Effects of Polyethylene-Oxide Solutions on the Performance of a Small Propeller

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Thrust and torque were measured and efficiency calculated for a 14.6-cm diam, two-bladed propeller in aqueous solutions of polyethylene oxide, WSR-301, with concentrations ranging from 0 to 75 wppm. For the propeller operating under heavily loaded conditions (advance coefficients from 0.04 to 0.2), the thrust decreased with increasing concentration while the torque passed through a minimum at 10 wppm. The net result was that the propeller efficiency remained essentially constant except for a small increase of a few percent at 10 wppm. Acoustic measurements demonstrated that the polymer greatly reduced the rate of propeller cavitation but did not influence the rotational speed at which cavitation was first noticed. The polymer had no effect on the sound pressure level (SPL) of the fundamental blade line.

Introduction

NOW that serious consideration is being given to the use of polymers to reduce the drag of waterborne vehicles,[1] it is necessary to take a critical look at some of the other consequences which might result from the use of these techniques. Foremost among the unanswered questions is what effect, if any, the polymer will have on the hydrodynamic and acoustic properties of the propeller.

The first reported experiments on propellers in polymer solutions were those by Wu[2] in 1969. Using a circular water channel driven by a propeller, he observed that, with all other parameters held constant, the fluid velocity obtained with a homogeneous solution of 500 wppm (weight parts per million) of polyethylene oxide was only half that obtained with pure water. He warned of "the possibility of a reduction of impeller thrust in additive solutions."

Direct measurements of propeller thrust and torque were reported by Kowalski.[3] The propeller was mounted in a single-pass water channel and the polymer was injected into the flow upstream from the propeller. It was reported that, at constant advance coefficient, the polymer decreased the thrust and increased the torque resulting in a decreased efficiency. This reduced propeller efficiency was approximately 5% for a 20 wppm concentration of polymer. He concluded, "Results obtained from these preliminary tests indicate a deleterious effect of polymer additives on the performance of a model propeller."

The experiments reported in this present paper are at variance with Kowalski's results in that it was found that the torque actually decreased under most operating conditions. In fact, under certain conditions the decrease in torque was sufficient to override the decreased thrust resulting in an increase in propeller efficiency by a few percent. This difference in experiments may be accounted for either by the fact that the propellers were of different design or because the present experiment was carried out with the propeller operating under a greater load (J = 0.04 to 0.20 compared to 0.3 to 0.4 for Kowalski).

Since a propeller is a rotating hydrofoil, measurements on the lift and drag of a hydrofoil would be of value in interpreting propeller results. Wolff and Cahn[4] report a "reduction in drag of about 45%" and "complete elimination of foil lift at (geometric) zero foil angle." On the other hand, the results of Sarpkaya and Rainey[5] show only a slight decrease in lift and little change in drag. Further work on hydrofoils in polymer solutions is needed.

Other aspects of propeller behavior that may be affected by polymer additives are related to cavitation and radiated noise. While several experimenters have reported that polymers inhibit the cavitation for flow about bodies[6,7] and in jets,[8] measurements of propeller cavitation in polymer solutions do not seem to have been done. Like-

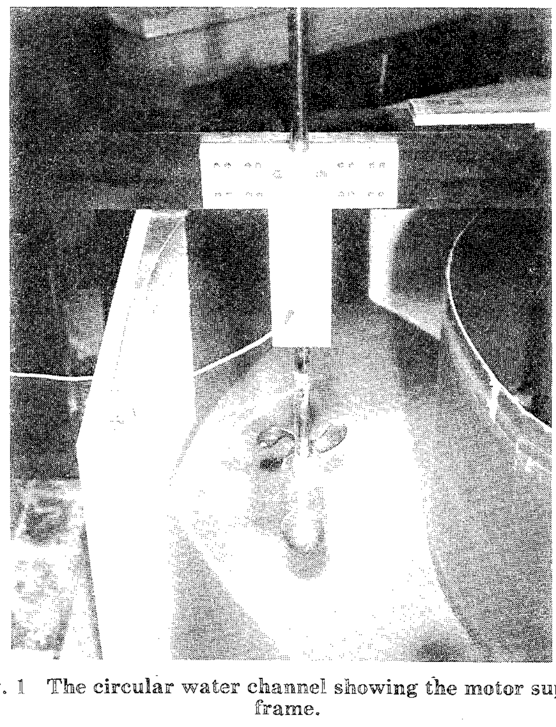

Fig. 1 The circular water channel showing the motor support frame.

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wise, reports of the effect of polymers on the noise radiation by propellers are absent.

Further details on the procedures and a full presentation of the data presented in this paper are to be found in the M. S. theses by Henderson[9] and White.[10]

Apparatus

The experiments reported herein were carried out in a circular water channel of 7-ft o.d., 4-ft i.d., and a depth of 18 in. (Fig. 1). Constructed of 1/4-in. steel plate, this tank contains 2000 lb of water when filled to depth of 15 in. Isomode Vibration Pads (MB Electronics) were used to isolate the tank from groundborne vibrations with frequencies greater than 10 Hz.

To avoid the hydrodynamic and acoustic disturbance of a separate impeller, the fluid in the channel was driven by the propeller under test and the flow rate, for fixed propeller rotation speed, was adjusted by a flow restrictor inserted into the channel 1/3 of the way around the tank downstream from the propeller. This restrictor consisted of a planar array of ten 4-in. diam vertical cylinders. The speed of the fluid is controlled by varying the placement and number of cylinders in the restrictor.

To avoid uncertainties in measuring the flow speed of the polymer solutions, the time required for a neutrally buoyant body to be carried over a known distance was measured. An ordinary fishing bobber, suitably loaded to make it neutrally buoyant, was mounted on a suspension to freely move on the centerline of the channel. A thin electrode, attached to the bobber, extended above the water surface to make contact with two rods extending across the channel, 1 m apart. Contact of the electrode with the first rod completed a circuit which started an electronic counter. This counter counted a 100-Hz signal until contact of the electrode with the second rod opened the circuit. For each run at a given speed, this measurement was repeated 10 times and the average used to calculate the speed. It is estimated that the precision of the speed measurement is 6%.

The propeller was driven by a Shakespeare Model 683549 electric trolling motor which was mounted on the centerline of the channel. The motor housing, 6.5 cm in diam, was mounted on a 2.2-cm diam cylindrical tubing shaft, which in turn was rigidly attached to a frame straddling the channel. The propeller axis was 46.0 cm below the crossbar of the frame. A 3/4-in. plywood board covered the water surface for a distance of 1/4 the circumference up- and downstream from the motor. This board prevented air bubbles from being drawrn down into the field of the propeller during testing. The driving power for the motor was supplied by a variable-voltage DC power supply with a maximum current capacity of 30 amp.

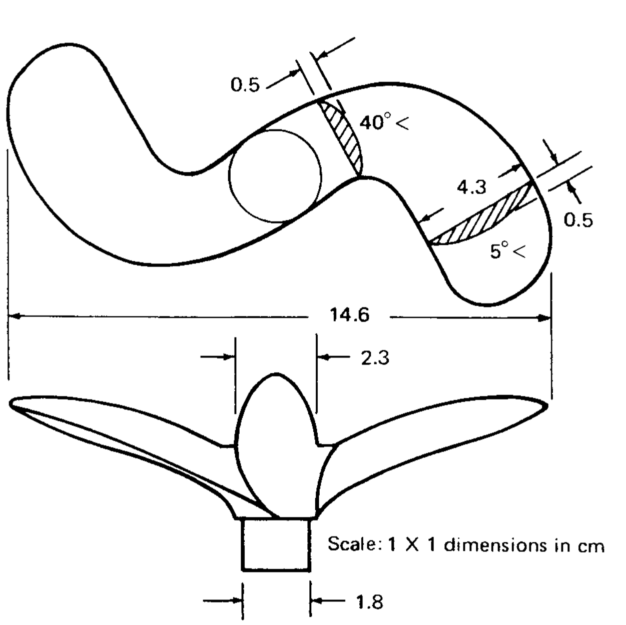

Fig. 2 The Shakespeare No. 658P04 outboard trolling propeller.

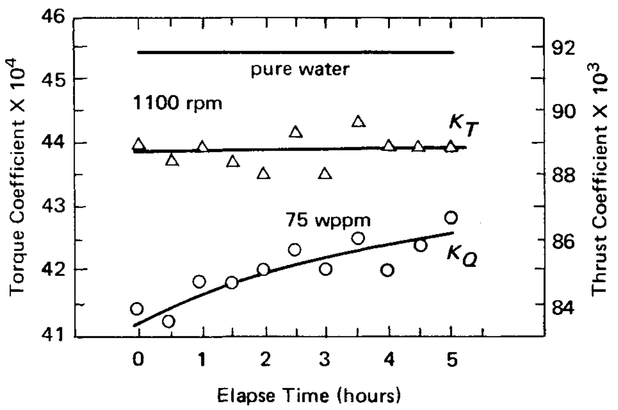

Fig. 3 Thrust and torque degradation for a 75 wppm WSR-301 solution with propeller running at 1100 rpm.

The propeller tested (Fig. 2) was a Shakespeare Model 658P04 nylon, two-bladed, outboard trolling propeller with a 14.6-cm diam. The pitch varied from 40° near the hub to 0° at the tip. This propeller is mounted just behind the motor and supporting shaft. The propeller parameters measured were the rotation frequency, thrust, and torque.

Easiest to obtain was the frequency; a General Radio Strobatac (1531A) was set at the desired frequency and the motor speed was adjusted until the propeller appeared stationary.

The thrust was determined by measuring the bending of the support shaft under load. A strain gauge (Statham UC3) located 7.3 cm below the crossbar of the support frame was calibrated by applying a known force on the axis of the propeller by means of a string-and-pulley system.

The torque can be determined from the input electrical power and the rotation frequency, if the motor efficiency (η_m) is known. The torque (Q) in dyne-cm is

$$Q = (\mathrm{IV}\eta_m/2\pi n)10^7 \tag{1}$$

where the current (I) is in amps, the voltage (V) is in volts, and the rate of rotation (n) is in revolutions/sec.

If it is assumed that the motor efficiency is only a function of n, η_m can be found by measuring the input power for known torques. The propeller was replaced by a smooth disk of 15.3-cm diam and measurements of I, V, and n were performed in pure water. The torque was then calculated from Goldstein's equation for turbulent flow on a rotating, free disk and the motor efficiency given by

$$\eta_m = (Q_{\mathrm{disk}} 2\pi n/\mathrm{IV})10^{-7} \tag{2}$$

It was found necessary to operate the motor for at least 1 hr before the motor efficiency stabilized.

For the acoustic measurements, an Atlantic Research LC-32 hydrophone, was vertically mounted with its center of acoustic field on the axis of the channel an arc distance of 60 cm downstream from the propeller. An Atlantic Research LC-1344 high input impedance (1000 Mohm) preamplifier provided 40 db of amplification with the low frequency roll-off at 15 Hz.

This low frequency response was necessary for the measurement of the discrete component of the propeller noise.

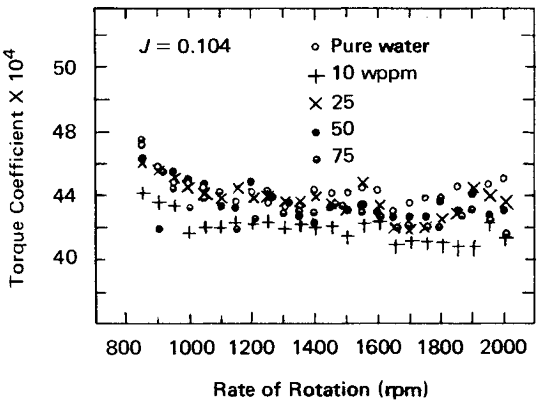

Fig. 4 Typical performance data for the propeller operating under heavily loaded conditions in solutions of WSR-301.

The frequency of this line is equal to the number of blades times the rate of rotation and falls between 30 and 60 Hz for the range of n attainable in this experiment. This signal was analyzed with a Hewlett Packard 302A wave analyzer which has a fixed 6-Hz bandwidth and is useable down to 20 Hz.

For the cavitation measurements, low-frequency response was not needed but greater gain was. Two further stages of amplification were added (a Burr Brown 110 and a Hewlett Packard 467A) for a total gain of 80 db.

Analysis on a Kay 675B Spectrograph of the noise produced by the cavitating propeller revealed the characteristic broad-band, short-duration signature of individual cavitation events, superimposed on continuous narrow-lines associated with motor noise. To isolate the cavitation events, a General Radio 1/10-octave filter (1564A) was set at a center frequency of 1500 Hz where spectral analysis showed there would be a minimum of extraneous noise. The filtered signal, clearly displaying each event as a distinct pulse, was rectified and demodulated. A Hewlett Packard 521C counter was used to count the events in a 10-sec interval. Ten such intervals were counted for each datum.

The spectrograph was also used to study the spectra of the individual cavitation events.

Propeller Performance

The standard nondimensional parameters used to describe the performance of a propeller are the advance coefficient, the thrust and torque coefficients, and the propeller efficiency.

The advance coefficient is a measure of the ratio of the speed of advance of the propeller through the fluid to the tip speed of the propeller; $V_A/(\pi nD)$ where V_A is the speed of the propeller relative to distant water, n the rate of rotation, and D the diameter of the propeller. For practical purposes the π is usually dropped and the advance coefficient (J) is defined by

$$J = V_A/(nD) \tag{3}$$

A low value of J corresponds to the propeller operating under a heavily loaded condition, i.e., low forward speed even though the propeller is rotating at a high rate. A high J corresponds to lightly loaded conditions with high forward speed being obtained at low rpm.

The thrust coefficient (K_T) and the torque coefficient (K_Q) are defined as

$$K_T = T/\rho n^2 D^4 \tag{4}$$

and

$$K_Q = Q/\rho n^2 D^5 \tag{5}$$

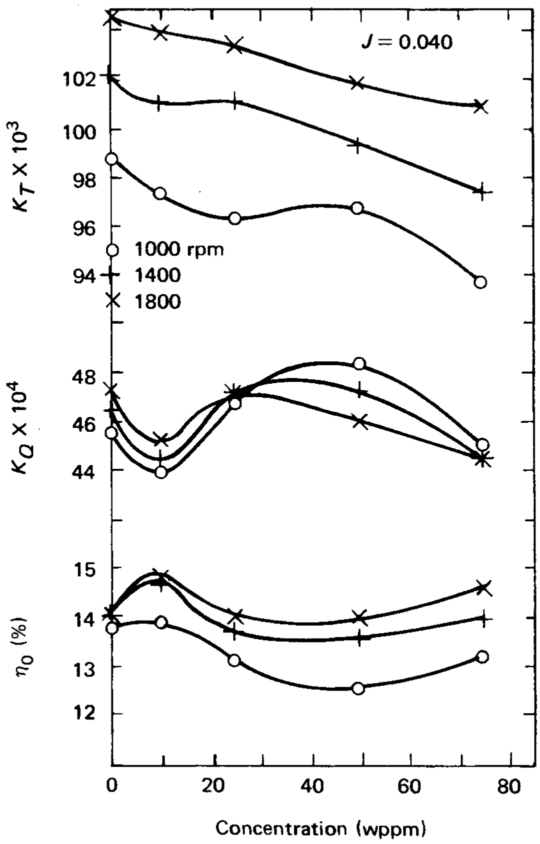

Fig. 5 Effect of polymer concentration on propeller performance at an advance coefficient of 0.040.

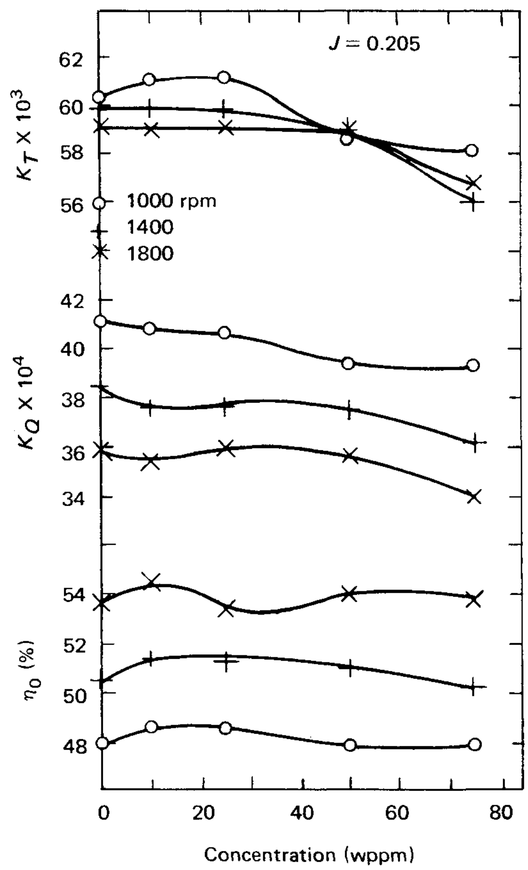

Fig. 6 Effect of polymer concentration on propeller performance at an advance coefficient of 0.205.

where T is the thrust, Q the torque, and ρ the density of the fluid.

Since the power supplied to the propeller is $(2\pi Qn)$ and the useful power output is (TV_A), the propeller efficiency (η_0) is

$$\eta_0 = TV_A/2\pi Qn \quad (6)$$

or in terms of the nondimensional coefficients

$$\eta_0 = JK_T/2\pi K_Q \quad (7)$$

Polymer Mixing and Degradation

All data reported herein were taken with the propeller operating in homogeneous solutions of polyethylene oxide, WSR-301. This polymer was chosen because of its proven drag-reducing ability and the ease with which it can be used.

Mixing was accomplished by slowly pouring a slurry of resin and Polyglycol P400 (Dow Chemical) into the rotating water. (Since the resin is completely insoluble in Polyglycol, it is held in suspension until it dissolves. If the resin were added directly to water, it would gather into lumps, called fisheyes, which would take an exorbitant time to dissolve.) The motor was operated at 1000 rpm while the mixture was allowed to circulate for 1 hr.

It was experimentally found that, for a given flow-restrictor setting, the value of J was essentially a constant, independent of both n and the polymer concentration. This fact dictated the manner in which the data were collected, i.e., T and Q were measured as a function of n for constant J with the polymer concentration as a parameter.

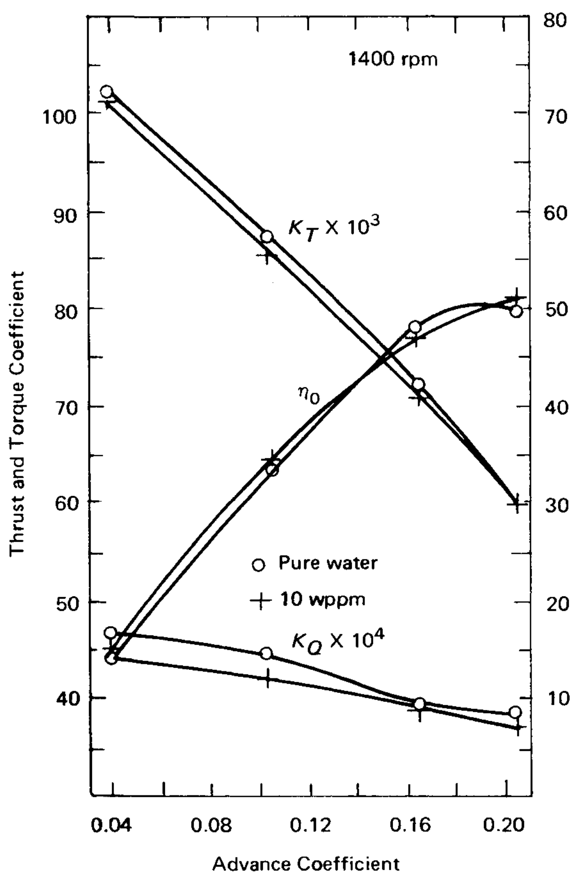

Fig. 7 Performance of a heavily loaded propeller in a 10 wppm solution of WSR-301.

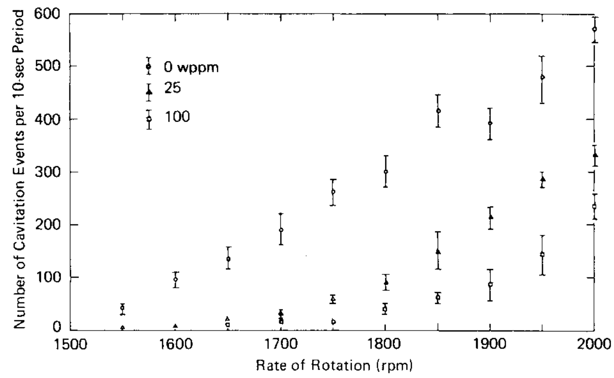

Fig. 8 Rate of occurrence of propeller cavitation events in solutions of WSR-301.

All measurements for a given flow-restrictor setting were obtained from a single master solution. The procedure was to first mix a 75 wppm solution and successively dilute to obtain 50, 25, and 10 wppm solutions. The entire run for a given flow-restrictor setting was accomplished within 5 hr.

To check the degradation of the solution a special run was made. The propeller was run at 1100 rpm in a 75-wppm solution for 5 hr with the flow restrictor set for J = 0.09. Readings of thrust and torque were taken every 1/2 hr and the results are plotted in Fig. 3. There was no noticeable change in thrust and an approximately 3% increase in torque in this period.

Results

Propeller Performance

The range of variables studied was: n from 850 to 2000 rpm in 50 rpm steps; J = 0.040, 0.104, 0.165, and 0.205; polymer concentrations of 75, 50, 25, 10 wppm and pure

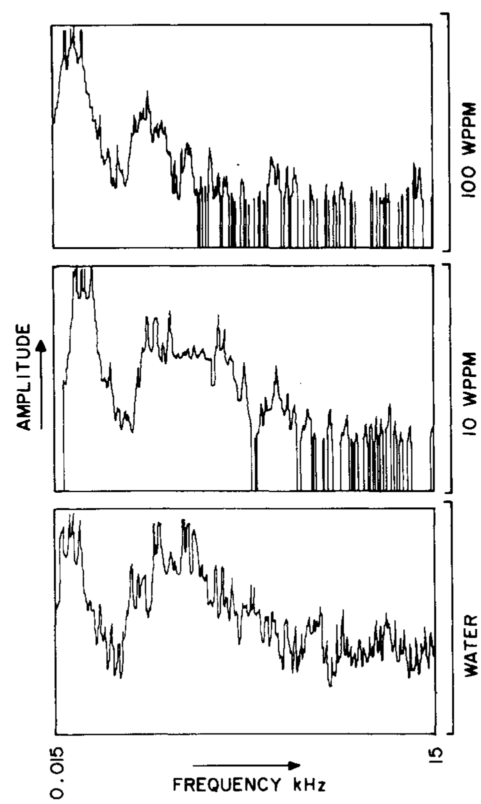

Fig. 9 Noise spectra for individual propeller cavitation events in solutions of WSR-301.

tap water. Typical results are shown in Fig. 4 where K_Q is shown for $J = 0.104$.

The effect of polymer concentration is more clearly presented in Figs. 5–6 where K_T, K_Q, and η_0 are shown for constant values of n. For constant n, K_T decreases with increasing concentration, this reduction being least marked for the highest value of J (0.205) where solutions less than 25 wppm have little effect on K_T. At the lower values of J, K_Q shows a marked minimum for concentrations around 10 wppm. For all other conditions, K_Q decreases slowly with increasing concentration. Only under a few conditions, was K_Q observed to rise above the value for pure water. The propeller efficiency (η_0) varies only a few percent, with the only significant feature being an increase of 1 or 2% at 10 wppm for the lower two values of J.

Figure 7 is a plot of K_T, K_Q, and η_0 as a function of J for the 10 wppm solution and n = 1400 rpm. It is seen that the results cover the heavily loaded side of the efficiency curve and that in these conditions the polymer has a slight advantageous effect on η_0.

Propeller Cavitation

The number of cavitation events per unit time as a function of n for various concentrations is shown in Fig. 8. Each datum is the average of ten 10-sec intervals and the rms variation is indicated. It is seen that while the polymer had no appreciable effect on the value of the threshold (the value of n at which cavitation was first detected), the polymer greatly reduced the rate of cavitation for all n above threshold. This reduction increases with increasing concentration, but for concentrations greater than 25 wppm, there is little additional reduction to be gained by further increasing the concentration.

The spectra of the individual cavitation events (Fig. 9) display a marked reduction in high frequency components at 10 wppm and higher concentrations. Similar spectral changes have been reported by Sendek[11] for cavitation in flow about a body.

Propeller Blade Lines

Measurements were made of the SPL of the main propeller blade line over the full range of n, for J = 0.104 and 0.205, and for concentrations of 10, 25, 50, and 75 wppm. No measureable effect on the acoustic blade signal was observed.

Conclusions

This study of a small, two-bladed propeller in dilute aqueous solutions of drag-reducing polymers covered a range of advance coefficients on the heavily-loaded side of the propeller efficiency curve. No deleterious effects of the polymer on the behavior of the propeller were uncovered.

In general, both the thrust and torque coefficients decreased with increasing concentration, while the propeller efficiency remained constant to within a few percent. There appeared to be a slight peak in efficiency when the concentration of the polymer was about 10 wppm.

The polymer had no measurable effect on the SPL of the fundamental acoustic blade line of the propeller. While the cavitation threshold was unaffected by the polymer, the rate of cavitation above threshold was drastically reduced by the polymer, this reduction reaching 70–80% at 25 wppm.

If these results can be extrapolated to full-size propellers, then it can be assumed that if polyethylene oxide were used to reduce the drag of large waterborne vehicles, 1) there would be no appreciable decrease in the performance of the propeller, 2) the source level of the acoustic blade signal would not be increased, and 3) the source level associated with propeller cavitation would be decreased.

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