Wear, *79* (1982) 283 - 293

EFFECTS OF APPLIED STRESS ON CAVITATION EROSION

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(Received October 23, 1981; in revised form November 30, 1981)

Summary

Cavitation erosion under static applied stress and/or alternating stress was studied using steel specimens which were set in close proximity to an oscillating horn in ion-exchanged water. For increasing static applied tensile or compressive stress, weight loss and its rate do not vary in a monotonic fashion but first decrease, then increase through a peak, and then decrease again. Tensile stress except for given stress regimes, and compressive stress at all stress levels, decreases erosion damage compared with zero-stress values. Under alternating stress, the weight loss rate varies with trends similar to those under static applied stress. However, the weight loss rate is larger than for the same static stress, so that the erosion damage is more affected by alternating stress than by static stress. The behaviors under applied stress are discussed through the effect of stress on the erosion particles.

1. Introduction

In hydraulic machinery, some components exposed to cavitation erosion are often subjected to static stress and/or alternating stress simultaneously. In this case, it might be assumed that an increase in erosion would occur because of the combined action of the collapse pressure of cavitation bubbles and the applied stress. Hammitt [1] reported that the cavitation ero-

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sion rate of 304 stainless steel increased only slightly (about 8%) in a Venturi test when tensile loads up to 1.3 times the yield strength were imposed.

Shal'nev *et al.* [2] showed that the weight loss rate of 3003-O aluminum increased up to 40% as the tensile stress increased from zero to 50% of the yield strength. Palhan [3] reported that the cavitation erosion of mild steel and cast iron increased at higher tensile stress. However, the results under zero stress were not shown, so that it was not possible to judge whether applied stresses increase erosion rate or not.

Kemppainen [4] carried out cavitation erosion tests under applied stress using several materials and deduced that generally a compressive stress decreases and a tensile stress increases both the cavitation damage in the incubation period and the later damage rate. However, the dependence of damage on the stress level shows opposing tendencies for the various materials tested.

These scattered previous reports have not led to systematic progress in the study of stress effects on cavitation erosion. Further, the effects of applied alternating stress have not been included. Therefore, to clarify the effects of applied stress on cavitation erosion, it is necessary to conduct erosion tests where the applied stress is varied more widely.

In this paper, the results of erosion tests of steel under static tensile and compressive stress, or under alternating stress, are reported. Effects of applied stress on cavitation erosion are discussed and compared with the results obtained by other researchers.

2. Experimental procedure

Figure 1 shows the test apparatus, which consists of a fatigue testing machine with an electric servo tension–compression fatigue tester, with a ±5 tonf capacity (tester A), or a plate spring and an eccentric cam (tester B), a magnetostrictive oscillator for the cavitation erosion test and a cooling bath to maintain constant temperature. (The test specimens for the two testers are shown in Fig. 2.)

The test materials are SS41 carbon steel and HT60 high tensile steel. (SS41 and HT60 are equivalent to AISI 1012 carbon steel and AISI 1513

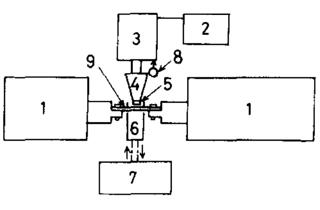


Fig. 1. Test apparatus: 1, tension–compression fatigue tester; 2, high frequency amplifier; 3, magnetostrictive oscillator; 4, amplifying horn; 5, cavitation disc; 6, test liquid container; 7, electronic cooling instrument; 8, dial gauge to set distance between disc and test piece; 9, test piece.

TABLE 1

Chemical composition of specimen materials

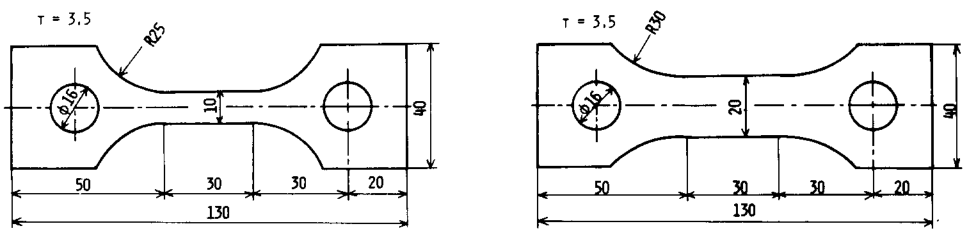
Material	*C*	*Si*	*Mn*	*P*	*S*
SS41	0.13	0.026	0.44	0.012	0.026
HT60	0.09	0.27	1.43	0.015	0.004

TABLE 2

Mechanical properties of specimen materials

Material	σ_s (kgf mm^{-2})	σ_B[a] (kgf mm^{-2})	δ (%)	*Hardness* (HV 0.025/30)
SS41	31.4	44.3	41	164
HT60	50.0	61.0	28	258

[a]Tensile strength.



(a) (b)

Fig. 2. Shape and dimensions of test specimens for (a) tester A and (b) tester B (all dimensions in millimeters).

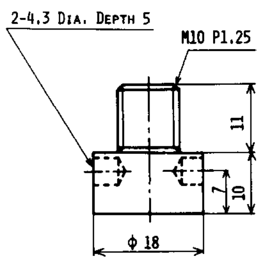


Fig. 3. Shape and dimensions of the disc (all dimensions are in millimeters).

steel.) The chemical compositions and mechanical properties are listed in Tables 1 and 2; the shape and dimensions of specimens are shown in Fig. 2. The specimen surfaces were polished with no. 1500 emery paper; the SS41 specimens were then vaccum annealed at 600 °C for 30 min to eliminate the effects of polishing.

The test specimens (Fig. 2) were fixed parallel to and a small distance from the disc (Fig. 3) attached to the free end of the cavitating horn (see Fig. 1) and tested in water. The disc material was an 18-8 stainless steel with relatively high cavitation erosion resistance. A new disc was used for each complete test to avoid possible effects from disc erosion. The horn frequency and double amplitude were 14.5 kHz and 50 μm for tester A and 22.1 kHz and 30 μm for tester B.

Ion-exchanged water (specific resistance, greater than 5×10^6 Ω cm) was used as the test liquid. The water temperature was maintained at 25 °C; the water circulated between the container and the electronic cooling bath.

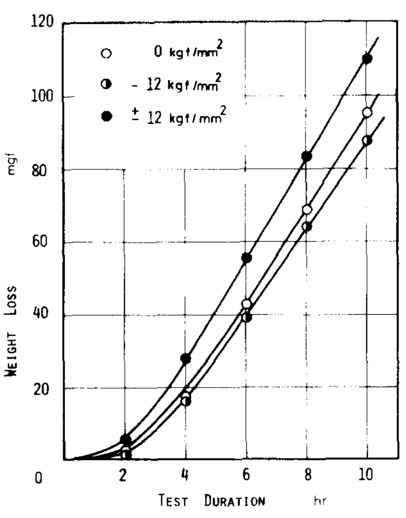
The distance h between disc and test piece was fixed at 0.5, 1.0 and 1.5 mm for the different tests. Since the damage rate of the test piece is affected by h [5], h was carefully measured with a dial gauge (Fig. 1). The end plane of the disc was immersed to a depth of about 3 - 4 mm that was maintained by a weir in the container vessel.

The weight loss was measured (with a precision balance of sensitivity 0.1 mgf) after test intervals of 0.5 or 2 h as required.

3. Experimental results and discussion

3.1. Cavitation erosion rates

Figure 4 shows curves of weight loss caused by cavitation erosion for SS41 carbon steel under zero stress, a static compressive stress of -12 kgf mm^{-2} (-17.0 klbf in^{-2}) and an alternating stress of ± 12 kgf mm^{-2} (± 17.0 klbf in^{-2}) *versus* time. From these curves, weight loss rates are then obtained (Fig. 5). The erosion results for various applied stresses are similar to each



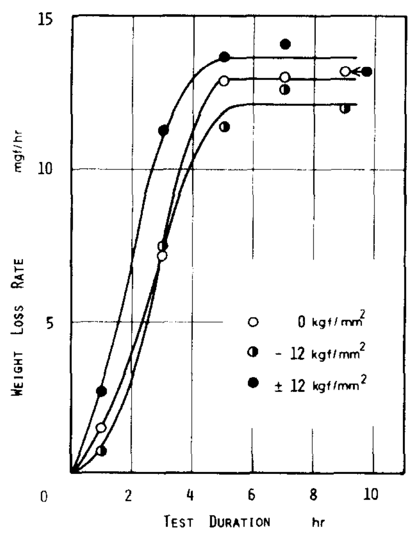


Fig. 4. Weight loss *vs.* test duration under various applied stresses for SS41 carbon steel (tester A).

Fig. 5. Weight loss rate *vs.* test duration (data from Fig. 4).

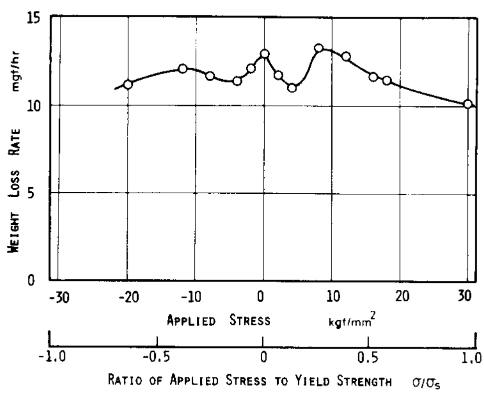
other and to the unstressed curves. They can be roughly divided into three stages: an incubation period where little weight loss occurs, a transition period with increasing weight loss rate and finally a stable period during which the weight loss rate is approximately constant. Kemppainen [4] reported that erosion rates in the incubation period are most affected by applied stress. However, no difference in the incubation and transition periods between zero stress and applied stress was found in the present tests. The test duration required to attain a stable period was also substantially independent of applied stress. The weight loss rate for the stable period was calculated by the least-mean-square method using the weight loss from 4 to 10 h.

3.2. Effect of static stress on erosion

Figure 6 shows the weight loss rate against applied static stress for SS41 steel, a tensile stress being considered positive. The ratio of applied stress to yield strength is also included on the abscissa. From the literature (*e.g.* refs. 1 - 4), it would be assumed that erosion damage would increase under either tensile or compressive applied stress for such a steel. The present results unexpectedly indicate a much more complex behavior.

Erosion behavior under applied stress was also observed when we used a different testing machine to apply the stress, different dimensions of the test specimen and different test conditions such as amplitude, frequency and distance *h*.

Figure 7 shows the cumulative weight loss during 7 h from the beginning of a test against static applied stress for SS41 steel. The variations in



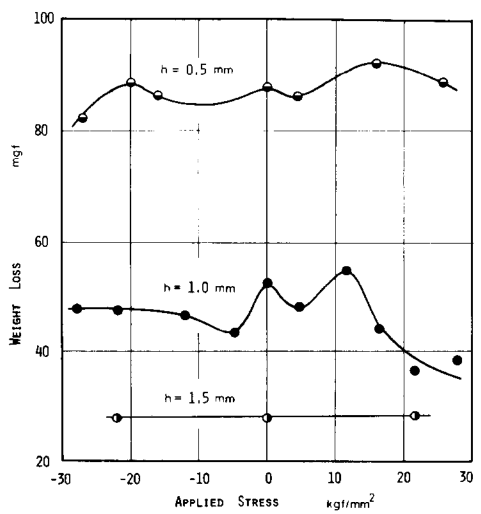


Fig. 6. Effect of applied static stress on weight loss rate for SS41 carbon steel (tester A).

Fig. 7. Effect of applied static stress on cumulative weight loss during 7 h from the beginning of the test for SS41 carbon steel (tester B).

weight loss with static stress become smaller when the distance h is both short and long. For a short distance, the cavitation intensity is so severe that applied stress may not affect erosion. By contrast, the effect of stress on weight loss for a long distance was not determined because of the slight erosion damage. Therefore, the effect of stress on erosion damage is most notable for the limited case where the correlation between cavitation intensity and applied stress is relatively moderate.

To clarify further the stress effect on erosion damage, we have here calculated

$$\Delta W\,(\%) = \frac{\text{erosion damage for applied stress} - \text{erosion damage for zero stress}}{\text{erosion damage for zero stress}} \times 100 \quad (1)$$

where the erosion damage is shown by the weight loss or the weight loss rate. The results calculated from Figs. 6 and 7 are shown in Fig. 8 for different stress levels. We use the term "promotive effect" to describe the situation where erosion damage for an applied stress is larger than that under zero stress, *i.e.* $\Delta W > 0$. For the reverse case, *i.e.* $\Delta W < 0$, we use the term "suppressive effect".

For an applied compressive stress, the suppressive effect exists throughout, since $\Delta W < 0$ for all stresses (Fig. 8). The weight loss or weight loss rate, however, decreases and thereafter increases to a given value, and then again decreases, with increasing compressive stress. By contrast, for increased tensile stress, a minimum point is again shown, followed by a maximum, and then a further decrease. The promotive effect exists then only for a stress σ/σ_s = 0.3 - 0.5. Thus the region of applied stress which shows a suppressive effect is much larger than that for the promotive effect.

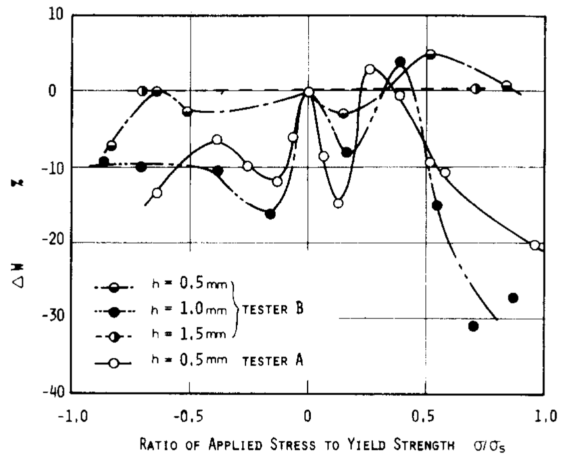
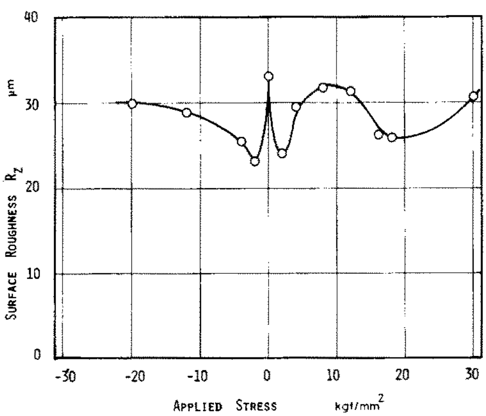


Fig. 8. Relation between ΔW and applied static stress (ΔW is defined in eqn. (1)).

If we compare these results with previous results in the literature, the present findings differ substantially and show that the effect of applied stress on erosion is highly complex. Unfortunately we cannot discuss the relationship between Kemppainen's data [4] and ours because his tests were carried out only at a stress level $\sigma/\sigma_s = 0.75$. However, it is found that a static applied stress increases the erosion damage up to only about 10% in the worst case.

To investigate the mechanism of applied stress effects upon erosion (see Fig. 6), the eroded surface roughness and cracks formed therein were observed for the specimen tested by tester A with a distance $h = 0.5$ mm. The ten-point surface roughness R_z was measured at 6, 8 and 10 h after the beginning of the test. These roughnesses were then averaged and plotted against the applied stress (Fig. 9). Cracks were observed by microscopic examination of a cross section of the test piece after termination of the test. Figure 10 shows the relation between the average crack length (almost 170 cracks were measured) and the applied stress. The variation in behavior with respect to applied stress (Figs. 9 and 10) is very similar to the curves for weight loss rate (Fig. 6). Since the surface roughness and crack length are closely related to the erosion particle size [6, 7], it is considered that the variation in weight loss rate with applied stress may be due to the difference in size of erosion particles ejected.

The variations in size of erosion particles with applied stress were studied theoretically using the following model. The surface of a two-dimensional semi-infinite plane is assumed to be subjected to a concentrated load because of the collapse of cavitation bubbles and the stress applied at an infinite distance which is parallel to the surface. If the erosion particle is produced and removed when the principal shearing strain caused by the combined action exceeds a given critical value, then the erosion particle size would decrease first and then increase with increasing tensile and compressive stress [8].



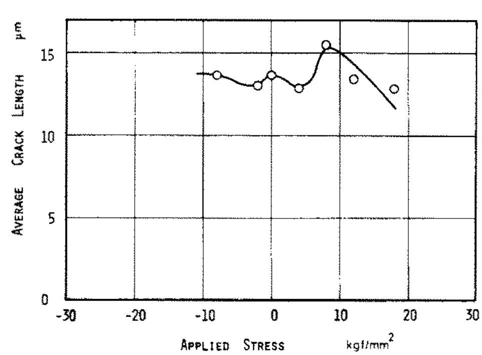
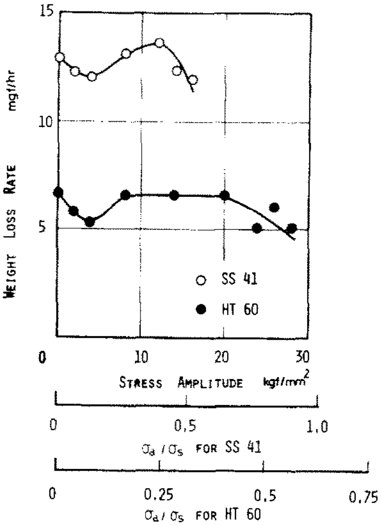


Fig. 9. Variation in ten-point surface roughness R_z *vs.* applied static stress.

Fig. 10. Averaged crack length *vs.* applied static stress.



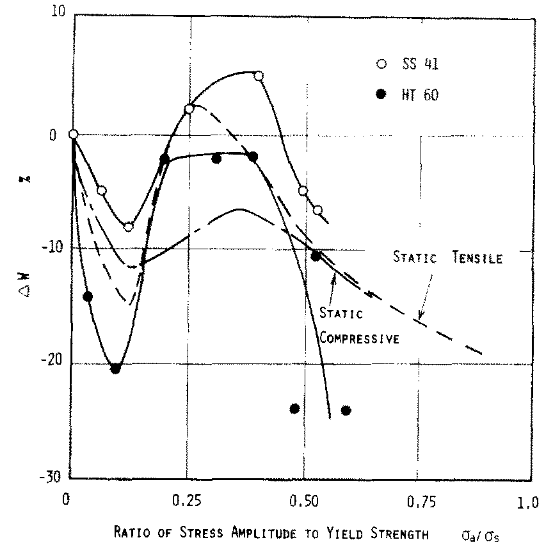


Fig. 11. Effects of stress amplitude on weight loss rate under alternating stress loading for SS41 carbon steel and HT60 steel (tester A).

Fig. 12. Relation between ΔW and σ_a/σ_s (σ/σ_s) (ΔW is defined in eqn. (1)).

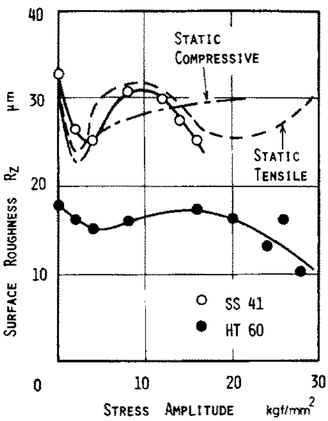
Further, it may be considered that a compressive stress would tend to prevent crack propagation and that a tensile stress, by contrast, would merely increase the crack length in the direction of depth, thus never contributing to erosion particle removal. Only when most of the cracks initiate in the direction of maximum shear stress (45°) because of the combined action of the collapse pressure of cavitation bubbles and the applied stress is it possible that the static applied stress would increase erosion damage above that of zero-stress values. Consequently, the weight loss rate or weight loss would vary with applied stress, as shown in Figs. 6 and 7.

3.3. Effect of alternating stress on erosion

The effect of alternating stress on erosion was investigated using the same apparatus (tester A), and test specimens described in Figs. 1 and 2, for SS41 carbon steel and HT60 high tensile steel. Completely reversed tensile and compressive stress (sine wave) was applied to the test specimen at a frequency of 5 Hz. The oscillator frequency was 14.5 kHz, the double amplitude was 50 μm and the distance between disc and test piece was 0.5 mm.

Figure 11 shows weight loss rate under various stress amplitudes. The weight loss rate for both materials, smaller for HT60 with its higher mechanical properties than SS41, shows minimum and maximum points with increasing stress amplitude.

By calculating ΔW from Fig. 11 according to eqn. (1), its relation to the stress amplitude is shown in Fig. 12. The broken lines exhibit the results obtained under static stress for SS41 from Fig. 8. The promotive effect ($\Delta W > 0$) exists at $\sigma_a/\sigma_s \approx 0.2$ - 0.4 for SS41. The suppressive effect ($\Delta W < 0$)



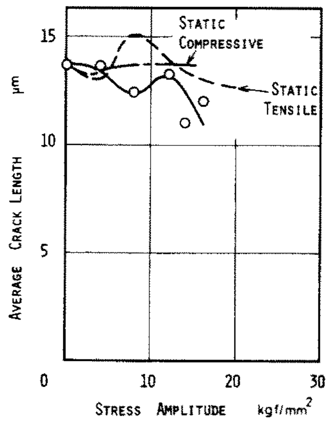


Fig. 13. Variation in ten-point surface roughness R_z *vs.* stress amplitude.

Fig. 14. Averaged crack length *vs.* stress amplitude.

exists either above or below these stress levels for SS41 and over the whole stress range for HT60. This behavior for SS41 is similar to that under static tensile or compressive stress. In general, the weight loss rates under alternating stress are larger than under the same static stress, so that the damage rate is more affected by alternating than by static stress.

Figures 13 and 14 show the relations between surface roughness and stress amplitude and between average crack length and stress amplitude. In both figures, the results for static applied stress for SS41 are shown by broken lines. From these results, we consider that the behavior of the weight loss rate with alternating stress is primarily due to the effect of the stress amplitude on the size of the erosion particle.

Although there is little difference in resultant surface roughness between static and alternating stress tests, the crack length is smaller under alternating stress than for static stress. The distribution of the cumulative frequencies of cracks for zero stress and for stresses of 8 kgf mm^{-2} (11.4 klbf in^{-2}) and ± 8 kgf mm^{-2} (±11.4 klbf in^{-2}) is shown in Fig. 15. The behaviors of the distributions are almost the same but more small cracks exist for ± 8 kgf mm^{-2} than for 8 kgf mm^{-2}. This may be because cracks are more easily propagated by alternating stress and accordingly are able to join with their neighbors. Therefore, the number of erosion particles may increase rapidly but their size becomes slightly smaller under alternating stress, resulting in an increased or the same weight loss rate than that with the same static stress value.

4. Conclusions

The following significant conclusions can be drawn.

(1) For increasing static applied tensile or compressive stress, the weight loss and its rate do not vary in a monotonic fashion but first decrease, then

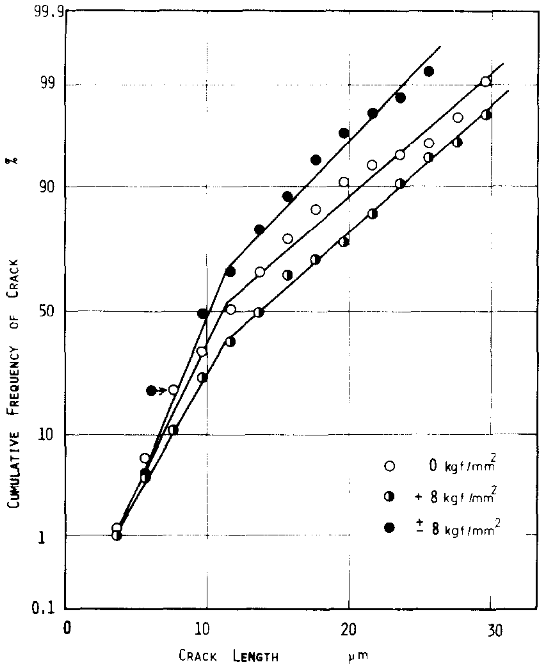


Fig. 15. Cumulative frequency of crack length.

increase through a peak, and then decrease again. In general, both applied tensile and compressive stresses decrease erosion damage. However, the maximum peak of erosion damage obtained for quite a limited tensile stress is greater by several per cent than zero stress results.

(2) For alternating applied stress, the weight loss rate varies with trends similar to those under a static applied stress. However, the weight loss rate is larger than for the same static stress so that erosion damage is more affected by alternating than by static stress.

(3) Roughness variation and surface crack length formation under applied stress behave in a very similar way to the weight loss rate. It is thus concluded that applied stress affects the size of erosion particles, resulting in the observed variation in erosion damage with applied stress.

Acknowledgments

The present study is part of a joint research study between Fukui University, Japan, and the University of Michigan, U.S.A.

Financial support for some of this work was provided by the Office of Naval Research Contract N00014-76-C-0697.

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