteristics of the closed loop control systems for ship impressed current cathodic protection (ICCP) for different hull and operational conditions with three ICCP configurations. A one-hundredth scale metal model hull, with intact and damaged paint coatings, and with a damaged plastic cladding, were protected by ICCP under static and flowing electrolyte conditions. The three types of ICCP system all showed at least second order control characteristics in response to switch-on in static conditions. The damping ratios and natural frequencies of the dominant mode depended upon the hull condition and the ICCP system configuration. Characteristics of two single zone systems changed when they were combined as a two-zone configuration. Maximum peak overshoots, and times to overshoot, were lower with an intact paint coating than with a damaged, whereas natural frequencies and damping ratios were higher. Less damping occurred with damage to cladding than to a paint coating. In response to simulated underway conditions, driving voltages were oscillatory. Damping ratios were much lower than in static electrolyte and natural frequencies were higher. Such studies provide further insight into the processes of ICCP.

1. Introduction

Cathodic protection is an electrical method for controlling metallic corrosion in an aqueous environment in which the structure to be protected is polarized so that surface electrochemical potentials are made more negative (i.e., cathodic), thus driving the corrosion equation (Equation 1) to the left:

$$M \rightleftharpoons M^{n+} + n\,e^- \tag{1}$$

A metal can be regarded as effectively protected when its potential has been negatively polarized some 150 to 200 mV from its free-corrosion value. For mild steel in aerated seawater, a value between −800 to −850 mV relative to the silver/silver chloride (SSC) electrode is generally considered to be necessary. Polarization at sea is achieved either by the dissolution of attached sacrificial anodes, made of aluminium or zinc alloys, or by impressing a current from a d.c. power supply in conjunction with nonconsumable anodes.

Impressed current cathodic protection (ICCP) is widely employed in conjunction with surface coatings to control the corrosion of the underwater hull of ships. The potentiostatic ICCP systems (Figure 1) normally fitted employ closed loop control in which the current output from a d.c. power supply is controlled via a reference electrode (RE) which measures surface potential in its vicinity. This potential is compared with the required protection value (set potential), typically −800 or −850 mV vs SSC. System current output is then varied, via the driving voltage of the power supply, to maintain a zero error signal and hence a constant potential at the RE. Current output is thus controlled automatically in response to the state of the hull and operational conditions and the system is, therefore, demand-responsive. The processes involved in cathodic protection are essentially electrochemical phenomena at the interfaces between the seawater and the cathodic hull (and the anodic surfaces). ICCP system current output, as determined via the maintenance of the set potential in the vicinity of the RE(s), will be affected by a number of factors, such as surface condition, coatings and the presence or absence of flow.

An ICCP system can be single zone as shown in Figure 1 (one power unit with an RE, supplying a number of anodes) or multizone with two or more power supplies and REs. Physical scale modelling studies (e.g., [1]) have shown that system configuration is critical, that is, the number and location of zones, REs and anodes relative to the hull in general, the nonferrous propellers and each other. Configuration will determine system characteristics such as potential profiles over a hull and current outputs. Thus, it might be expected that for a ship, the establishment of the set potential at an RE following initial switch-on at anchor, and the

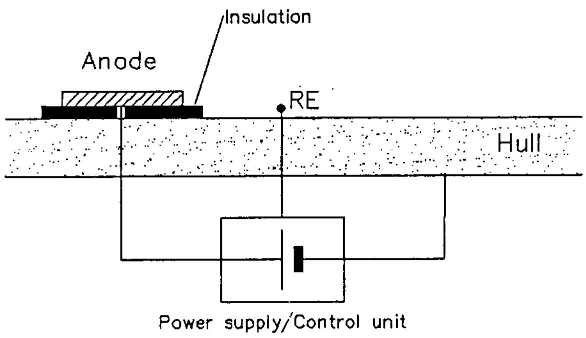

Fig. 1. Ship potentiostatic ICCP.

responses to flow past the hull as a result of underway conditions, will be largely determined by the condition of the hull and its coatings and, possibly, by the configuration of the ICCP system.

As part of an experimental programme on developing the understanding of ICCP and designing optimum systems for ship and other marine systems, studies have been made of the control mechanisms involved. The dynamics of potentiostatic ICCP while in its transient state, that is, from switch-on to establishment of the set potential at the RE, can be described by a transfer function, namely, the relationship between input (θ_i) and output (θ_o). The order of such a function is proportional to the complexity of the system (e.g., [2]). The identification of a system constitutes determination of this transfer function; one method is comparison of time responses from experimental observation and control theory. Figure 2 shows typical responses for first and second order systems when a step input is applied. First order responses exhibit a continuous build-up to the required output. With a second order system, there is an overshoot followed by an undershoot before the required output is established. Associated with each response is a standard form of transfer function which can be expressed as follows:
First Order

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{K}{1 + \tau s} \tag{2}$$

Second Order

$$\frac{\theta_o(s)}{\theta_i(s)} = \frac{K\omega_n^2}{s^2 + 2\,\zeta\omega_n s + \omega_n^2} \tag{3}$$

where τ is the time constant, ω_n the natural frequency, ζ the damping ratio, K the gain, and s the Laplace operator.

1.1. *Previous system identification*

A preliminary study [3] of the identification of the control characteristics of a single zone ship ICCP configuration was carried out employing physical scale modelling, which is an experimental approach to examining system performance (e.g., [4, 5]). This first examination of control phenomena was based on the DACS (dimension and conductivity scaling) technique [4] in which a one-hundredth scale metal model of the underwater area of a hull was protected by ICCP in seawater diluted to an electrical conductivity one-hundredth that of 'standard' seawater. It was found that after initial switch-on, the closed loop transfer function while the set potential was being established at the RE was at least second order. As shown in Figure 3, the characteristics of the control system in response to a step input (X) from the free corrosion value of the unprotected model to the set potential following switch-on in static conditions were such that a peak overshoot (M_p) occurred at a time t_p after switch-on, before the potential at the RE was established at its set value.

As soon as the system had been identified the various constituent parts of the standard form in Equation 3 were derived. The dynamic behaviour, as described by the natural angular frequency (ω_n) and damping ratio (ζ), was determined, via Equations 4 and 5 below, from values of M_p and t_p obtained from the experimentally measured system time response:

$$\zeta = \sqrt{\frac{(\ln M_p - \ln X)^2}{(\ln M_p - \ln X)^2 + \pi^2}} \tag{4}$$

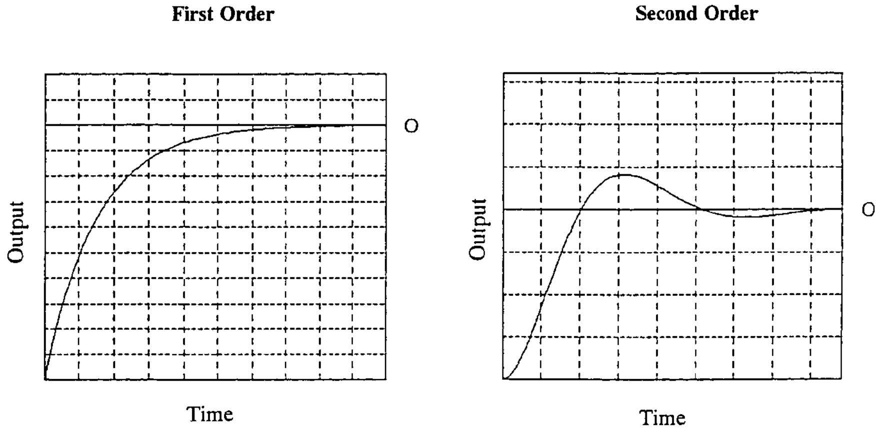

Fig. 2. Time responses for first and second order transfer functions following a step input; (O) required output.

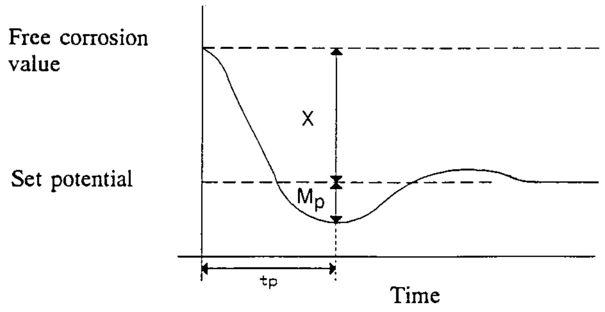

Fig. 3. ICCP second order response to switch-on.

$$\omega_n = \frac{\pi}{t_p\sqrt{1-\zeta^2}} \tag{5}$$

The hull–ICCP system was found to have a low damping ratio of 0.52 and a natural angular frequency of 0.45 rads s^{-1}; a damping ratio within the range of 0.4 to 0.8 is considered to be satisfactory for practical second order control systems.

This preliminary study was carried out with a model coated with a water-impermeable cladding, such as used for submarines, with areas of bare steel to represent coating damage. This was a two-component cathode; that is, the exposed steel hull and the bronze disc employed to represent propellers. The model was protected in static conditions, only, by an All-aft single zone ICCP system, with one anode and the RE located at the stern. A ship, however, is a complex cathode with usually three components: the underwater ferrous hull covered by water-permeable paint coatings (or impermeable claddings), bronze propellers and areas of bare steel exposed as a consequence of coating or cladding damage. The hull may be exposed to static or flowing electrolyte conditions when at anchor or underway at sea. These are very different conditions in relation to cathodic surface processes and polarization requirements. Also, there are various types of ICCP system and these have been shown to respond differently to coating damage and underway conditions in relation to the protection profiles produced along a hull and current outputs from the ICCP system (e.g., [1]). This paper describes an examination of the effects of hull state, flow conditions and ICCP configuration upon the dynamic control characteristics of three different types of ICCP system.

2. Materials and methods

A one-hundredth scale metal model of the underwater area of a generic hull (representing an 89.7 m overall length vessel) was protected in appropriately diluted seawater by a PC based software controlled potentiostatic ICCP control system. Data acquisition facilities were incorporated to measure the responses at the RE(s), the driving voltages of the d.c. power supply and surface potentials along the model. Three different hull states were protected by three ICCP system configurations in static and flowing seawater electrolyte conditions.

On the basis that potentiostatic ship ICCP following switch-on in static conditions has previously been identified as satisfying the characteristics of a second order control system [3], natural frequencies and damping ratios were derived (Equations 4 and 5) from experimentally observed values of M_p and t_p at the RE according to Equations 4 and 5. The responses at the RE of the different ICCP systems to flow – simulating a ship getting under way – were examined as oscillatory responses (Figure 4) according to Equation 6.

$$\zeta = \sqrt{\frac{(\ln m_k - \ln m_{k+2})^2}{(\ln m_k - \ln m_{k+2})^2 + 4\pi^2}} \tag{6}$$

2.1. *Model hull*

The model (Figure 5) was constructed from a shaped half-cylinder of mild steel bar (0.15% C) with a length of 897 mm and a diameter of 50 mm. A 12.5 mm radius half disc, 5.0 mm thick, of nickel aluminium bronze (9.27% Al, 4.26% Fe, 4.15% Ni, remainder Cu) was attached to one end to represent propellers/propulsor. The model was either clad with polyethylene in a fluidized hot plasticising bath or painted with a 225 μm thickness of coal tar epoxy. Coating damage in both cases was represented by exposing six areas of bare steel comprising 5% of the hull. Transverse strip anodes were prepared from lengths of 0.16 mm diameter platinum wire. Miniature SSC electrodes were employed as REs and, as an array, to measure surface potential profiles. This flat surface of the half-hull model was glued to an acrylic sheet and attached, immersed, to the side of an acrylic recirculating flow tank holding seawater diluted to an electrical conductivity of 53.0 mS m^{-1} (i.e., one-hundredth that of 'standard' seawater).

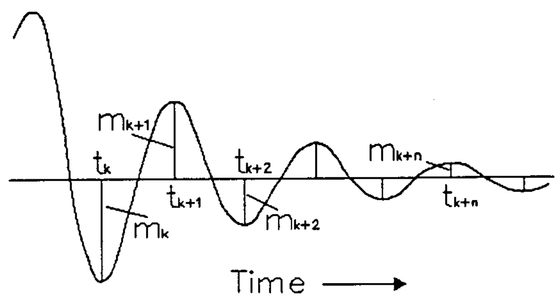

Fig. 4. Oscillatory under damped response.

2.2. *ICCP systems*

As shown in Figure 5 three types of ICCP system configuration were examined: All-aft single zone, Midship single zone and a combined two-zone system.

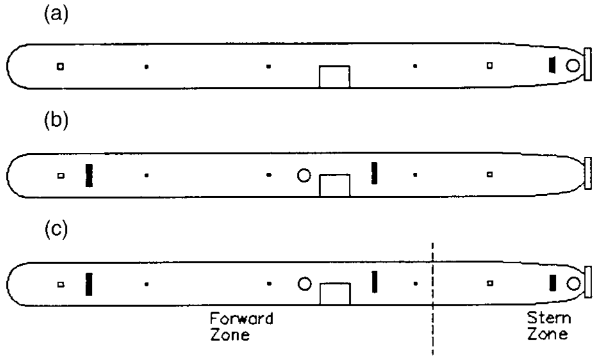

Fig. 5. Model hull, ICCP system configurations: (□) coating damage; (▌) anode, (○) RE. (a) All-aft single zone (one anode); (b) Midship single zone (two anodes); (c) two-zone (three anodes).

2.3. *Control and data acquisition*

An ICCP power supply/control system for each configuration was replicated by a PC-based system, as described previously [3]. Potentiostatic control of the impressed current was performed by a comparator routine within a software programme written in PASCAL which controlled current output via a digital-to-analogue converter (Figure 6). Potentials at an RE were sampled at intervals of 0.1 s. Data on time responses and driving voltages were transferred to a VAX computer for analysis via the MATLAB mathematical applications software package. A set potential of −800 mV vs SSC was employed throughout.

After potentials along the unprotected model had been allowed to settle in static conditions, a step input from the free-corrosion value at the RE to −800 mV was impressed for each hull state and ICCP system. Responses to flow were then determined after potential profiles along the protected hull had settled. Dotted lines on the profiles presented in following Figures represent the upper and lower limits of protection specified in the Naval Engineering Standard (NES); that is, ±50 mV from the set potential.

3. Characteristics of the All-aft single zone ICCP system

3.1. *Potential profiles over model hull*

The profiles produced along the protected model with the three different hull states in static and simulated under way conditions were similar for the three states, and are illustrated by the damaged paint coating (Figure 7). With this hull condition, the unprotected potential before switch-on was −240 mV (which determined the step input (X) of −560 mV to the set potential). The All-aft ICCP configuration provided poor protection, with the settled potential profile along most of the model lying at or just outside the −750 mV NES limit under static conditions with a negative spike at the anode: current output was 0.421 mA. The overall profile became markedly less negative in response to flow, despite current increasing to 0.884 mA with more negative anode spikes. Similar profiles were produced with a damaged cladding. With an intact paint coating, the potential profiles lay within both NES limits except for negative anode spikes.

3.2. *System dynamic responses*

System time responses at the RE and driving voltages were similar in form for all three hull states (as illustrated for damaged cladding in Figure 8). Nevertheless, dynamic characteristics varied according to

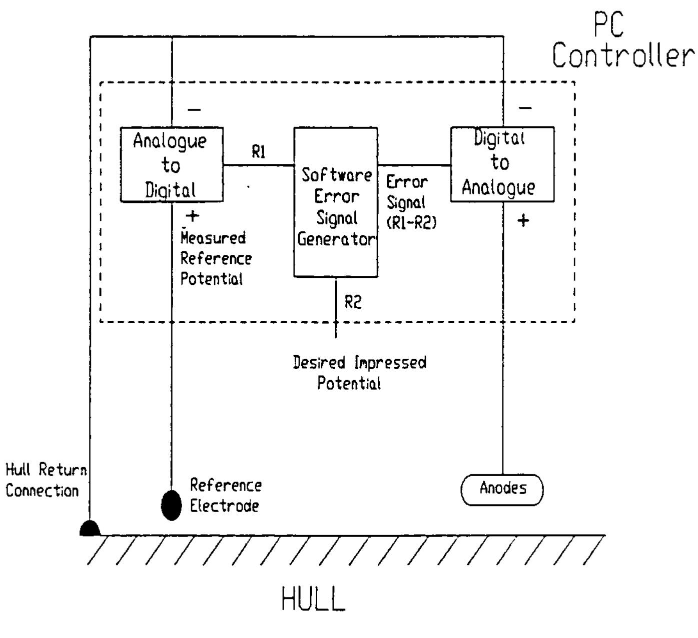

Fig. 6. ICCP control system circuit diagram.

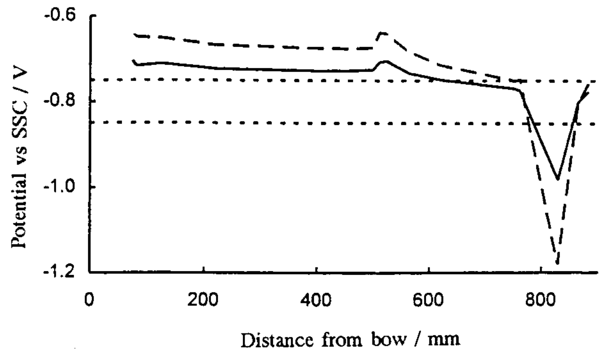

Fig. 7. All-aft single zone ICCP system; potential profiles over model hull with paint damage. Key: (——) static, (– – – –) flow conditions.

Table 1. Dynamic characteristics of model All-aft single zone ICCP system

Experimental condition	M_p/mV	t_p/s	ζ	ω_n/rad s^{-1}
Static switch-on				
Painted hull (intact)	27	4.2	0.693	1.04
Painted hull (damaged)	36	5.1	0.656	0.816
Clad hull (damaged)	56	4.3	0.603	0.916
Flow response				
Painted hull (intact)			0.290	2.40
Painted hull (damaged)			0.257	2.28
Clad hull (damaged)			0.225	3.10

whether the model was clad or painted, and whether the latter coating was intact or damaged.

Potential responses at the RE exhibited second order characteristics, with M_p values ranging from 27 to 56 mV more negative than the set potential of −800 mV (Table 1). The lowest overshoot occurred with intact paint and the greatest with damaged cladding. The intact paint coating resulted in the highest damping ratio (0.693) whereas the lowest (0.603) was with the damaged clad model. The highest natural frequency (1.04 rads s^{-1}) for the ICCP system occurred with intact paint.

Driving voltages following switch-on increased rapidly (Figure 8), peaking before the potential at the RE reached its maximum overshoot prior to settling at −800 mV. The lowest voltage peak was 4.6 V with an intact paint, compared with 5.3 and 5.5 V for the damaged paint and damaged cladding, respectively.

Potentials at the RE in response to flow (Figure 8) initially became less negative than the established −800 mV and then, following an overshoot and oscillation, settled again at the set value. Driving voltages for the system increased as the potential at the RE initially became less negative in response to flow, still increasing as the RE was at its least cathodic value, and then oscillated in a manner reflected by the potential values. The overall driving voltage response to the onset of flow conditions was very different from that following switch-on, being oscillatory. Damping ratios were much lower than under static conditions, ranging from 0.225 to 0.290. Again, the highest damping was with an intact paint coating and the lowest with damaged cladding. Natural frequencies, ranging from 2.40 to 3.10 rads s^{-1}, were much higher than for switch-on.

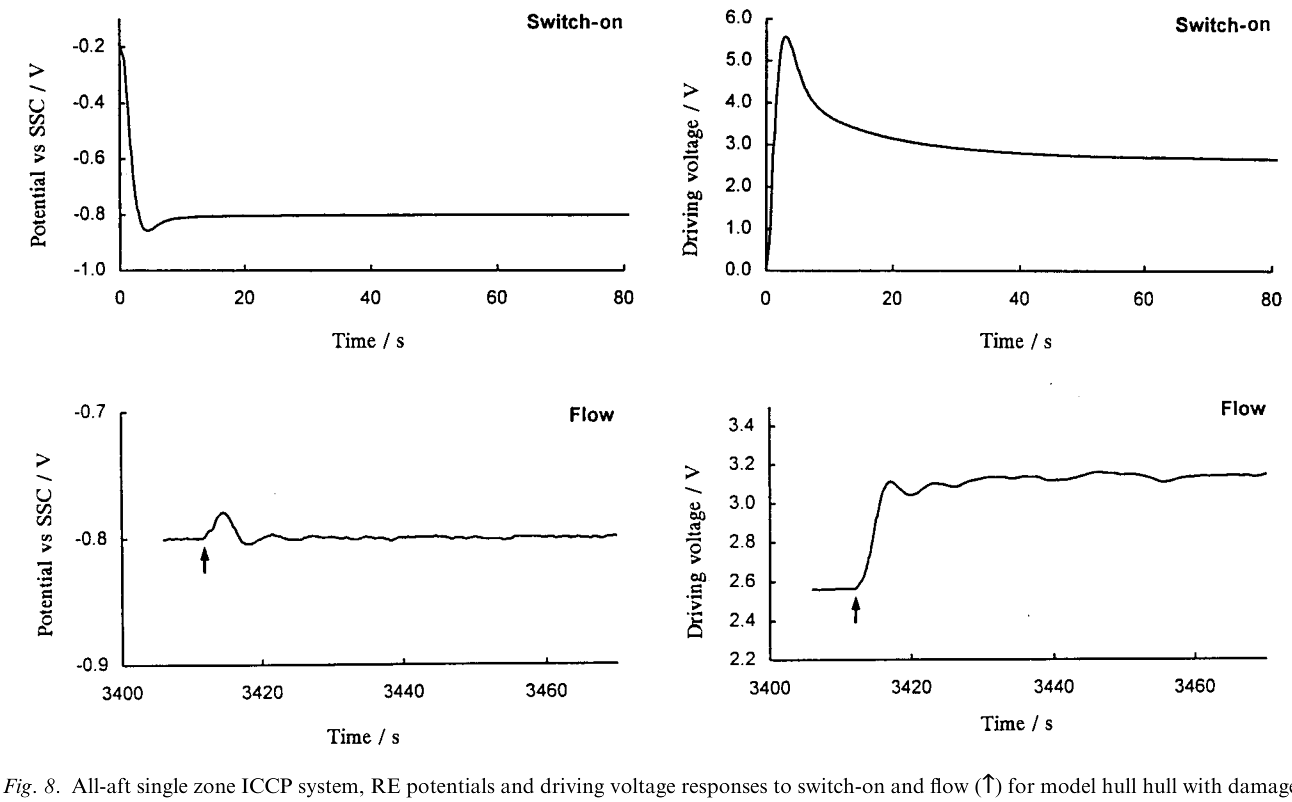

Fig. 8. All-aft single zone ICCP system, RE potentials and driving voltage responses to switch-on and flow (↑) for model hull hull with damaged cladding.

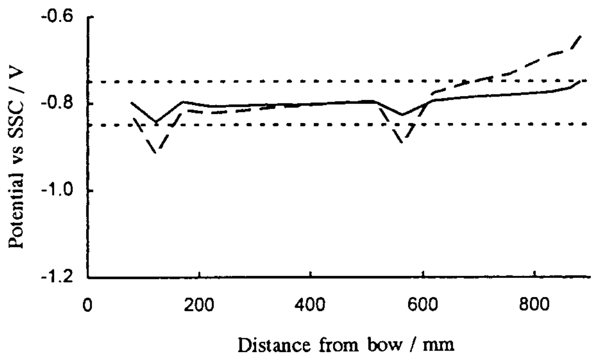

Fig. 9. Midship single zone ICCP system; potential profiles over model hull with an intact paint coating. Key: (——) static, (– – – –) flow conditions.

4. Characteristics of the Midship single zone ICCP system

4.1. *Potential profiles over model hull*

Potential profiles produced along the model for the different hull states were similar and are illustrated by the intact paint in Figure 9. Profiles in static conditions lay within the NES limits except for small potential spikes at the fore and aft anodes. Flow conditions with an intact coating resulted in a only a small increase in anode spikes whereas the increase was much greater with coating and cladding damage. As is typical of Midship single zone systems, the profiles 'see-sawed' about the RE with potentials becoming more negative towards the bow and less towards the propellers (falling outside the −750 mV NES limit).

4.2. *System dynamic responses*

Following switch-on, system time responses at the midship RE, and driving voltages, were similar for all three hull states and followed the form of those reported above in Figure 8 and Table 1 for the All-aft ICCP system, although natural frequencies were higher (Table 2). Driving voltages after switch-on in static conditions peaked earlier than with the All-aft ICCP system, between 3.4 – 4.4 s, with the most rapid response again occurring for the model with the intact paint coating. This hull state also resulted in the lowest overshoot and the highest damping ratio. Time responses of the settled Midship system to flow followed the form for the All-aft system (Figure 8). Damping ratios were again lower, and natural frequencies much higher, than in static conditions.

Table 2. Dynamic characteristics of model Midship single zone ICCP system

Experimental condition	M_p/mV	t_p/s	ζ	ω_n/rad s^{-1}
Static switch-on				
Painted hull (intact)	13	3.4	0.768	1.44
Painted hull (damaged)	35	4.4	0.650	0.94
Clad hull (damaged)	54	3.6	0.609	1.10
Flow response				
Painted hull (intact)			*	*
Painted hull (damaged)			0.274	3.12
Clad hull (damaged)			0.215	3.17

* Results not available

5. Characteristics of the two-zone ICCP system

5.1. *Potential profiles over model hull*

Profiles produced along the model when the All-aft and Midship single zone ICCP configurations were combined as a two zone system are illustrated in Figure 10 for the damaged cladding. Good protection was provided along the hull, lying within the NES limits except for anode spikes outside the −850 mV limit in flow conditions. The forward zone dominated; current outputs in static conditions settled at 0.251 mA (0.095 mA, stern zone) and at 0.714 mA in response to flow (0.290 mA, stern zone). Similar responses were obtained with the a damaged paint coating.

With an intact paint coating there was very good protection along the hull under static conditions, with the profile hardly changing in response to flow, although potentials at the stern anode then fell outside the −850 mV NES limit. The stern zone dominated, with its output in static conditions settling at 0.060 mA; the forward zone initially switched on but then turned off as a result of the output from the stern zone, although later switching on again with a current of 0.032 mA. Both zones operated in response to flow, with the stern still dominating with an increased output of 0.387 mA; as a result, current from the forward zone reduced to 0.017 mA.

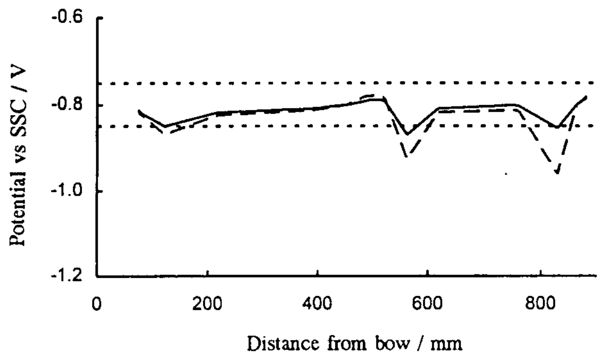

Fig. 10. Two zone ICCP system; potential profiles over model hull with damaged cladding. Key: (——) static, (– – – –) flow conditions.

5.2. *System dynamic responses*

System time responses were much more complex than before and differed not only with hull state but also between the two zones. These are illustrated by Figure 11 which shows potentials at the RE and driving

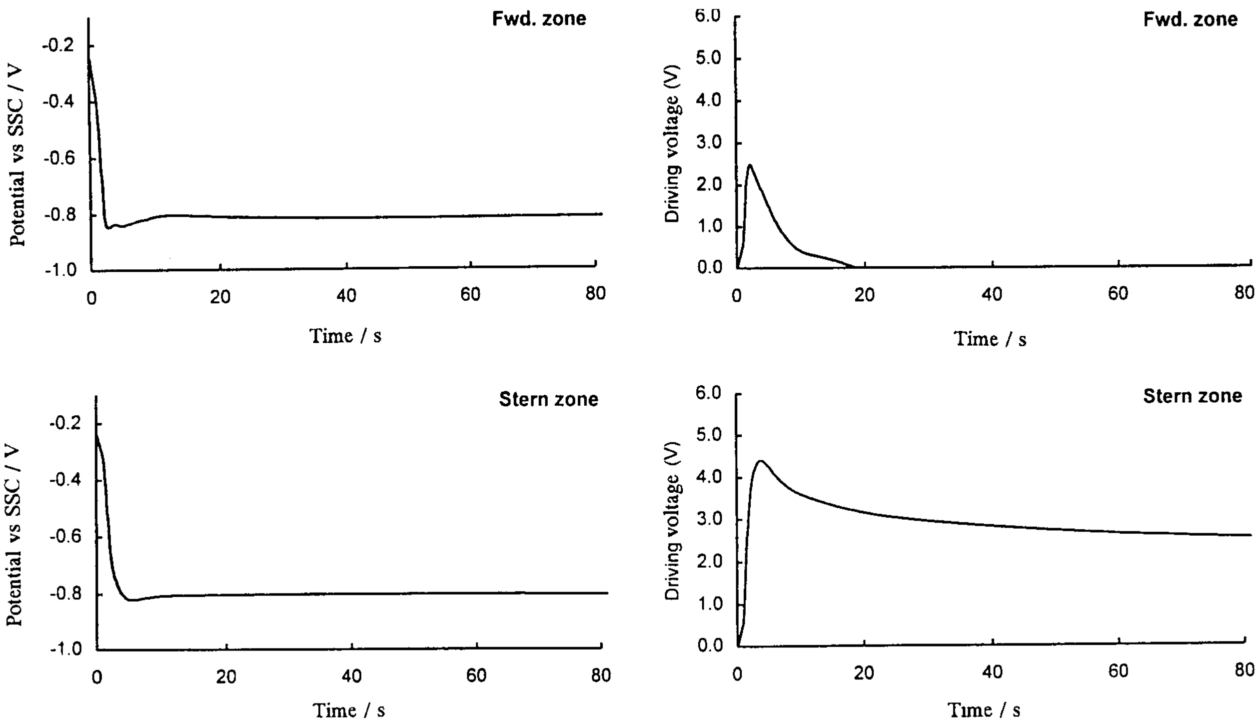

Fig. 11. Two zone ICCP system; RE potentials and driving voltage responses to switch-on for model hull with intact paint.

voltages following switch-on in static conditions, for the hull with an intact paint coating. Figure 12 shows the responses to flow with paint damage.

With damaged paint and cladding, potentials at the RE, and driving voltages, for both zones following switch-on followed the general pattern reported before for single zones (Figure 8). Responses differed markedly, however, with an intact paint coating (Figure 11) where the forward zone was affected by the current output of the stern. This is shown by the perturbation of potentials at the forward RE between 2.6–4.8 s, and subsequent switch-off of the driving voltage after 18.6 s. Later, after

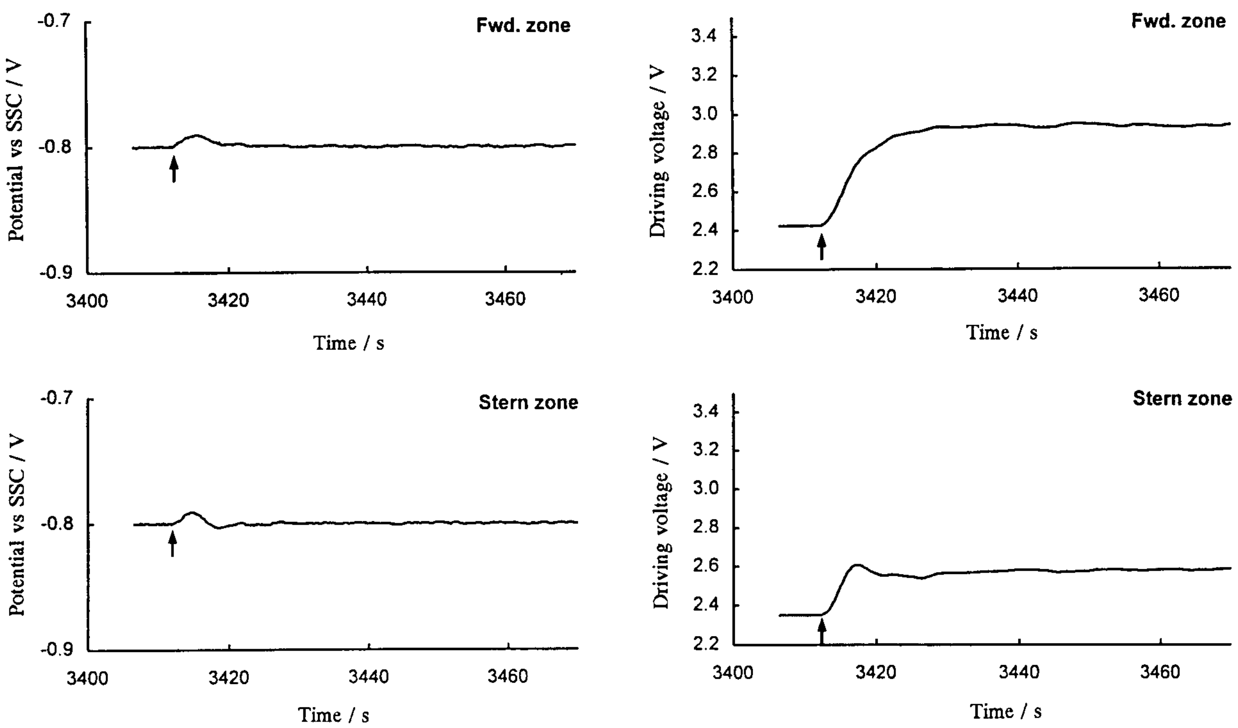

Fig. 12. Two zone ICCP system; RE potentials and driving voltage responses to flow (↑) for model hull with damaged paint.

the potential profile had settled along the model the forward zone switched on again after 408 s, with a low current output of 0.032 mA (compared with 0.146 mA for the stern zone). Switch-on responses of the dominant stern zone, however, had the form of the 'All-aft' system (Figure 8) although there was less of a potential overshoot at the RE and a lower peak driving voltage.

Changes in potential at the RE in response to flow for the three hull conditions were similar, as illustrated by the damaged paint coating (Figure 12), and followed the general pattern shown in Figure 8 for the single zone systems. Marked differences were evident, however, between the driving voltages of the two zones: the voltage of the dominant forward zone increased steadily, with relatively little perturbation, while that of the stern zone, however, initially peaked and then declined before settling. This interaction reversed with an intact paint coating, when the stern zone dominated and the forward zone peaked and declined (not illustrated). With damaged cladding, both zones had similar time responses even though the forward zone had the higher current output as reported above. All of these responses were more oscillatory than with the single zone configurations.

Dynamic characteristics for the three hull states are summarised in Table 3. Overall, for all hull states in response to switch-on in static conditions, the forward zone exhibited higher peak overshoots and lower times to overshoot than did the stern zone. In association, the forward zone had the lower damping ratios and higher natural frequencies. Compared with their behaviour as single zone systems, the stern zone of the combined two zone configuration had higher damping ratios and the forward zone had lower.

Table 3. Dynamic characteristics of model two zone ICCP system

Experimental condition	M_p/mV	t_p/s	ζ	ω_n/rad s^{-1}
Static switch-on				
Painted hull (intact)				
Stern zone	22	5.3	0.717	0.85
Fwd zone	46	2.6	0.620	1.54
Painted hull (damaged)				
Stern zone	23	4.2	0.715	1.07
Fwd zone	43	3.6	0.636	1.13
Clad hull (damaged)				
Stern zone	29	4.3	0.697	1.11
Fwd zone	69	3.0	0.571	1.28
Flow response				
Painted hull (intact)				
Stern zone			0.286	1.88
Fwd zone			0.441	1.89
Painted hull (damaged)				
Stern zone			0.344	2.88
Fwd zone			*	*
Clad hull (damaged)				
Stern zone			0.368	2.15
Fwd zone			*	*

* Results not available

6. Discussion

There are various methods for determining transfer functions and the present study is by no means claimed to be definitive. The subject is complex and it is evident that ship ICCP is a combined process involving both the ICCP control system and the hull/seawater interactions. Although establishment of the set potential at an RE is evidently a second order control function following a step input after switch-on, the driving voltage responses to seawater flow were very different, being oscillatory. A step input would not occur with flow past a model hull as pumps run up to speed over time, relatively uniform conditions over the surface cannot be established immediately, if at all, and surges will occur before steady state hull surface potentials are established. Similar considerations apply at sea. No doubt this is partly why the damping ratios are lower in response to flow and natural frequencies are higher. The complexity of the dynamic responses presented above shows that the ICCP–hull processes are complex; polarization of the hull and the distribution of potentials away from anodes, at least, are nonlinear. The study examined the combined response of the overall system. A more detailed identification is still required, particularly in relation to determining transfer functions for the hull itself under a range of conditions. Unpublished DACS physical scale modelling studies show that the time responses of potentials over a model hull following switch-on differ with location away from an RE and anodes.

The results from the present paper show that the dynamic characteristics of a ship ICCP system depend upon the nature and state of the underwater hull coating, whether the ship is at anchor or getting under way and upon system configuration. Practical observations in relation to ship operation are that the damping ratios and natural frequencies will be at their highest in response to switch-on, and potential overshoots will be at their lowest, when a hull is painted and has an intact coating. A vessel with a damaged clad hull will be likely to have lower damping ratios than with a damaged paint coating. Response at the RE when a ship gets underway will be much less damped, and have a higher natural frequency, than following switch-on at anchor.

Significant interactions can evidently occur between different zones. It is apparent that identification of a single zone will not predict its dynamic characteristics when incorporated into a two zone configuration, as these will depend upon the other zone. Whether the forward or the stern zone dominates evidently depends upon the condition of the hull coating and, perhaps, upon their configuration. Studies of dynamic responses under various operational conditions assist in the quantitative examination of this important aspect of system design.

Dynamic characteristics at an RE cannot be considered in isolation. Responses to switch-on and the onset of seawater flow past a hull are transient phenomena, but water speed will be changing throughout ship activities. An examination has not yet been made of the robustness of a system, that is, its response to changes in operational conditions such as variations in seawater flow past the hull, (i.e., ship speed). In terms of the protection provided to a hull, the practical outputs of an ICCP system are the settled potential profiles provided over the underwater area of a hull, under a range of operational conditions. Nevertheless, what happens over the hull surface away from the REs in terms of changing potential profiles will affect conditions at an RE. Additionally, it has been reported that propeller/shaft rotation modulates ICCP system current output [6]. More recent studies suggest that RE location has an important role in determining the nature and magnitude of these modulations, thus possibly involving the ICCP control system.

In parallel with physical scale modelling, computer modelling has been widely examined for the prediction of ship cathodic protection system performance ([7] gives a comparison). Both finite and boundary element methods have been employed [7, 8]. The computing approach is dependent upon data on the cathodic polarisation characteristics of painted and unpainted marine alloys, in combined states in static and flow conditions. Also, either the behavioural relationships between sets of data must be known or assumptions must be made. Surface condition and interactions with the electrolyte are critical. Physical scale modelling creates its own data under the spectrum of hull and operational conditions. Studies such as these presented and discussed above deepen the understanding of ICCP processes and the relationships between cathodic surface–electrolyte reactions and system performance.

7. Conclusions

The following can now be stated:

(i) Dynamic characteristics of ship ICCP systems depend upon the hull state and operational condition, with system configuration having some effect.

(ii) Response to switch-on in static conditions is at least a second order transfer function.

(iii) Driving voltages in response to the onset of under way conditions are oscillatory.

(iv) Responses to underway conditions have lower damping ratios and much higher natural frequencies than occur following switch-on in static electrolyte.

(v) With single zone systems, damage to paint and cladding results in higher peak overshoots and lower damping ratios than with intact paint. Two zone systems are more complex.

(vi) Different zones in a system have their own characteristics.

(vii) Characteristics of a single zone configuration change when combined with another in a two zone system.

(viii) Such studies deepen the understanding of ICCP and behavioural relationships.

References

1. D.J. Tighe-Ford and P. Khambhaita, Effect of ship ICCP configuration on system current output, Proc. NACE 95 Corrosion Conference, Orlando, USA, March (1995), Paper 308.
2. K. Ogata, 'Modern Control Engineering' (Prentice Hall, Hemel Hempstead, UK, 1997), 864 pp.
3. D.J. Tighe-Ford, P. Khambhaita, J. Buckley and W. Paris, Identification and characteristics of a ship ICCP system, Proc. NACE 94 Corrosion Conference, Baltimore, USA, Feb. (1994), Paper 498.
4. R.W. Ditchfield, J.N. McGrath and D.J. Tighe-Ford, *J. Appl. Electrochem.* **25** (1995) 54.
5. A.R. Parks, E.D. Thomas and K.E. Lucas, *Mats. Perf.* **30**(5) (1991) 26.
6. P. Khambhaita, J.N. McGrath, K.H.D. Slack and D.J. Tighe-Ford, Physical scale modelling of ship ICCP current output by propeller rotation, Proc. Marelec 99, 2nd International Conference on 'Marine Electromagnetics', Brest, France (Spearhead Publications, New Malden, UK, 1999), pp. 269–279.
7. I. Gurrappa, *Corr. Prev. & Cont.* **41**(4) (1994) 40.
8. V.G. DeGiorgi, Finite resistivity and shipboard corrosion prevention system performance, *in* A. Kassab, C.A. Brebbia and M. Chopra (Eds), 'Advances in Boundary Elements', Vol. XX (Computational Mechanics Publications, Southampton, UK and Boston, USA, 1998), pp. 555–563.