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INVESTIGATION OF HULL EXCITATION CHARACTERISTICS ON *CFAV QUEST*

James L. Kennedy

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Approved by: R.W. Graham
Head / Hydronautics Section

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Abstract

The NSMB Co-operative Research Ships organization is investigating various aspects of hull excitation from highly skewed propellers. As part of this effort DREA measured hull excitations and made concurrent cavitation observations onboard CFAV QUEST. Results from these are presented and discussed. Varying amounts of sheet, leading edge vortex, tip vortex and hub vortex cavitation were observed. Bursting of the vortex cavitation was prominent in many cases. As ship speed and the amount of cavitation increased, so did the level of the higher harmonics of blade rate in the hull excitation spectra. There was some limited correlation between the appearance of the different forms of cavitation and the appearance of specific harmonics in the hull excitation. There was also data that indicated that no simple correlation would be possible. For instance, the harmonics at five and six times blade rate depended on the amount rather than the nature of the cavitation.

Résumé

L'organisme des navires de recherche coopérative du bassin de maquettes des Pays-Bas (NSMB) effectue des études sur divers aspects de l'excitation de la coque par des hélices fortement incurvées. Dans le cadre de ces recherches, le CRDA a mesuré les excitations de la coque et a fait des observations de la cavitation concomitante à bord du NAFC QUEST. Les résultats font l'object d'une présentation et d'une discussion. La cavitation a été observés à des degrés divers sur les lames, et dans les tourbillons marginals, de bords d'attaque, et de moyeux. L'éclatement de la cavitation des tourbillons dominait dans de nombreux cas. Au fur et à mesure que la vitesse du navire, et la cavitation, augmentait, le niveau de la plus haute harmonique de la fréquence pales dans le spectre d'excitation de la coque augmentait. Il y a une corrélation limitée entre l'aspect des différentes formes de cavitation et l'aspect d'harmoniques spécifiques dans l'excitation de la coque. De plus, certains données montrent qu'une corrélation simple n'est pas possible. Par example, l'harmonique correspondant à cinq ou six fois la vitesse de l'hélice dépend davantage de la quantité de la cavitation que de sa nature.

Executive Summary

DREA TM 98/212

INVESTIGATION OF

HULL EXCITATION CHARACTERISTICS

ON

CFAV QUEST

JAMES L. KENNEDY

Introduction

Moderately skewed propellers have been used for some time on naval vessels as a means of reducing propeller radiated noise. In recent years commercial ship owners have increasingly adopted highly skewed propellers as a means of controlling noise and vibration. A significant number of these commercial vessels encountered unexpected hull excitations, resulting in high levels of local vibration. These have unusually high levels of the higher harmonics of blade rate and of some broadband frequency ranges. These ships and their propellers were designed with state-of-the-art technology; hence, these problems show the need for improved design criteria for highly skewed propellers. The consequences for naval vessels are that current design methods risk yielding radiated noise signatures containing strong lines at the blade rate harmonics as well as increased broadband levels.

With the above background in mind, the NSMB Co-operative Research Ships organization has funded a working group to investigate various aspects of hull excitation from highly skewed propellers. As part of this effort DREA performed some measurements onboard Canadian Forces Auxiliary Vessel QUEST to add to our general knowledge about the relationship between cavitation and hull excitation. For these trials QUEST was fitted with accelerometers and a hydrophone to measure the hull excitation and a propeller viewing video system to record the cavitation.

Principal results

Trials data were obtained for a series of conditions, over a broad range of ship speeds. The data consisted of hull excitation measurements and concurrent cavitation observations on one of QUEST's propellers. A wide range of different cavitation conditions was obtained during the trials. At the lowest speeds only blade rate was detectable on the hull-mounted sensors. Broadband levels, blade rate harmonic levels and the amount of cavitation all increase with increasing ship speed. The blade rate harmonic levels became more prominent as ship speed increased. At the full power condition, harmonics up to six times blade rate were clearly identifiable.

The propellers experienced a range of cavitation types, namely, leading edge vortex, tip vortex, hub vortex and sheet cavitation. The leading edge and tip vortex cavitation frequently burst in the wake of the shaft bossing.

There was some limited correlation between the appearance of the different forms of cavitation and the appearance of specific harmonics in the hull excitation. There was also data that indicated that no simple correlation would be possible. For instance, the harmonics at five and six times blade rate depended on the amount rather than the nature of the cavitation.

Future work

This work is simply one of the early steps in identifying the causes of unusually high levels of the higher harmonics of blade rate and of some broadband frequency ranges. This trial alone could not produce enough data to allow reliable extrapolation to other ships. The Co-operative Research Ships working group will continue to investigate the topic in several ways. The group has reviewed available data from ships and their model tests and it will continue to gather relevant data from existing ships. It will also conduct more model tests and possibly full scale trials on known problem ships. This effort will culminate in the development of design guidance to minimize potential higher harmonic and broadband hull excitation problems.

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f	Frequency, Hz.
f_{max}	Maximum frequency for analysis, Hz.
L_p	Pressure spectrum level, db.
N	Shaft revolution rate, RPM
Np	Port shaft revolution rate, RPM
Ns	Starboard shaft revolution rate, RPM
$Navg_{1200}$	Average shaft revolution rate on Run 1200, RPM
N_{max}	Pre-set maximum shaft revolution rate, RPM
Pp	Port shaft power, kW
Ps	Starboard shaft power, kW
Pt_{1200}	Total power on Run 1200, kW
Vs	Ship speed, knots
Vs_{1200}	Ship speed on Run 1200, knots

1. Introduction

The NSMB Co-operative Research Ships organization funded the "PRES" Working Group (WG) to investigate various aspects of hull excitation from highly skewed propellers. At the first meeting of the PRES WG, held at Lloyd's Register in Croydon, in January 1996, DREA volunteered to perform some measurements onboard CFAV QUEST. The object of the trial was to add to the general knowledge about the relationship between cavitation and hull excitations. It was recognized at the outset that QUEST would not likely exhibit strong hull excitations as its propellers are lightly loaded and designed to minimize cavitation. The WG assigned Task B1 to DREA.

Task B1 consisted of propeller observations and simultaneous hull pressure, shaft torque and shaft speed measurements. The measurements were made at various uniform speeds and also during accelerating manoeuvres. Lloyds Register loaned DREA a pressure transducer, to be fitted in place of one of the viewing ports on QUEST, to make the hull excitation measurements. The propeller observations were made by video.

2. Background

At DREA there is an interest in understanding the causes of higher harmonics of blade rate that may be detectable in a ship's hull vibration spectrum. This interest is quite well aligned with the working group's interest in understanding the causes of higher harmonics in hull excitations. As part of DREA's ongoing research program, QUEST was fitted with several accelerometers, a hydrophone and a propeller viewing video system for a series of trials in April and May 1996. The extension of the trial to include a hull pressure transducer and to add some more runs was small.

As it turned out, it was not possible to fit the pressure transducer in place of a viewing port as the removable parts of the port had seized. The positive side to this was that the port was available for lighting the cavitation, and it was almost optimally placed for that purpose. Due to a complete failure of the shaft torque measuring system it was only possible to measure delivered power to the shaft motors. Fortunately, the engine power meters had been calibrated shortly before the trial.

2.1 CFAV Quest

The Canadian Forces Auxiliary Vessel (CFAV) QUEST was conceived and designed as an open ocean acoustic research vessel. Quest has a displacement of 2250 tonnes, a length of 77.25m, a beam of 13.05m and a mean draft of 4.73m. The propulsion system is DC electric, the prime mover being either one or two diesel generators or a gas turbine auxiliary propulsion generator.

QUEST has twin screws and twin rudders and the propeller shafts are supported in streamlined bossings. A schematic diagram of the propeller and bossing arrangement is shown in Figure 1 along with part of a body plan. A deep wake deficit is present immediately behind the bossing. Any cavitation from the propeller is principally a result of this wake deficit.

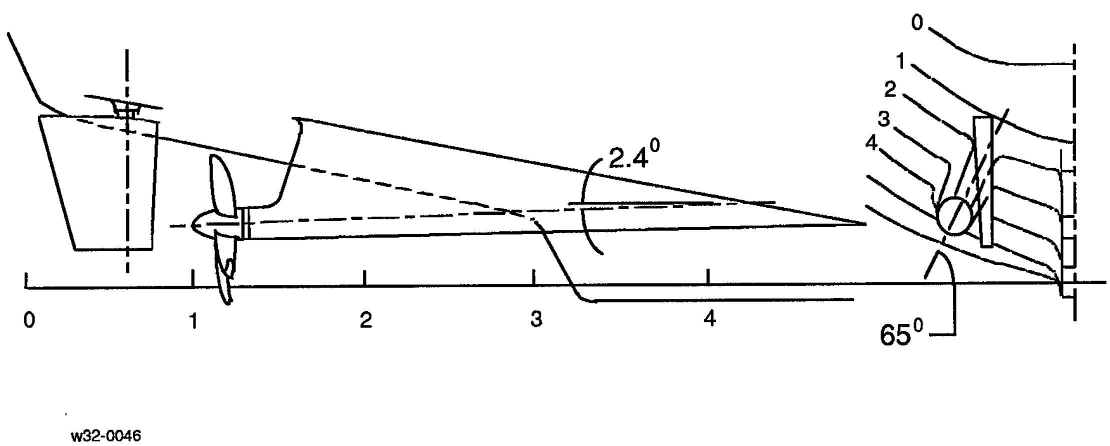

Figure 1 Propeller support bossing on CFAV QUEST

QUEST's five-bladed propellers are 3.048m in diameter with an expanded blade area ratio of 0.46. They are highly skewed and turn outwards over the top. A sketch of these is provided in Figure 2. QUEST was fitted out for making the measurements and observations on the port side only.

Figure 2 also shows the arrangement of accelerometers, the hydrophone, the propeller viewing ports, and underwater lights and camera for the trials. The frames shown in Figure 2 are minor bulkhead frames. Between these are intermediate frames (152mm x 89mm x 9.5mm) on which the accelerometers were mounted, at the locations indicated.

The hydrophone was fitted inside the hull in a 185mm long cylindrical can 180mm in diameter. The can was filled with water and set in place in the most outboard viewing port. It was acoustically connected to the port by silicone grease.

The propeller could be observed by eye, or illuminated, through the viewing ports located between frames 110 and 112. The cavitation observations reported here were made by two video cameras. One camera was mounted through the hull, ahead of frame 109. The other camera was mounted inside the hull, in the middle viewing port, between frames 110 and 111. The propeller motion was frozen by illuminating it with three General Radio Strobolume lamps. Two lamps were mounted through the hull in streamlined bodies, ahead of frame 109. Additional light was provided by a third lamp mounted in the viewing port between frames 111 and 112.

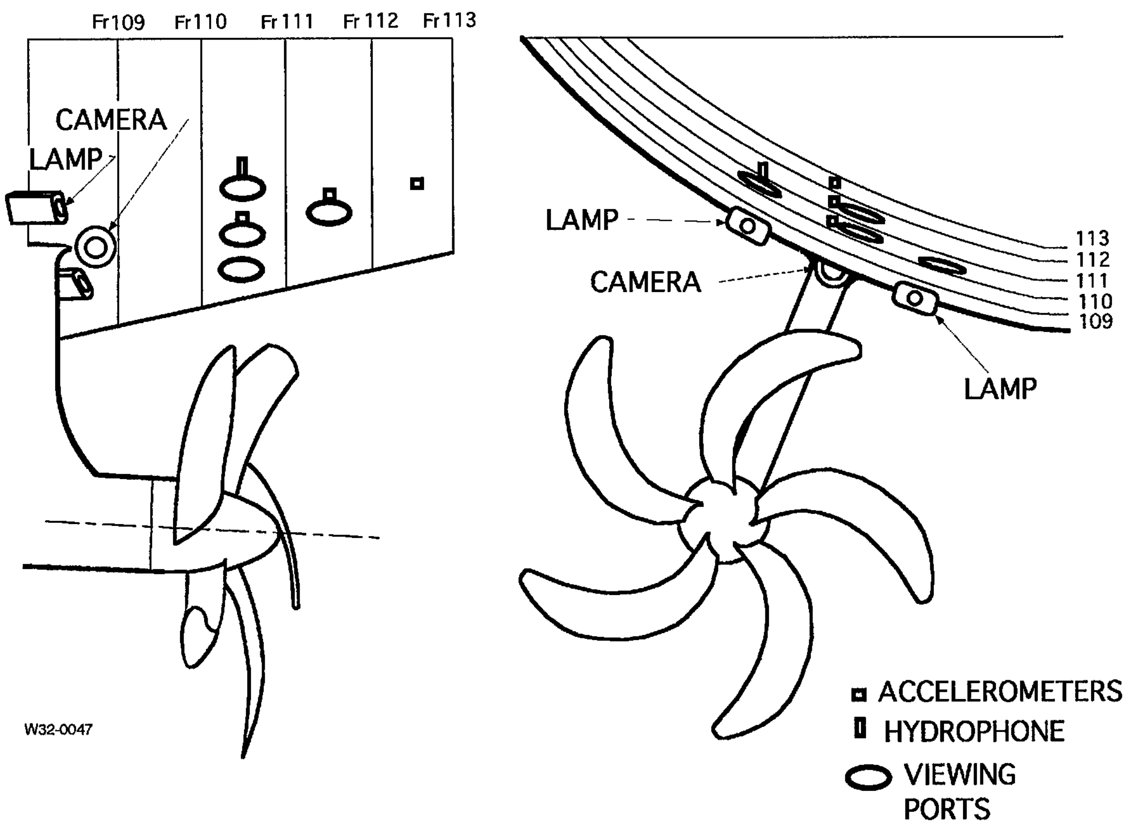

Figure 2 Arrangement of hydrophone and accelerometers on CFAV QUEST

The port propeller blades were marked with grid lines to enable observers to better identify the locations of the cavitation. Chord lines were marked at each 0.1 radius fraction from 0.3 to 0.9 radius fractions. Lines were also marked through the mid-chord and quarter-chord points. The lines were not always clearly visible in the video observations presented here. The lines had deteriorated a little in the 15 years since they were applied, and the blades were somewhat fouled at the time of the trials.

2.2 Ship Trials

The trials on QUEST took place en route from Nassau to Halifax. The uniform speed runs presented here were carried out on 27 April 1996 when QUEST was between 90 and 180 nautical miles north-east of Nassau. The sea was calm with an estimated 1m swell. For these runs, constant speed and course were kept and minimal rudder action was applied. The runs covered a wide range of shaft revolution rates, up to a pre-set maximum value. A list of the run numbers and the ratio of nominal revolutions requested to the pre-set maximum is supplied in Table 1.

The ship speed was taken from the QUEST's Doppler log. The shaft power was taken from each engines' current and voltage, and the shaft revolutions from 60-toothed wheels fitted to the shafts.

Run number	Nominal N/N_{max}
1100	.29
1110	.36
1120	.43
1130	.50
1140	.57
1150	.64
1160	.71
1170	.79
1180	.86
1190	.93
1200	1.00

Table 1 Uniform speed runs

The accelerating runs discussed here were also carried out on 27 April 1996 when QUEST was about 350 nautical miles north-east of Nassau. The sea was calm. For these runs the ship accelerated from a stopped condition, with rudders fixed amidships. A list of the run numbers, driven screws and the acceleration requested is supplied in Table 2. The acceleration represented by slow ahead was left to the engineer's judgment.

Run number	Driven screws	Acceleration
1210	Both	Full ahead
1211	Both	Slow ahead
1220	Port only	Slow ahead
1221	Port only	Full ahead
1222	Port only	Full ahead

Table 2 Accelerating runs

2.3 Data Analysis

An HP3562A dynamic signal analyzer processed the data from the accelerometers and the hydrophone. A low frequency range, 0 to $0.08f_{max}$, and a high frequency range, 0 to f_{max}, were covered for each sensor and the resulting power spectral density functions are presented here. A common reference acceleration was used for all accelerometer data presented and a common reference pressure was used for all hydrophone data. The hydrophone pressures reported here should not be confused with hull pressure measurements.

All spectra are presented in non-dimensional form. The ratio of the frequency band to the maximum frequency of analysis (f_{max}) is provided on the ordinate. Also, the pressures and accelerations are not provided specifically, rather 10db increments are identified on the abscissa. To ease comparison of data between runs, the abscissas on all plots of acceleration spectra cover the same range. Similarly, the abscissas on all plots of hydrophone spectra cover the same range.

Cavitation observations were made with two cameras and three flash-lamps. One camera faced aft and allowed a broad view of the back of the blade. Another camera viewed the propeller from above and provided a more detailed view of the cavitation at the tip. When the flash-lamps fired, both cameras recorded the image created by that flash.

3. Trials Data and Observations

In this section the data gathered is presented for each run separately. The measured test conditions for each run are given first, in non-dimensional form. The ship speed has been divided by the speed on Run 1200 (Vs_{1200}); the individual shaft powers have been divided by the total power on Run 1200 (Pt_{1200}); and the individual shaft RPM have been divided by the average shaft RPM on Run 1200 ($Navg_{1200}$).

Some representative images from the video cameras are presented for each run with a description of the cavitation observed. These still pictures do not do complete justice to the dynamics of the real situation. Finally the accelerometer and hydrophone spectra are presented together with some comment on them.

The accelerometer spectra are laid out as follows. Data at frame 110.5 (the farthest forward) are presented as measured. Data at frame 111.5 are presented as the measured data minus 20db. Data at frame 112.5 (the farthest aft) are presented as the measured data minus 40db. This arrangement is intended to assist in the comparison of the spectra at the three locations. The hydrophone spectra are presented as measured.

Two sets of spectra are presented for each run. The first set are low frequency spectra covering the range from 0 to $0.08f_{max}$. These highlight harmonics up to six times blade rate (6×BR), which are identified by the diamonds on the axis. The blade rate (BR), and harmonics were obtained from the shaft revolution meter, averaged over a period of the order of ten minutes. The spectra were obtained over a period of the order of one minute. Drift in the RPM signal can result in the calculated harmonics not matching the harmonic response in the spectra exactly. The second set are high frequency spectra covering the range from 0 to f_{max} that highlight the broadband signal.

Some of the terminology used in this report for describing propeller cavitation is outlined below. The term 'tip vortex' has been reserved for vortices that separate from the blade at the tip (Radius fraction 1.0). The term 'leading edge vortex' is used for vortices that detach from the leading edge at sections noticeably inboard of the blade tip. There is an element of judgment in making the distinction between these two. 'Vortex bursting' is used for the condition where the usual rope-like or ribbon-like appearance changes to a dispersed cloud of bubbles. In QUEST's case, vortex bursting was present when the vortex extended across the wake of the shaft bossing.

3.1 Run 1100

Table 3 presents the measured test conditions during Run 1100.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.28	0.01
Port shaft power, Pp/Pt_{1200}	0.02	-
Starboard shaft power, Ps/Pt_{1200}	0.02	-
Port revolutions, $Np/Navg_{1200}$	0.30	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.30	0.01

Table 3 Conditions for Run 1100

No cavitation was seen or heard at this condition. A view of the propeller with one blade tip in the wake peak is shown in Figure 3.

Figure 4 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. The data for all three locations are very similar. Figure 5 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

These spectra show the noise floor. The noise floor was not the same for all three accelerometers and this was attributed to small differences in their lower limits of sensitivity. The noise floor of the accelerometer at Frame 110.5 was noticeably lower than that for other accelerometers. The lines in the accelerometer data were not due to cavitation. The line in the accelerometer data close to blade rate (about $f/f_{max} = .0034$) was not primarily propeller related. A line at that frequency was seen in subsequent runs at different ship speeds. The same was true for the line at about $f/f_{max} = .008$ to .009. The lines at $f/f_{max} = .06$ are due to other known ship sources.

The line in the hydrophone data close to blade rate (about $f/f_{max} = .0034$) was probably propeller related. This line tracks blade rate in subsequent runs at higher ship speeds.

Figure 6 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 7 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

The high frequency analysis showed considerable noise in the regions $f/f_{max} = 0.1$ to 0.3 and $f/f_{max} = 0.8$ to 0.9. It is noteworthy that the noise in the higher frequency band did not extend as far aft as frame 112.5. These may come from the steering motors mounted on the deck above the instrumentation.

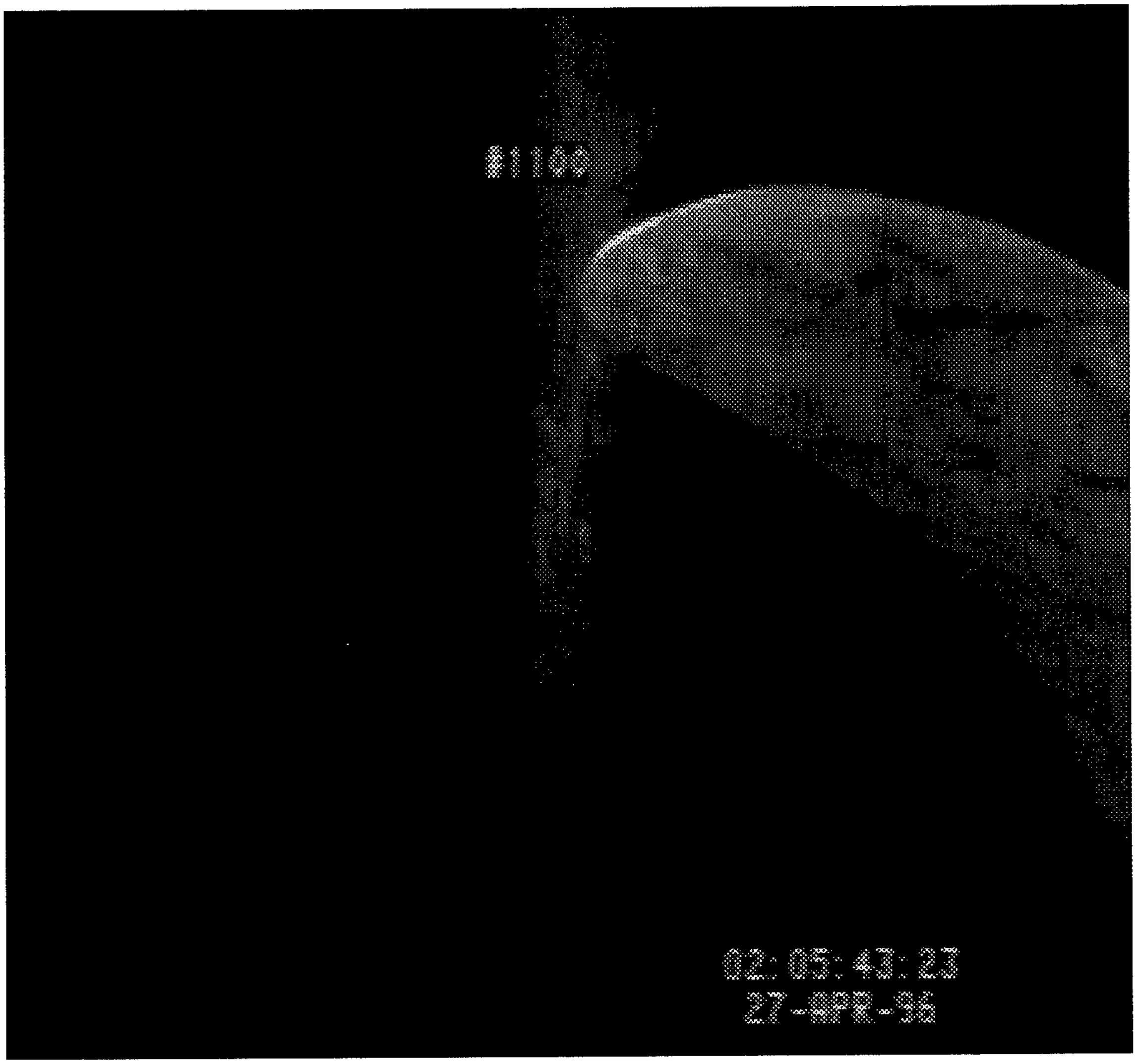

Figure 3 Propeller, looking aft, Run 1100

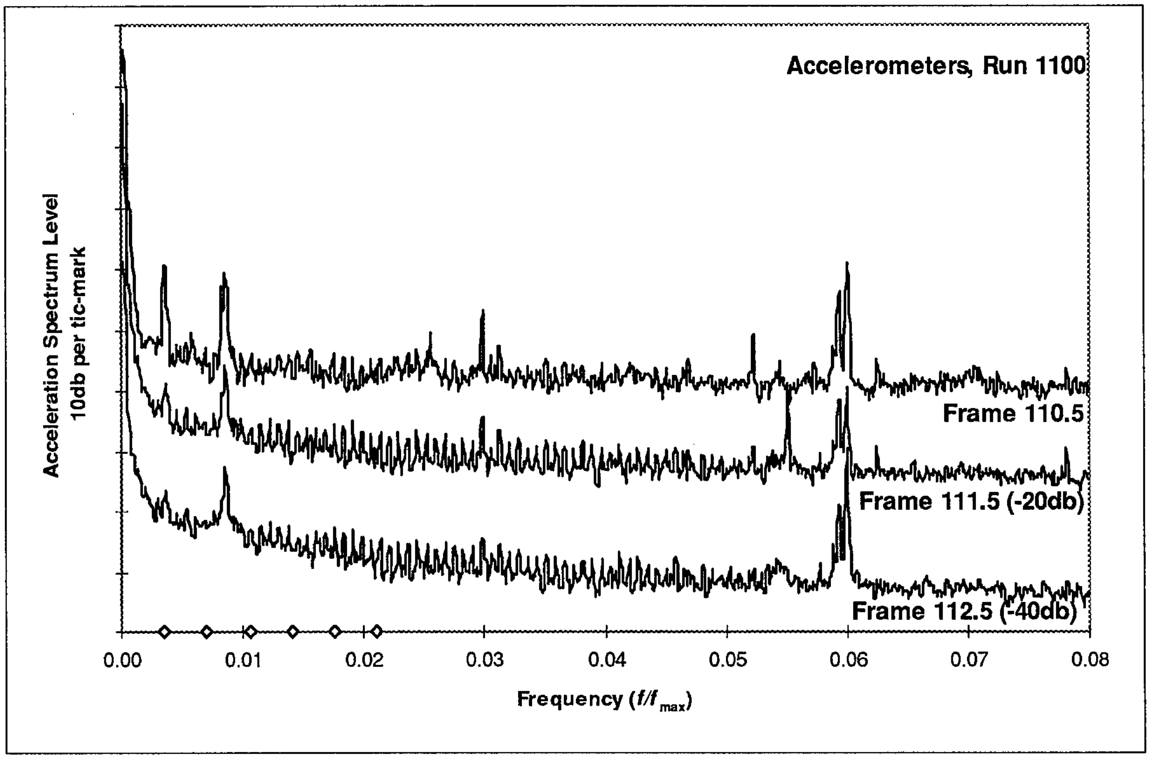

Figure 4 Low frequency accelerometer data, Run 1100

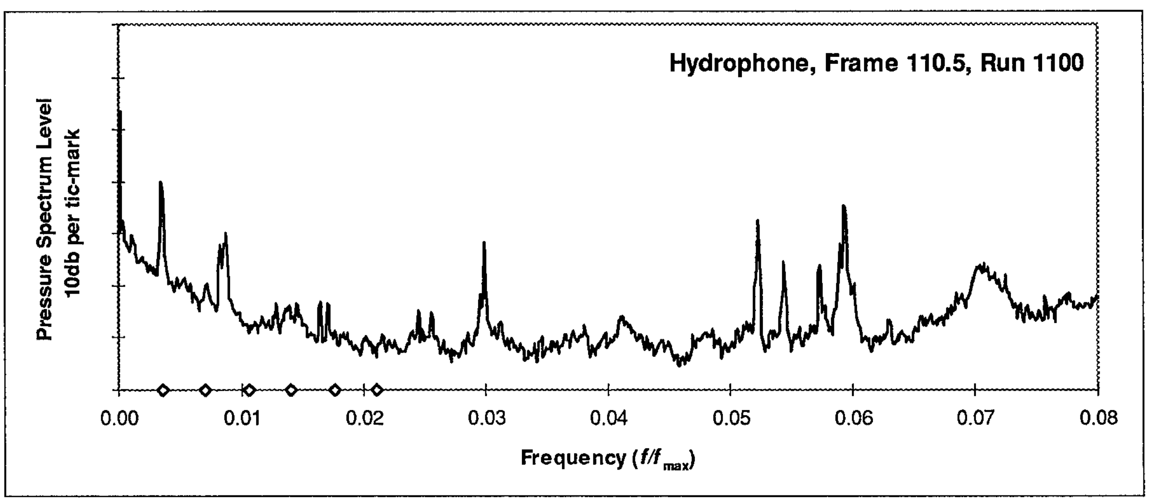

Figure 5 Low frequency hydrophone data, Run 1100

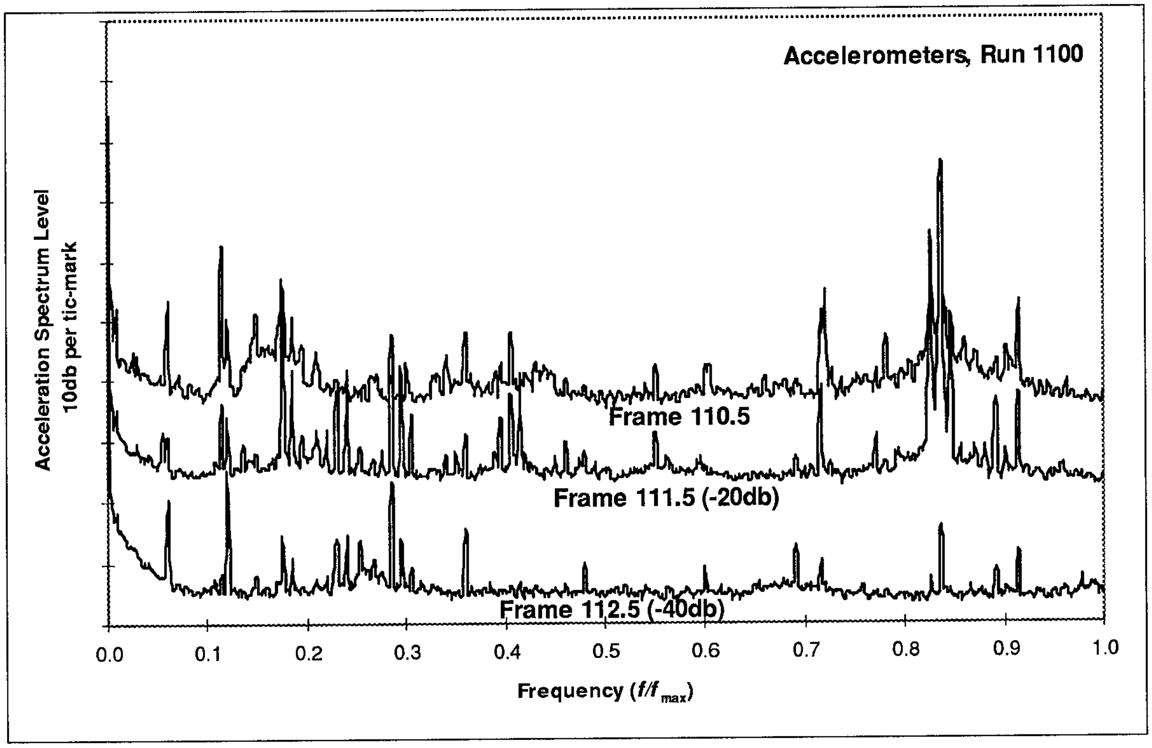

Figure 6 High frequency accelerometer data, Run 1100

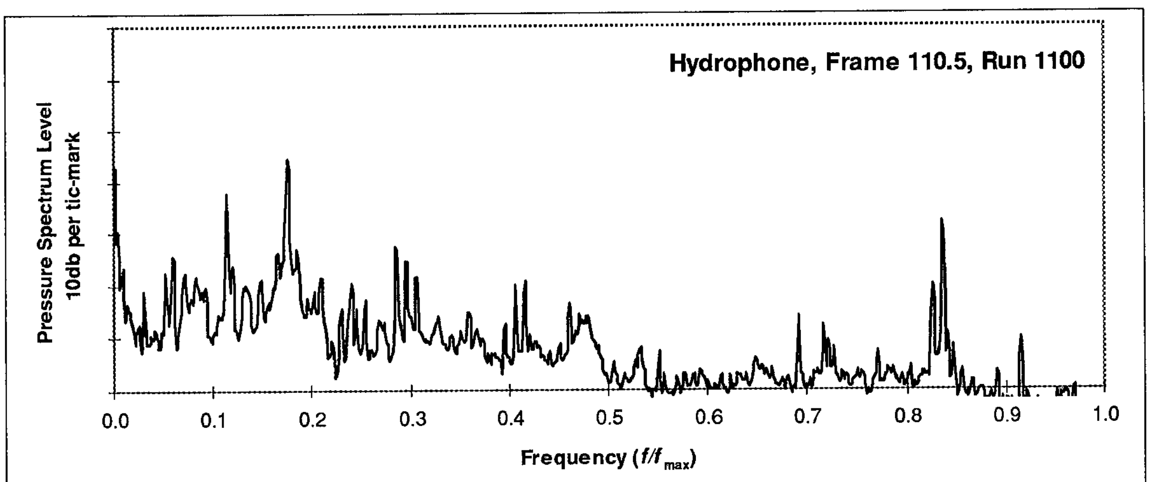

Figure 7 High frequency hydrophone data, Run 1100

3.2 Run 1110

Table 4 presents the measured test conditions during Run 1110.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.35	0.01
Port shaft power, Pp/Pt_{1200}	0.03	-
Starboard shaft power, Ps/Pt_{1200}	0.03	-
Port revolutions, $Np/Navg_{1200}$	0.37	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.37	0.01

Table 4 Conditions for Run 1110

No cavitation was seen or heard at this condition. A view of the propeller with one blade tip in the wake peak is shown in Figure 8.

Figure 9 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. The data for all three locations are very similar. Figure 10 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

As with the spectra from Run 1100, these spectra also showed the noise floor. The spectra in the accelerometer data were almost identical to those of Run 1100 and the features in them were not due to cavitation. The line at 2×BR was not primarily propeller related.

The lowest line in the hydrophone data tracked the propeller blade rate. This is quite unlike the accelerometer data and is an indication of the higher sensitivity of the hydrophone. The line at 2×BR was not primarily propeller related. It was present, at that frequency, in a wide range of runs.

Figure 11 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5 Figure 12 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

As with the spectra from Run 1100, these spectra also show the noise floor. The spectra in the accelerometer data are almost identical to those of Run 1100 with one exception. The noise floor for the accelerometer at frame 112.5 increased by about 5db. There is no explanation for this but it does not affect the conclusions that will be drawn from the data.

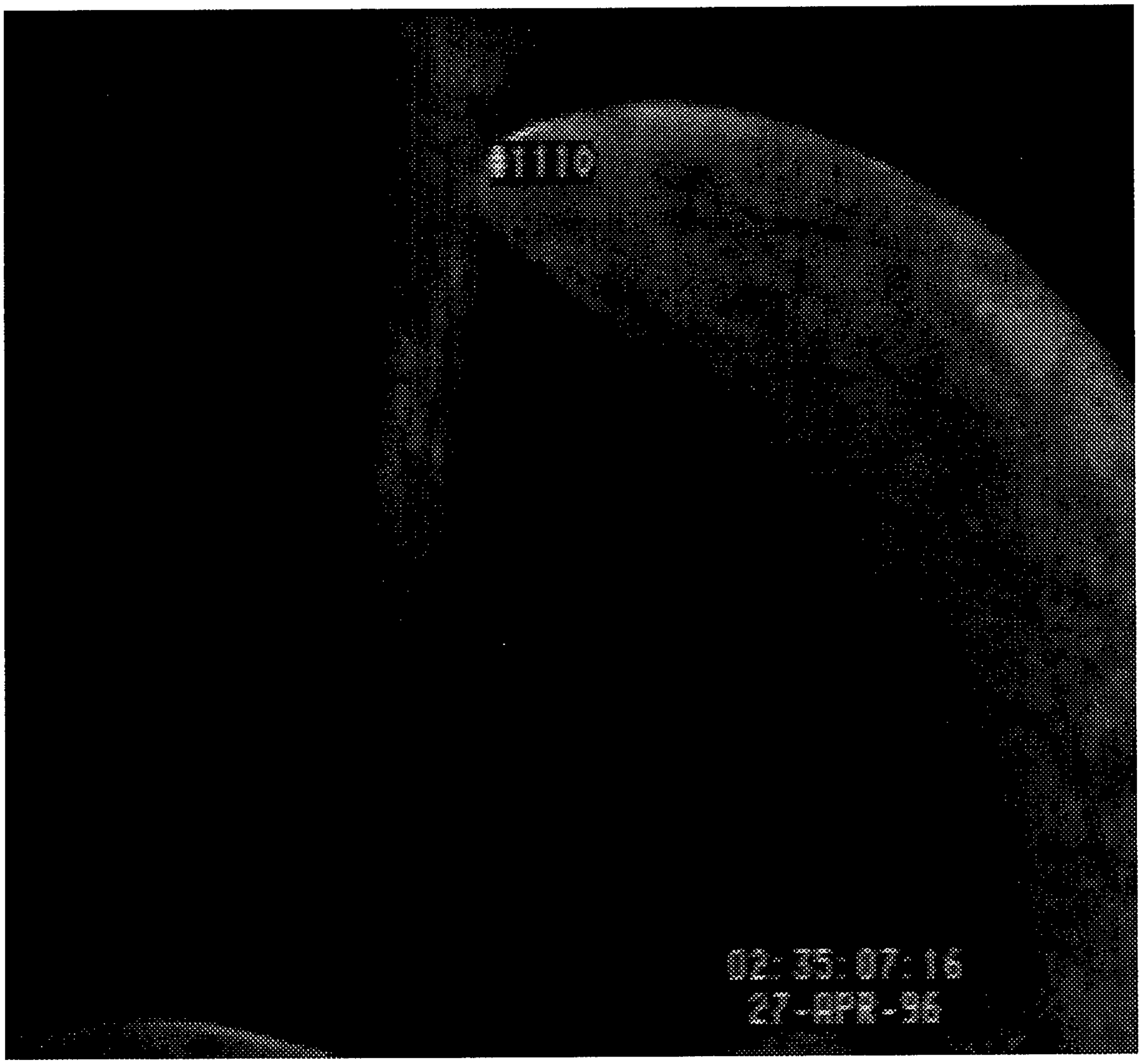

Figure 8 Propeller, looking aft, Run 1110

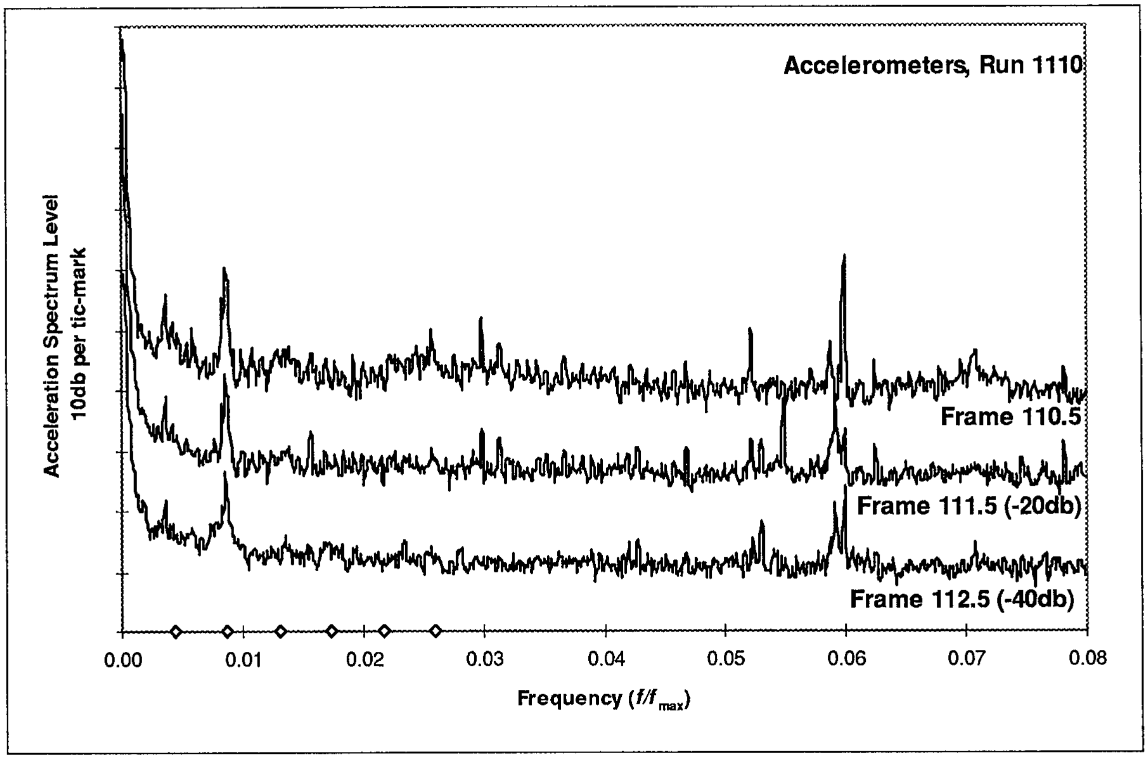

Figure 9 Low frequency accelerometer data, Run 1110

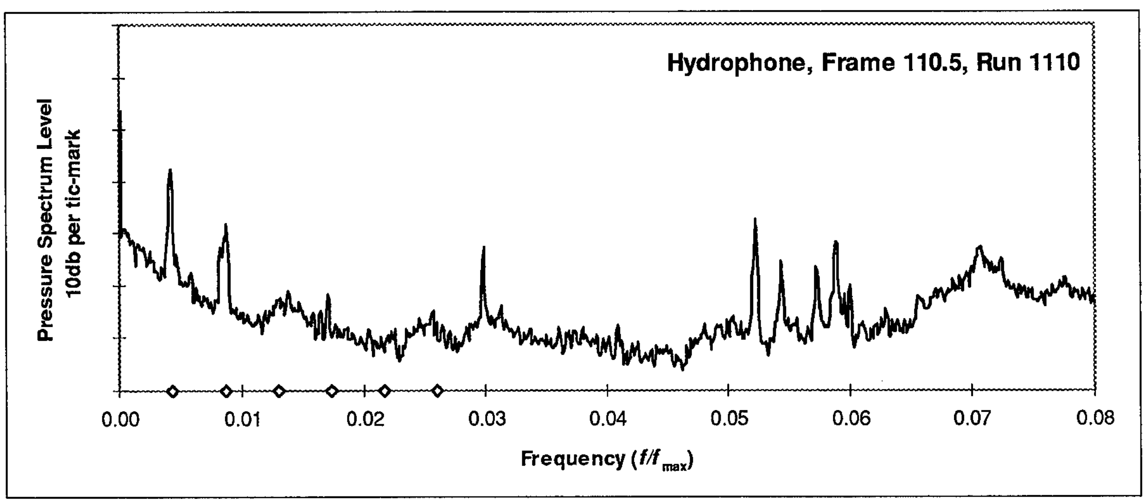

Figure 10 Low frequency hydrophone data, Run 1110

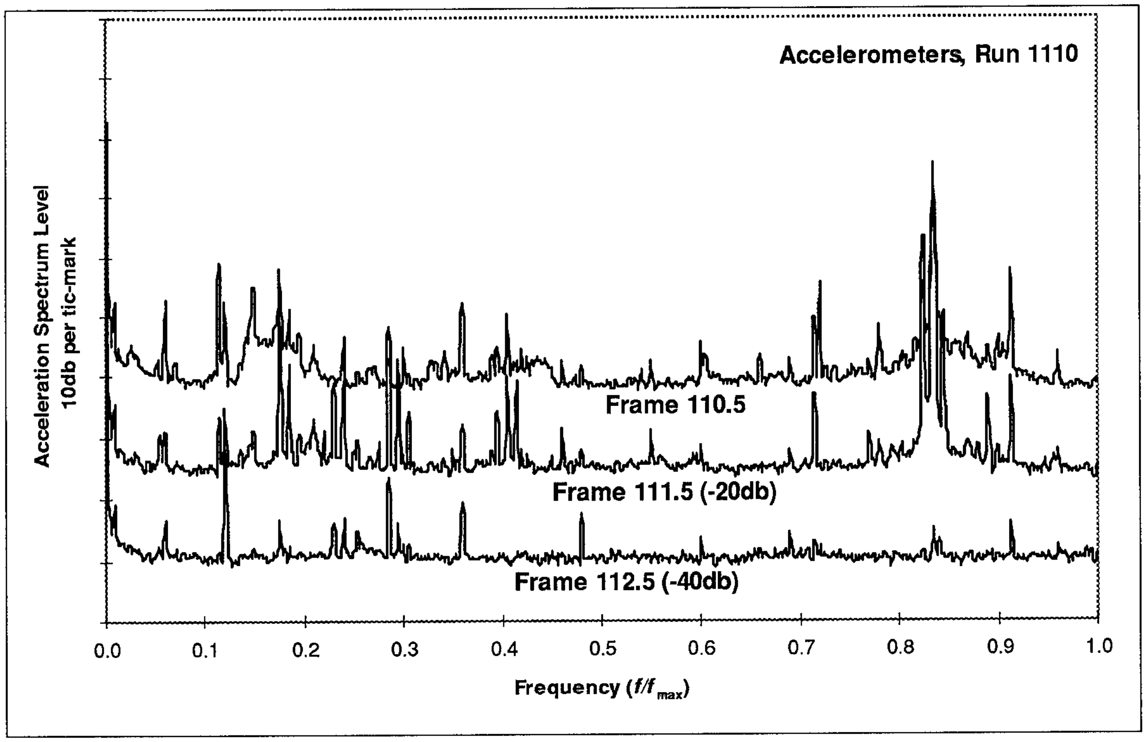

Figure 11 High frequency accelerometer data, Run 1110

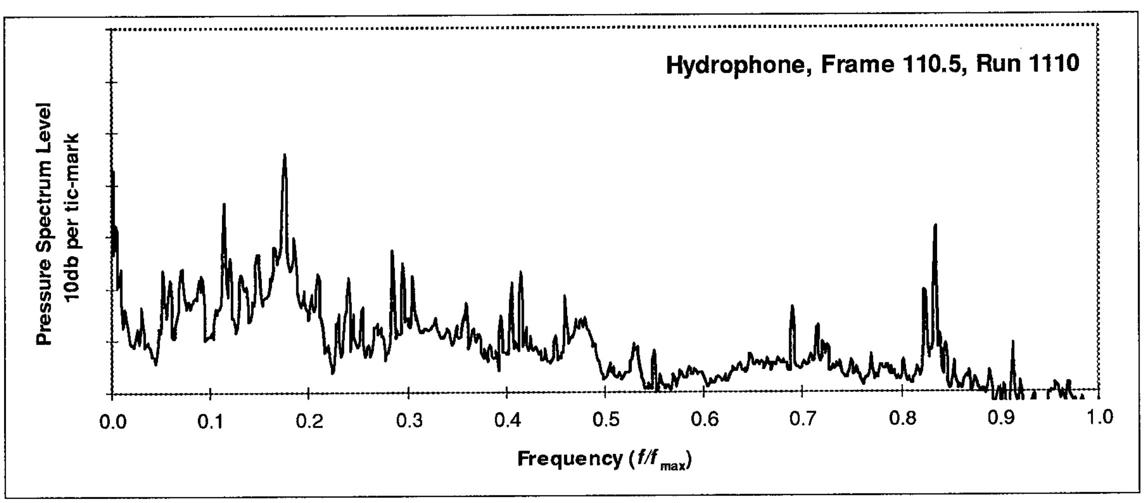

Figure 12 High frequency hydrophone data, Run 1110

3.3 Run 1120

Table 5 presents the measured test conditions during Run 1120.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.44	0.01
Port shaft power, Pp/Pt_{1200}	0.04	-
Starboard shaft power, Ps/Pt_{1200}	0.05	-
Port revolutions, $Np/Navg_{1200}$	0.45	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.45	0.01

Table 5 Conditions for Run 1120

The cavitation at this condition was very intermittent. About 1 percent of the blade passes were estimated to have experienced cavitation. These were detected audibly. One pair of images in the complete run picked up a vortex leaving the blade tip in the wake peak. This can be seen in Figure 13, identified by the arrow at the blade trailing edge. It is also visible in the fuzzy area identified by the arrow in Figure 14. These were the only visual indications of cavitation.

Figure 15 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 16 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers showed only a blade rate line rising above the noise floor. This was clear for the two forward accelerometers. The higher noise floor for the accelerometer at frame 112.5 obscured the blade rate line, if it existed there. In the data from the accelerometer at frame 111.5, the line at 6×BR was not propeller related.

The hydrophone data showed both blade rate and 2×BR lines. There was a small increase in broadband noise between $f/f_{max} = 0.03$ and 0.05. There was also a change in the frequency of the line at about $f/f_{max} = 0.055$ which was not likely related to the propeller.

Figure 17 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 18 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

There was no significant difference between the accelerometers' high frequency spectra for Runs 1120 and 1110. The hydrophone data for run 1120 showed a small increase, of the order of 2db, across much of the frequency band. This could be attributed to the cavitation.

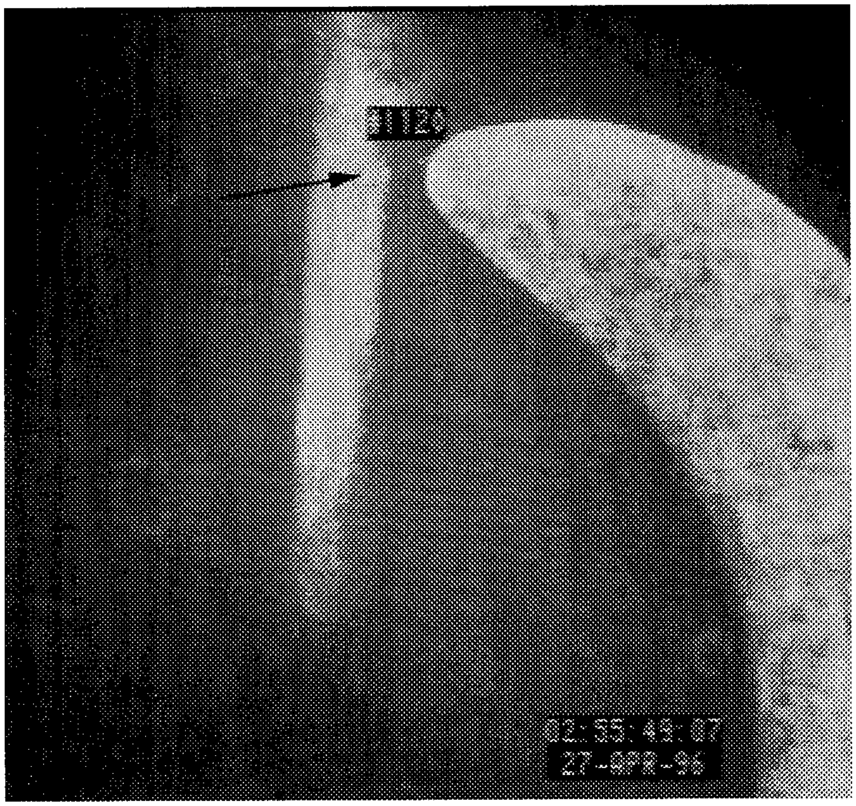

Figure 13 Propeller cavitation, looking aft, Run 1120

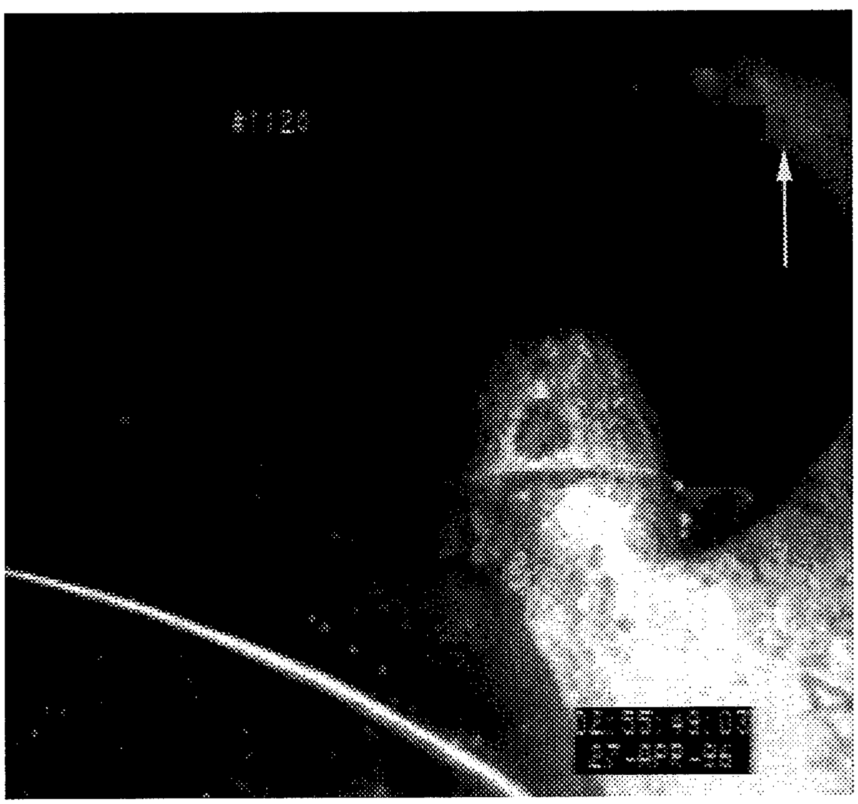

Figure 14 Propeller cavitation, view from above, Run 1120

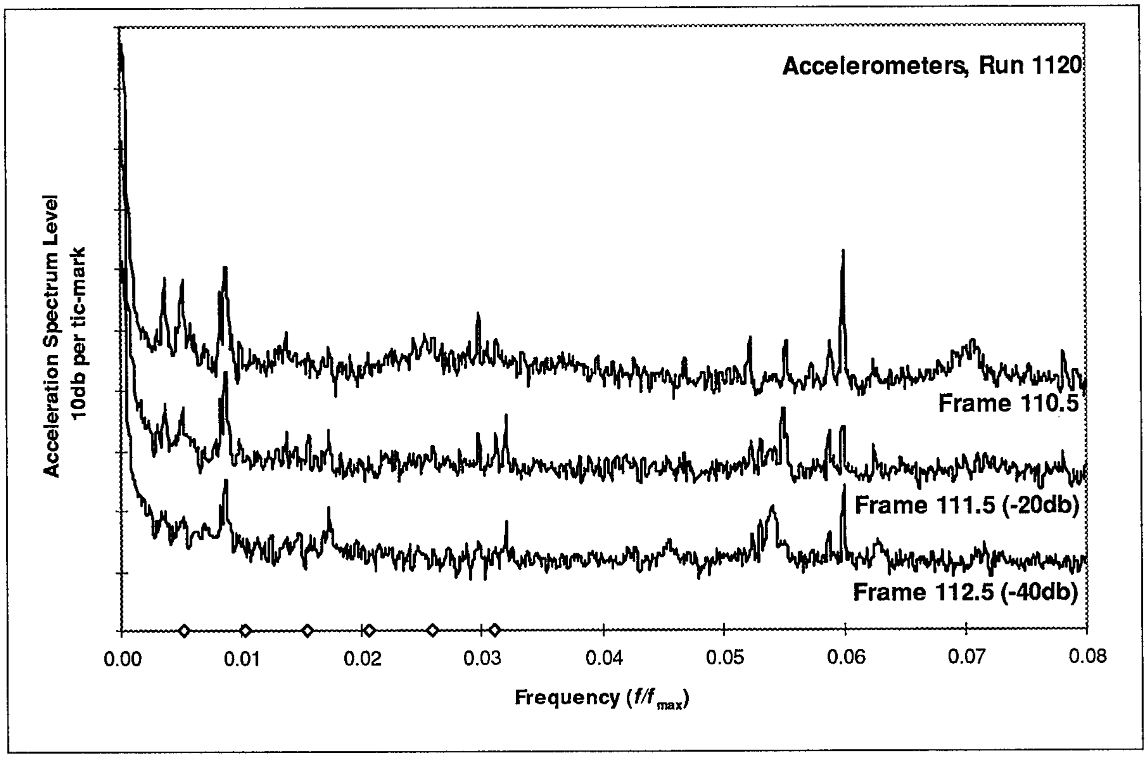

Figure 15 Low frequency accelerometer data, Run 1120

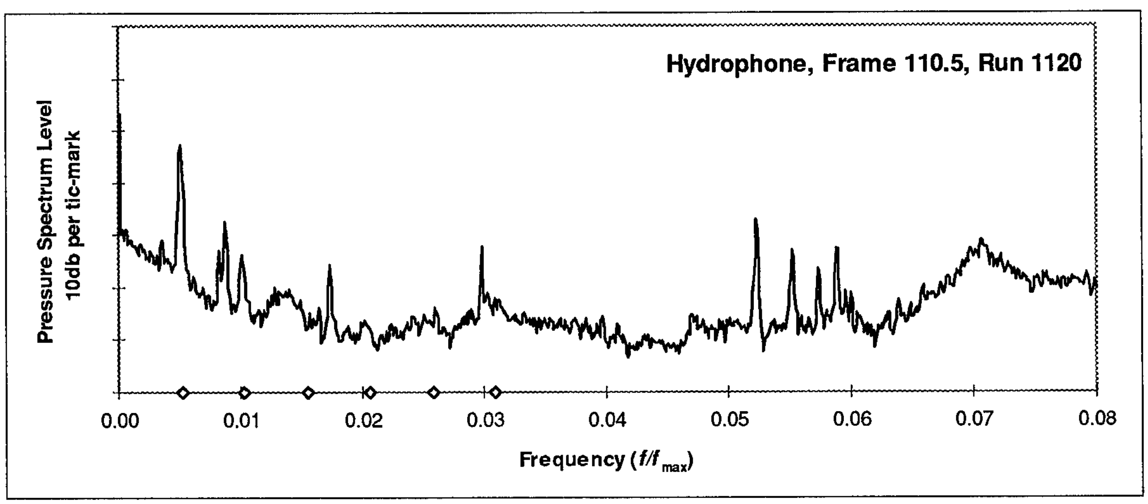

Figure 16 Low frequency hydrophone data, Run 1120

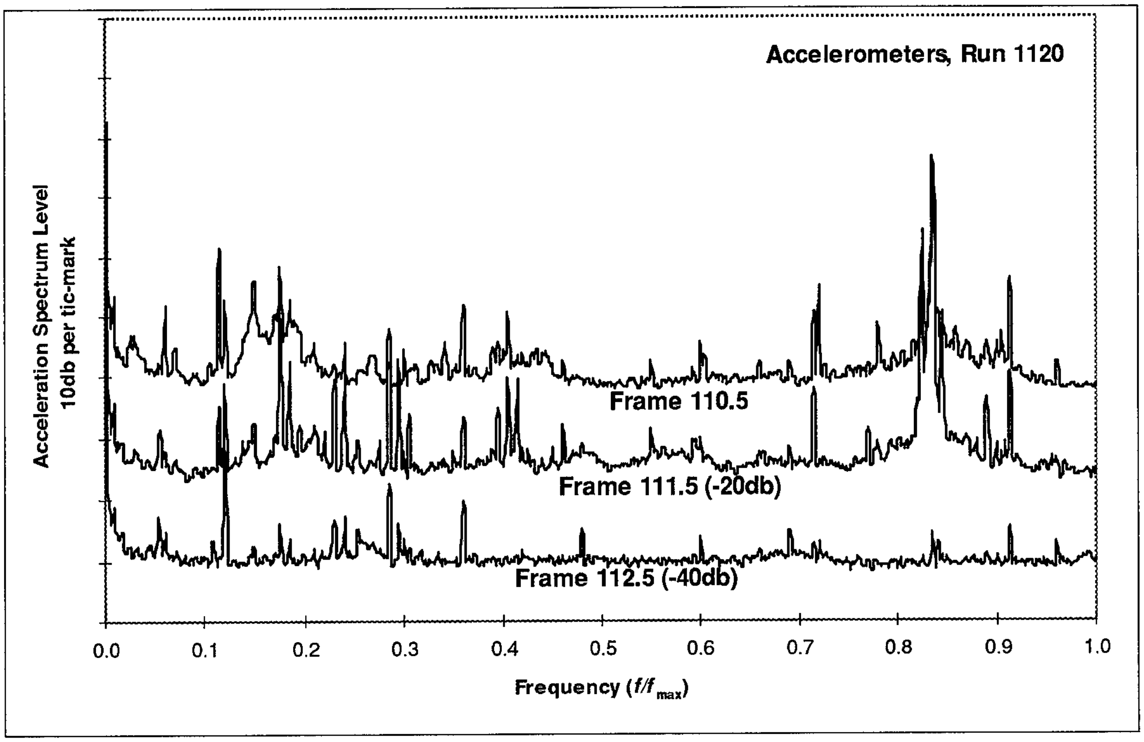

Figure 17 High frequency accelerometer data, Run 1120

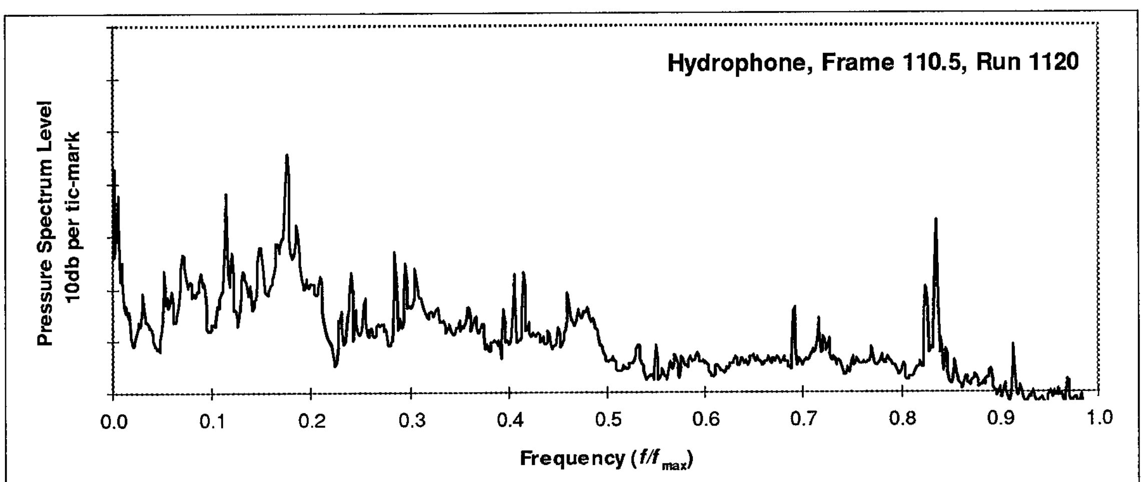

Figure 18 High frequency hydrophone data, Run 1120

3.4 Run 1130

Table 6 presents the measured test conditions during Run 1130.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.51	0.02
Port shaft power, Pp/Pt_{1200}	0.07	-
Starboard shaft power, Ps/Pt_{1200}	0.07	-
Port revolutions, $Np/Navg_{1200}$	0.51	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.51	0.01

Table 6 Conditions for Run 1130

Intermittent vortex cavitation was observed on all blades at this condition. Two views of this can be seen in Figure 19 and Figure 20. These pictures indicate that the cavitation came from a leading edge vortex which detached from the blade, at close to the 0.98 radius fraction. The vortex is seen, as indicated by the arrows, in Figure 19, downstream of the blade, and in Figure 20, as a short line of bubbles. In Figure 19 an arrow indicates a vortex from the previous blade, cavitating in the wake peak, close to the rudder.

Figure 21 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 22 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers showed only a blade rate line rising above the noise floor.

The hydrophone data showed blade rate and 2×BR lines. It was judged that the line at close to 3×BR was not a propeller blade rate harmonic. There was some further small increase in broadband noise between $f/f_{max} = 0.03$ and 0.05, and one line at about $f/f_{max} = 0.053$ replaced two separate lines in that region. The significance of this is not known.

Figure 23 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 24 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

At frame 110.5 there was an observable increase in both the acceleration and pressure levels over those of Run 1120. The hydrophone signal increased by about 2db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 5db in the frequency band from $f/f_{max} = 0.3$ to 1.0. The higher noise floor of the accelerometers at frames 111.5 and 112.5 hid this effect at these locations.

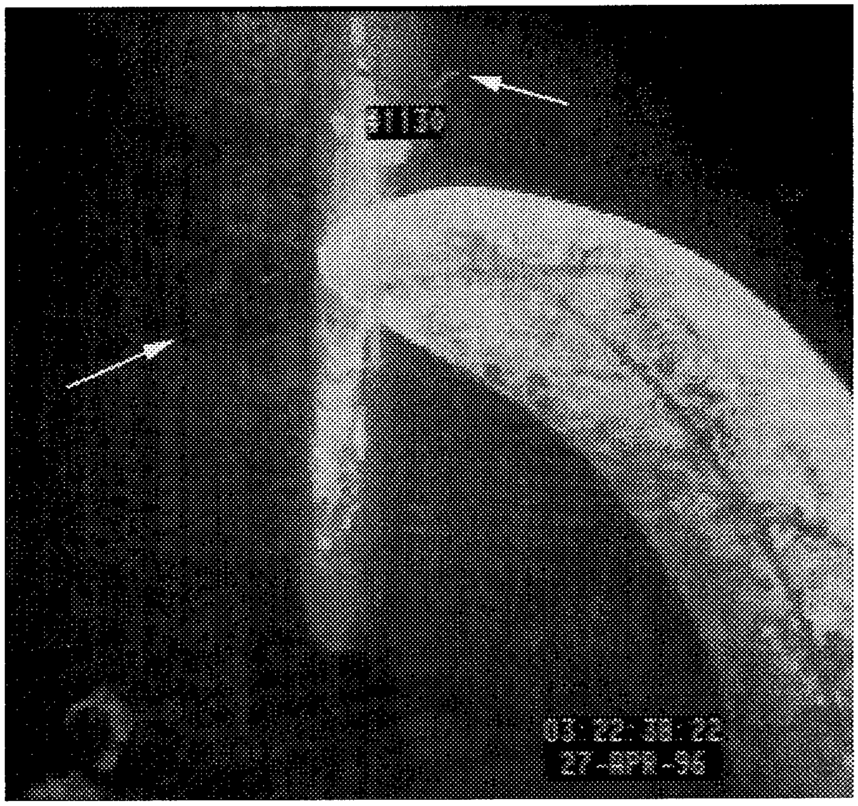

Figure 19 Propeller cavitation, looking aft, Run 1130

Figure 20 Propeller cavitation, view from above, Run 1130

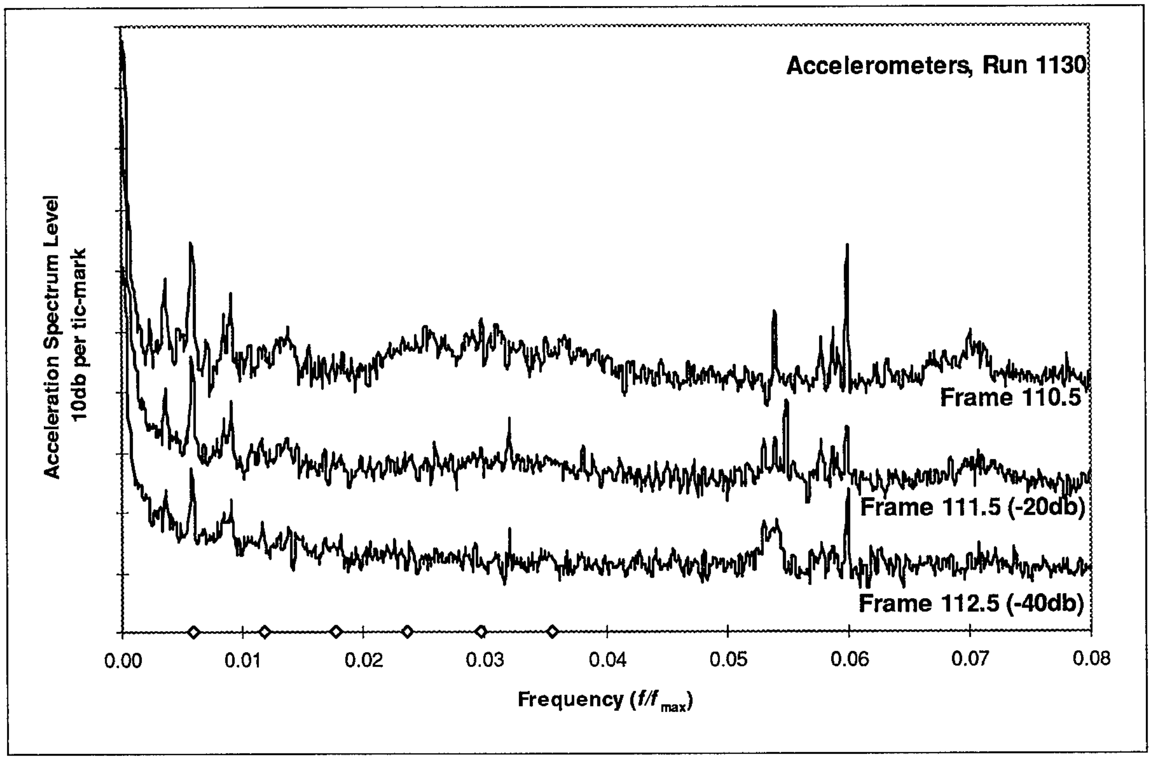

Figure 21 Low frequency accelerometer data, Run 1130

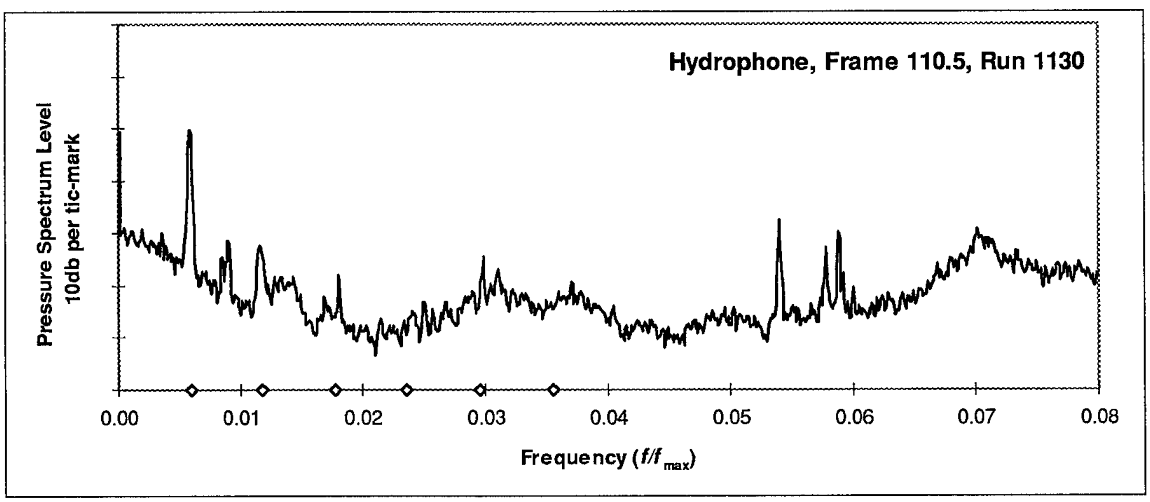

Figure 22 Low frequency hydrophone data, Run 1130

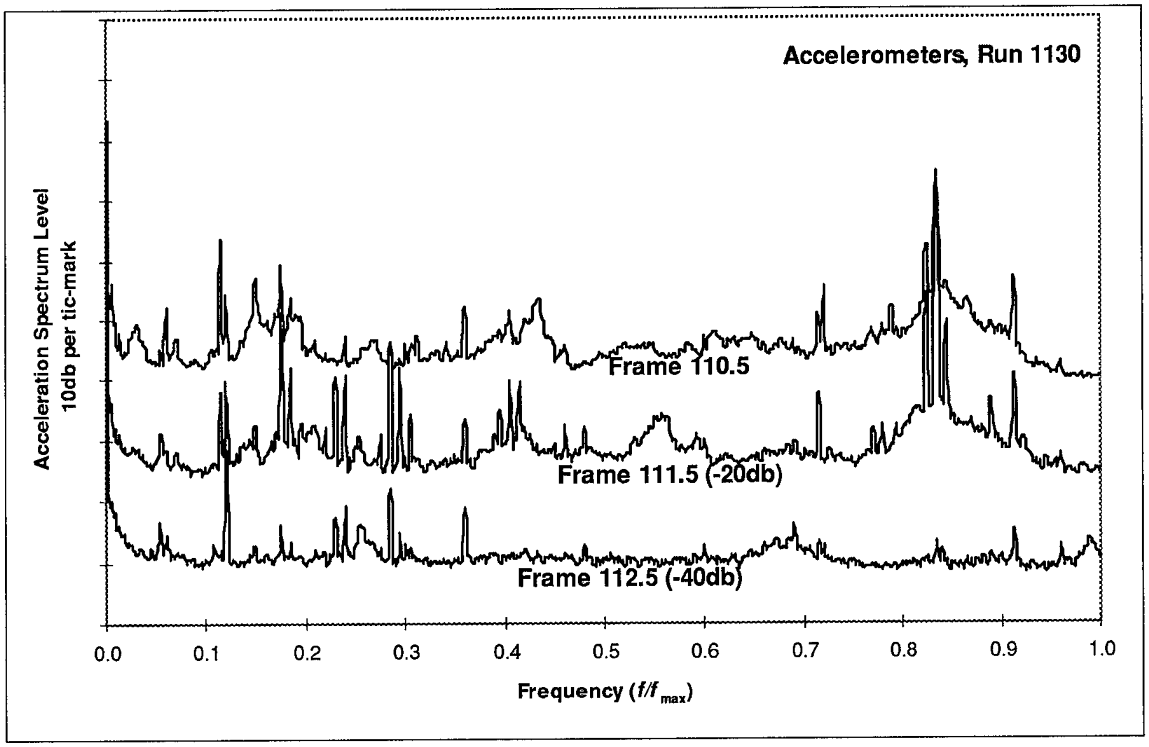

Figure 23 High frequency accelerometer data, Run 1130

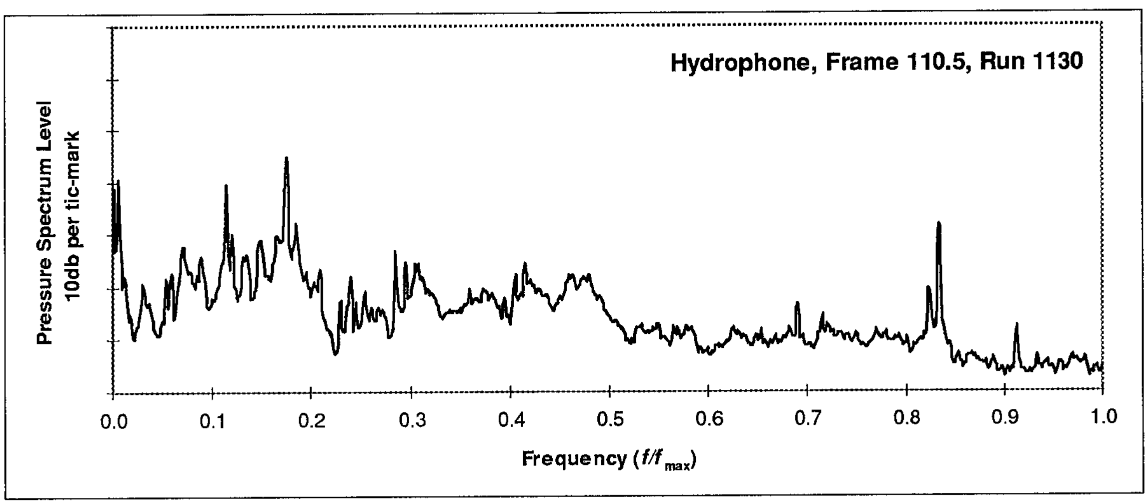

Figure 24 High frequency hydrophone data, Run 1130

3.5 Run 1140

Table 7 presents the measured test conditions during Run 1140.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.59	0.02
Port shaft power, Pp/Pt_{1200}	0.10	-
Starboard shaft power, Ps/Pt_{1200}	0.10	-
Port revolutions, $Np/Navg_{1200}$	0.58	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.58	0.01

Table 7 Conditions for Run 1140

Intermittent cavitation was observed on all blades at this condition. Two views of this can be seen in Figure 25 and Figure 26. A leading edge vortex, which detached from the blade close to the tip, cavitated from the leading edge back, as shown in Figure 26. Even less frequently, a patch of sheet cavitation was seen on some blades, as pointed out by the arrow in Figure 25. This sheet started at approximately the same location as the vortex. The vortex cavitation was not always a fine line of bubbles, as in Figure 25 or in Figure 19. Occasionally it burst into a cloud of bubbles, as seen in Figure 26. There was also an indication of a vortex from the previous blade, cavitating in the wake peak.

Figure 27 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 28 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers showed blade rate and 2×BR lines. For all accelerometers the blade rate level was about 10db lower than on Run 1130. The reason for this decrease is not known. The strength of the 2×BR lines is not solely due to the propeller. This frequency coincides with small peaks in the spectra for Runs 1130 and 1150.

The hydrophone data showed blade rate and 2×BR lines. The blade rate level was slightly increased from Run 1130, unlike the accelerometer data. The level increases at close to 3×BR and 4×BR were judged not to be propeller blade rate harmonics.

Figure 29 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 30 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerations at frames 110.5 and 111.5 and the pressure levels showed a substantial increase over those of Run 1130. The accelerations at frame 112.5 showed a smaller increase, confined largely to the $f/f_{max} = 0.3$ to 0.75 band. The hydrophone signal increased by about 3db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 9db in the frequency band from $f/f_{max} = 0.3$ to 1.0.

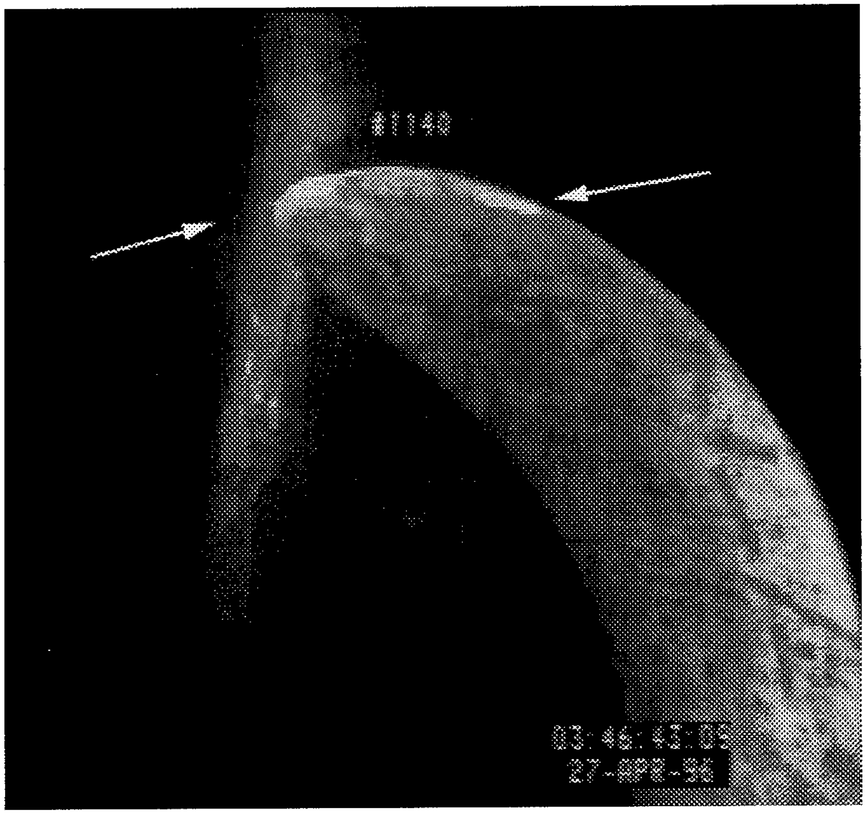

Figure 25 Propeller cavitation, looking aft, Run 1140

Figure 26 Propeller cavitation, view from above, Run 1140

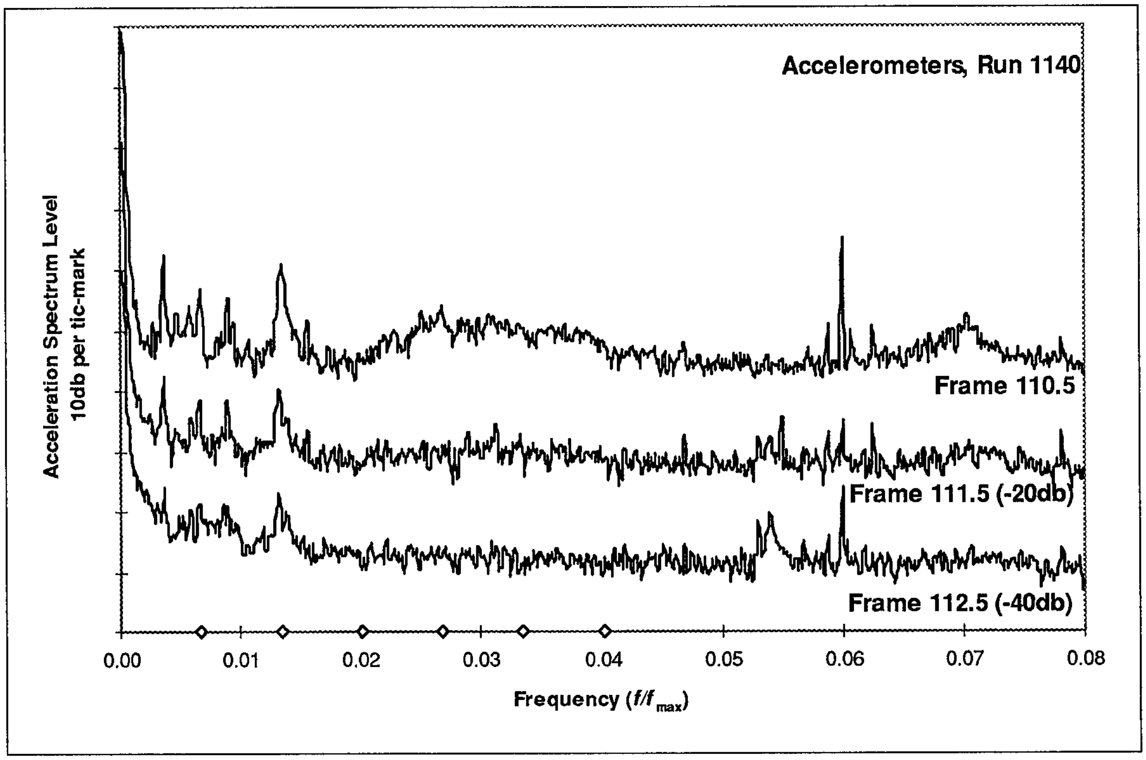

Figure 27 Low frequency accelerometer data, Run 1140

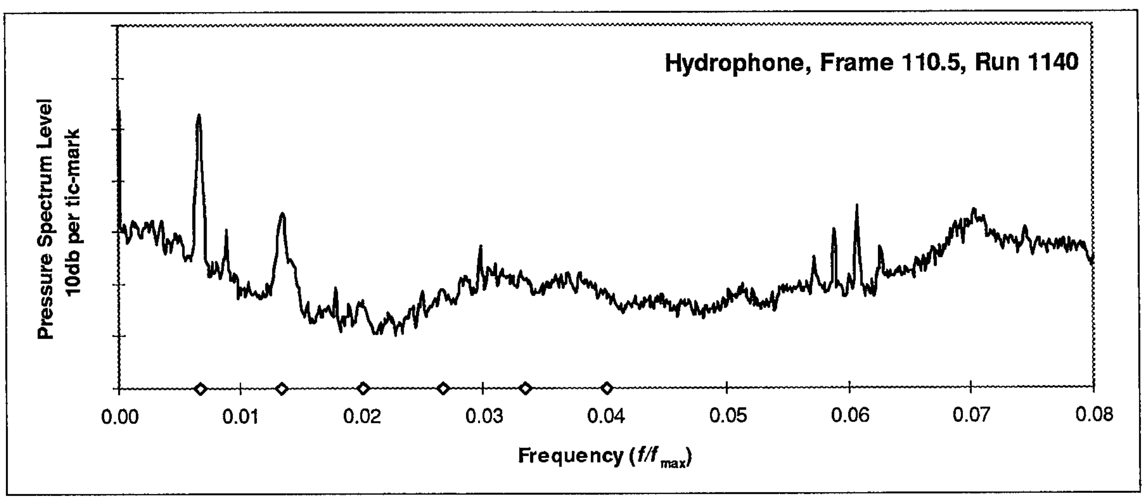

Figure 28 Low frequency hydrophone data, Run 1140

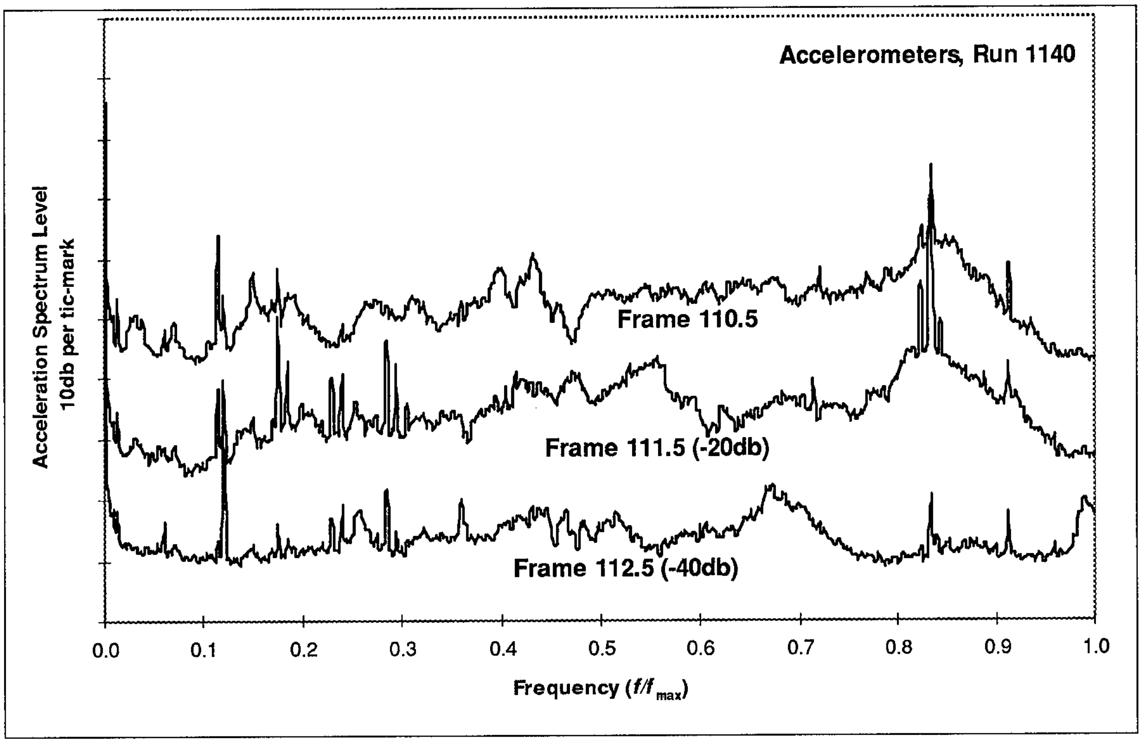

Figure 29 High frequency accelerometer data, Run 1140

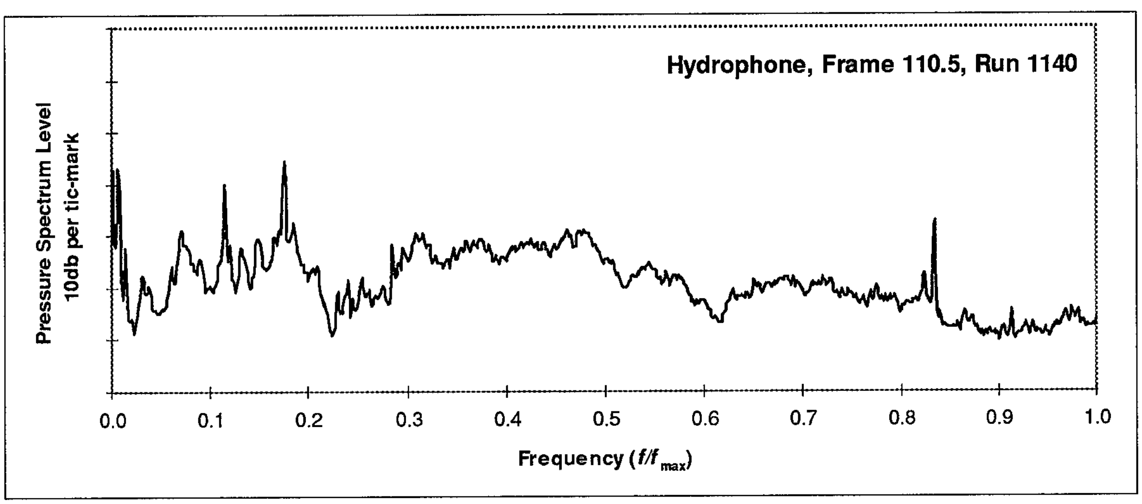

Figure 30 High frequency hydrophone data, Run 1140

3.6 Run 1150

Table 8 presents the measured test conditions during Run 1150.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.68	0.02
Port shaft power, Pp/Pt_{1200}	0.14	-
Starboard shaft power, Ps/Pt_{1200}	0.14	-
Port revolutions, $Np/Navg_{1200}$	0.66	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.66	0.01

Table 8 Conditions for Run 1150

The leading edge vortex cavitation was seen consistently in this condition, and the sheet cavitation was intermittent, although it was on all blades. The sheet cavitation was confined to a region close to the 0.95 radius fraction. The maximum amount of cavitation happened in the wake peak and its growth and collapse showed a consistent pattern as the blade swept through the wake peak. Representative views of the cavitation are given in Figure 31 and Figure 32. Initially, sheet and vortex cavitation formed at the leading edge, as shown in Figure 32. A few degrees of rotation later, these cavities collapsed and most of the cavitation disappeared. Finally the vortex would begin to cavitate some distance downstream of the tip. The vortex cavitation usually burst into a cloud of bubbles, as seen in Figure 31. Occasionally vortex cavitation from a previous blade was seen bursting in the wake peak near the rudder.

Figure 33 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 34 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers and hydrophone showed clear lines at blade rate and 2×BR. It was judged that the lines at close to 3×BR were not propeller blade rate harmonics. The spectral levels increased around 4×BR for all sensors. It is not clear if this should be labeled as a propeller blade rate harmonic. All features were less pronounced at frame 112.5 which is farthest astern.

Figure 35 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 36 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All spectral levels increased significantly from Run 1140, across most of the frequency band from $f/f_{max} = 0$ to 1.0. The increase was least pronounced for the accelerometer at frame 112.5. The hydrophone signal increased by about 8db across the entire frequency band.

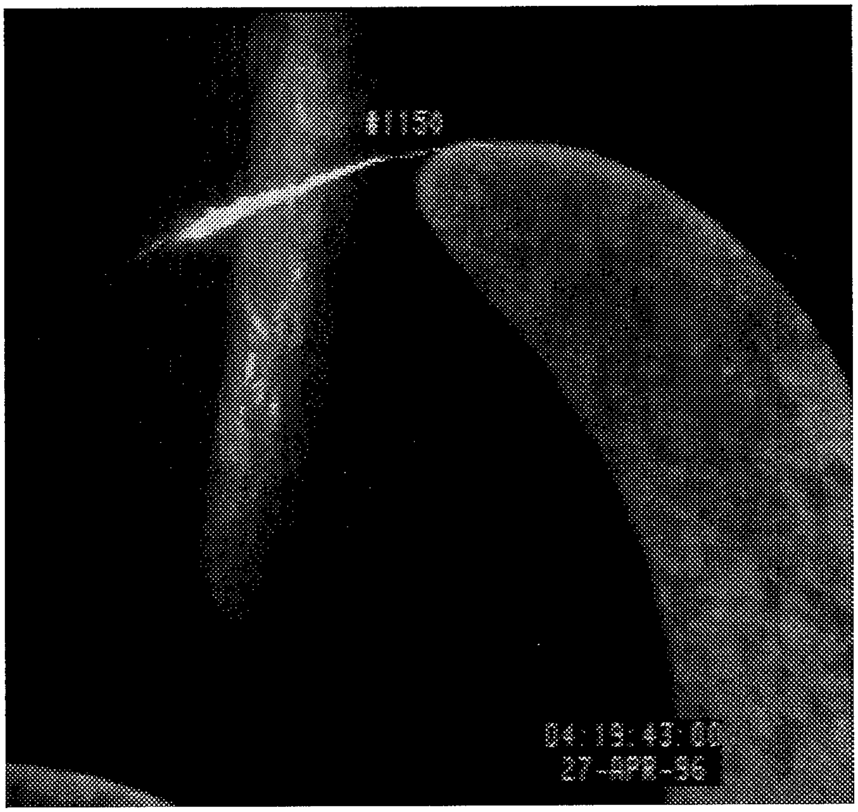

Figure 31 Propeller cavitation, looking aft, Run 1150

Figure 32 Propeller cavitation, view from above, Run 1150

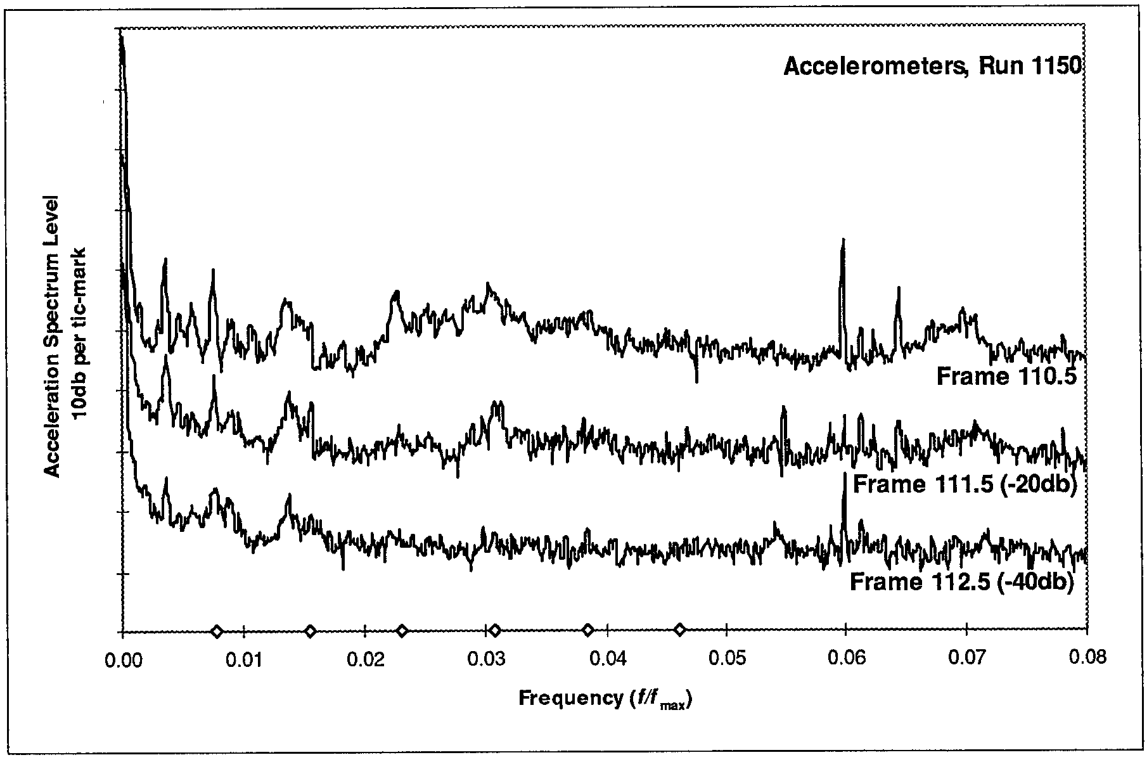

Figure 33 Low frequency accelerometer data, Run 1150

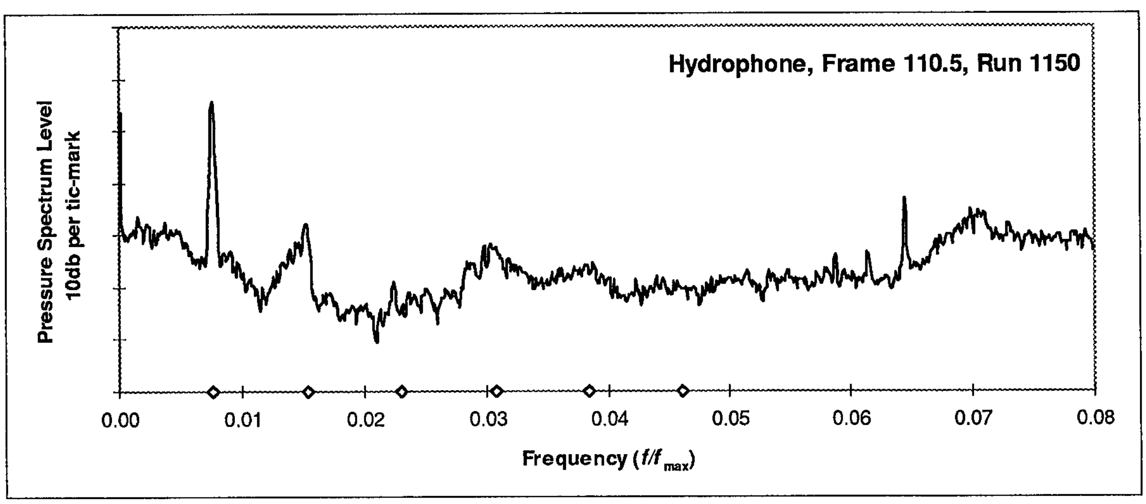

Figure 34 Low frequency hydrophone data, Run 1150

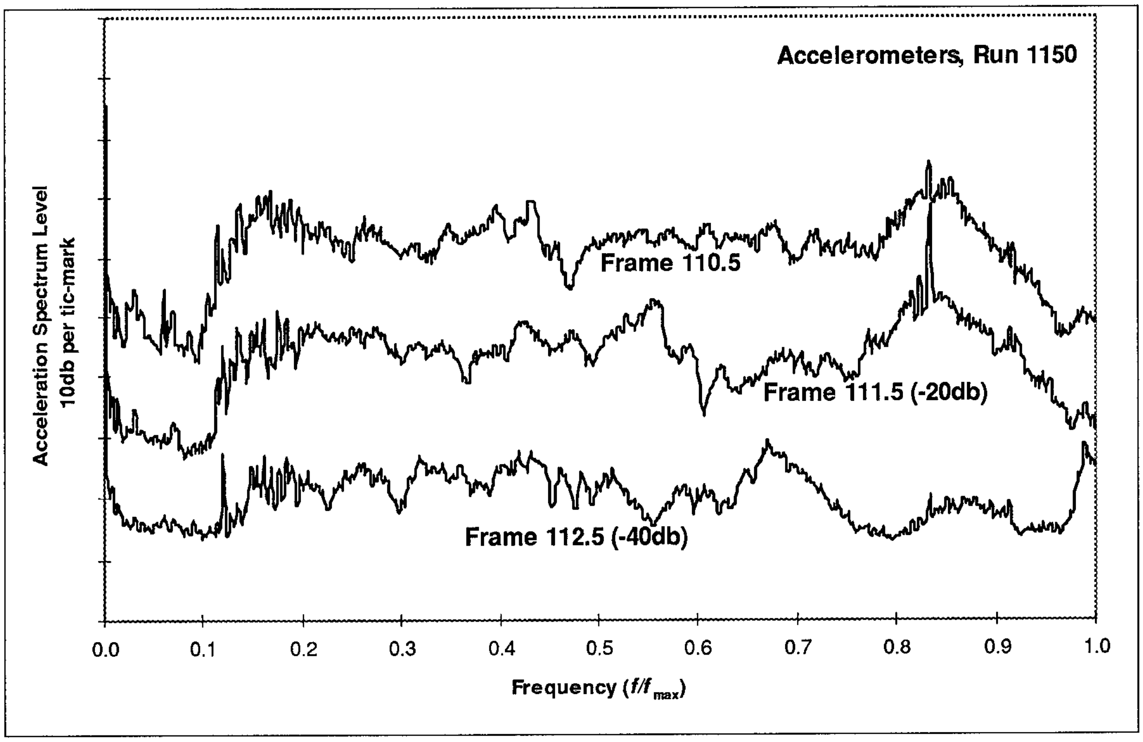

Figure 35 High frequency accelerometer data, Run 1150

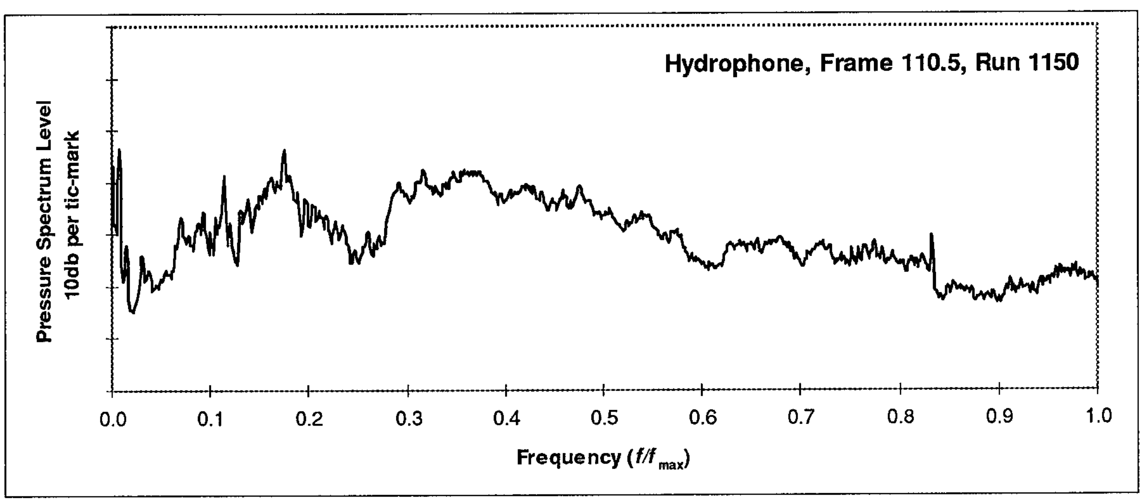

Figure 36 High frequency hydrophone data, Run 1150

3.7 Run 1160

Table 9 presents the measured test conditions during Run 1160.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.73	0.02
Port shaft power, Pp/Pt_{1200}	-	-
Starboard shaft power, Ps/Pt_{1200}	-	-
Port revolutions, $Np/Navg_{1200}$	0.72	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.72	0.01

Table 9 Conditions for Run 1160

By accident, the shaft power data were not recorded for this run.

The leading edge vortex and sheet cavitation were seen consistently in this condition on all blades. The sheet extended down the blade to the 0.9 radius fraction. The sheet was frequently in separate areas along the leading edge as shown in Figure 37. The vortex cavitation frequently burst into a cloud of bubbles, as seen in Figure 38. Frequently vortex cavitation from a previous blade was seen bursting in the wake peak near the rudder. The arrow in Figure 37 points to such a vortex.

Figure 39 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 40 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers and hydrophone all showed lines up to, and including, 3×BR. The lines were least pronounced at frame 112.5 which is farthest astern.

Figure 41 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 42 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All accelerometer spectral levels increased by about 5db, at all frequencies, from Run 1150. The hydrophone signal increased by about 7db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 5db in the frequency band from $f/f_{max} = 0.3$ to 1.0.

Figure 37 Propeller cavitation, looking aft, Run 1160

Figure 38 Propeller cavitation, view from above, Run 1160

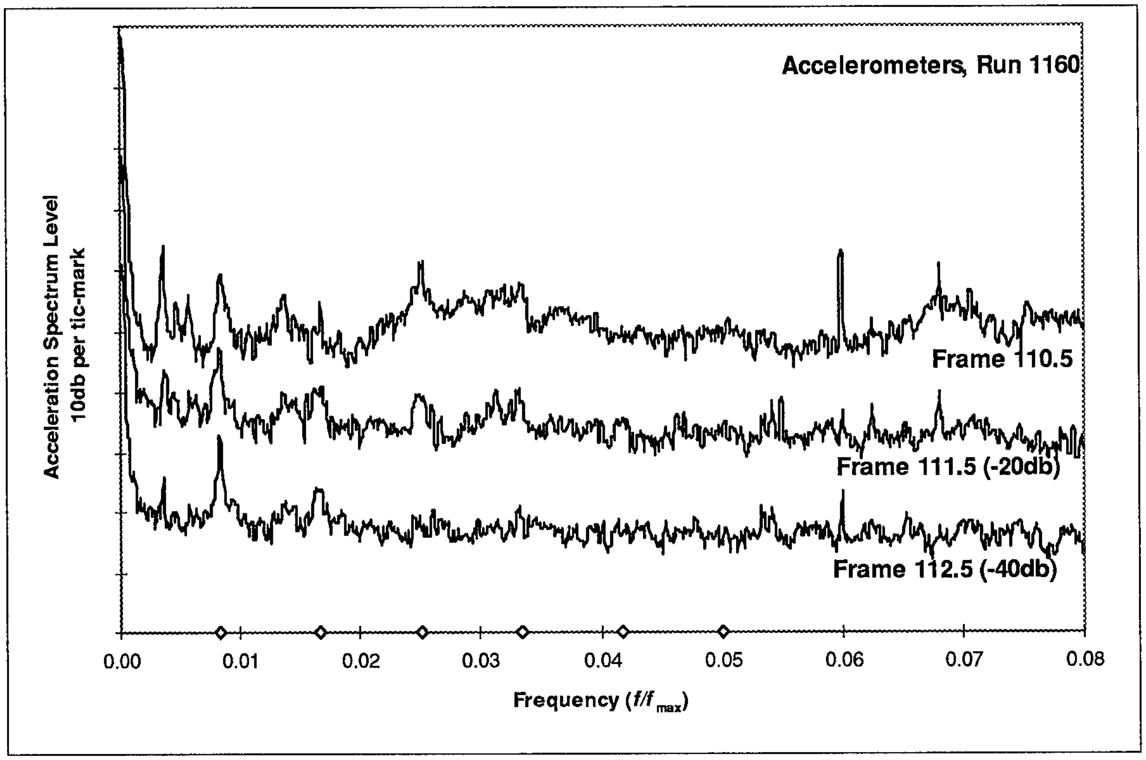

Figure 39 Low frequency accelerometer data, Run 1160

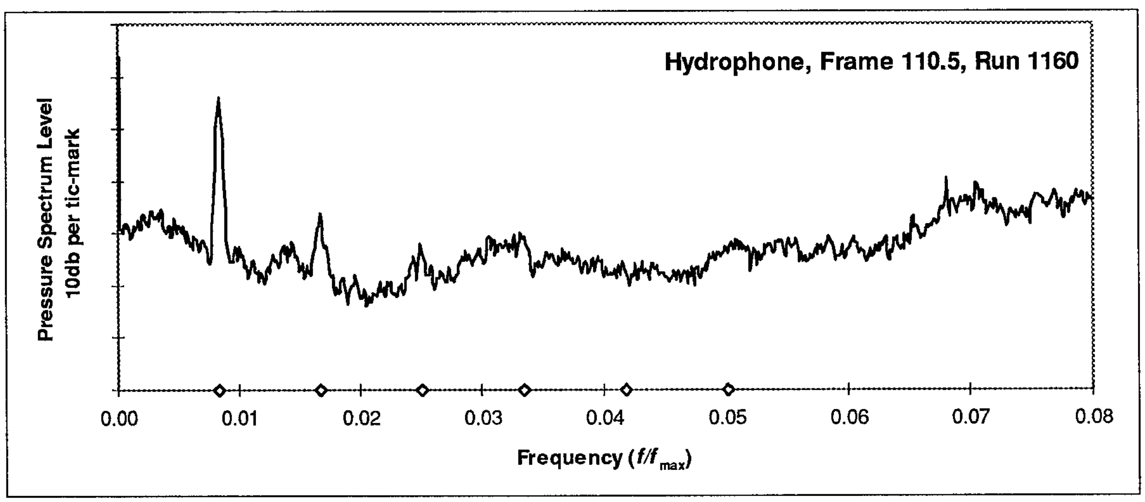

Figure 40 Low frequency hydrophone data, Run 1160

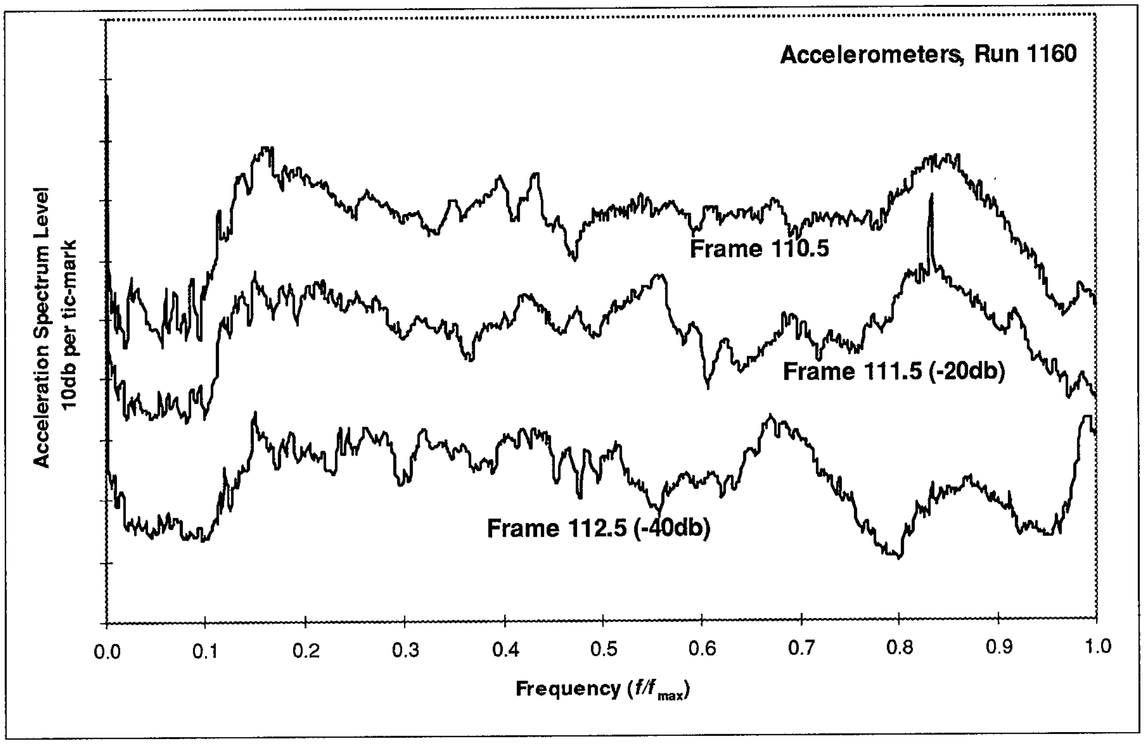

Figure 41 High frequency accelerometer data, Run 1160

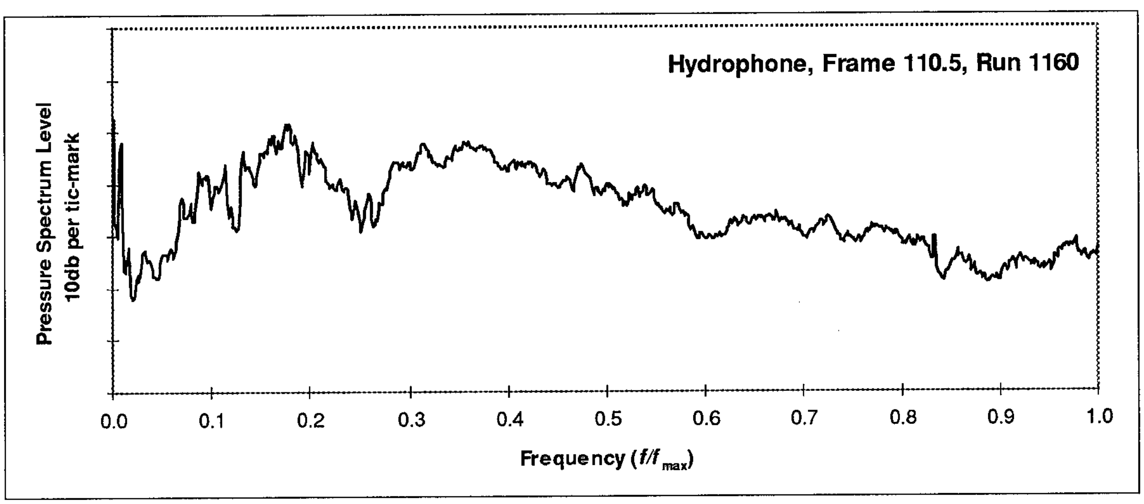

Figure 42 High frequency hydrophone data, Run 1160

3.8 Run 1170

Table10 presents the measured test conditions during Run 1170.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.81	0.01
Port shaft power, Pp/Pt_{1200}	0.26	-
Starboard shaft power, Ps/Pt_{1200}	0.26	-
Port revolutions, $Np/Navg_{1200}$	0.81	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.81	0.01

Table 10 Conditions for Run 1170

The leading edge vortex and sheet cavitation were seen consistently in this condition on all blades. The sheet extended down the blade to the 0.85 radius fraction. The sheet was frequently in separated areas along the leading edge as shown in Figure 43. The vortex cavitation usually burst into a cloud of bubbles, as seen in Figure 44. Frequently vortex cavitation from a previous blade was seen bursting in the wake peak near the rudder. Such a vortex can be seen bursting in Figure 43 as indicated by the arrow.

Figure 45 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 46 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers showed lines up to, and including, 3×BR. The 3×BR line was least pronounced at frame 112.5 which is farthest astern. The hydrophone showed lines at blade rate and 2×BR.. Any hydrophone line at 3×BR was submerged in the broadband response.

Figure 47 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 48 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All accelerometer spectral levels increased by about 5db from Run 1160. The hydrophone signal increased by about 6db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 4db in the frequency band from $f/f_{max} = 0.3$ to 1.0.

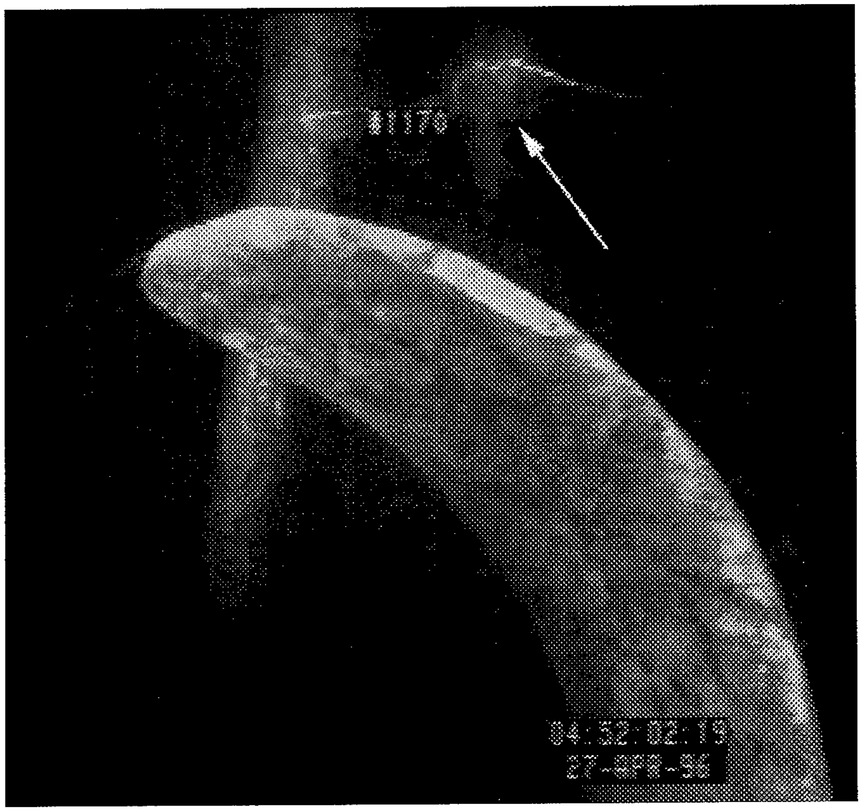

Figure 43 Propeller cavitation, looking aft, Run 1170

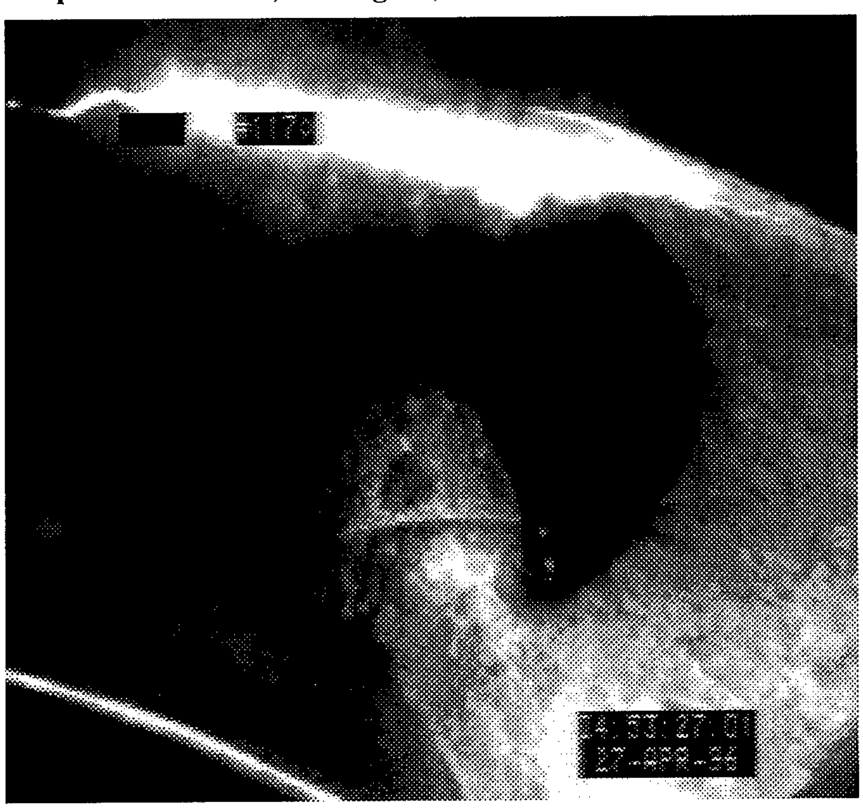

Figure 44 Propeller cavitation, view from above, Run 1170

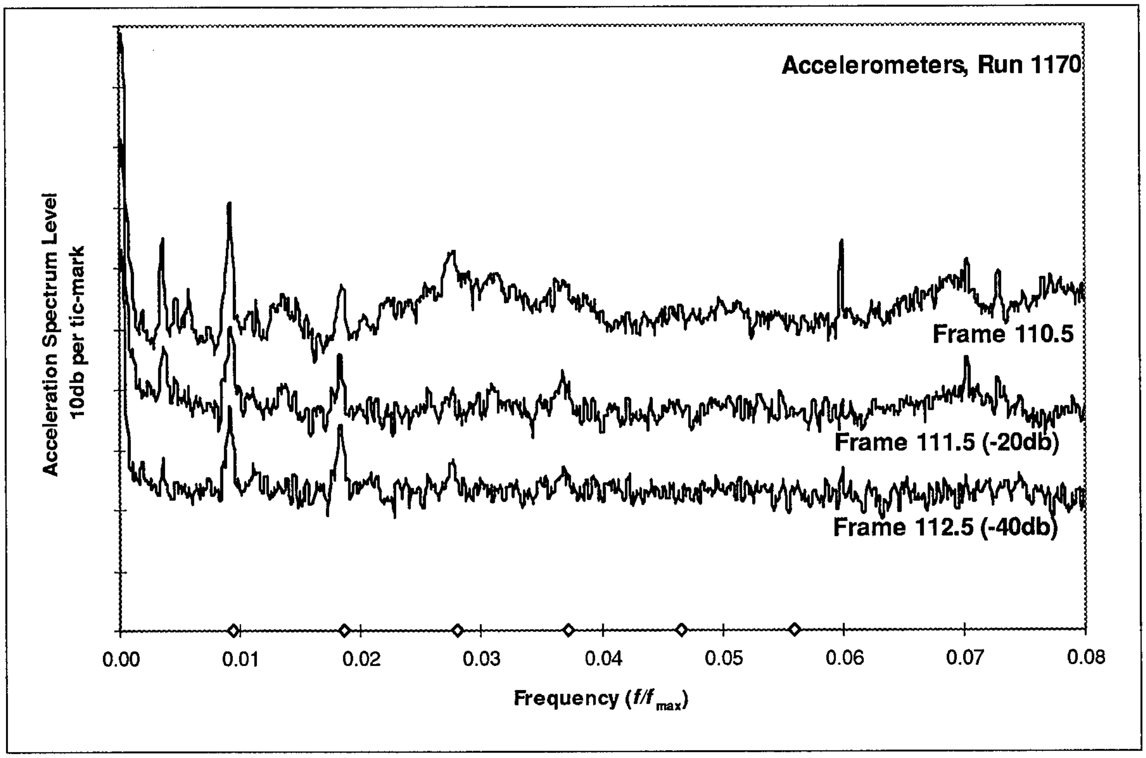

Figure 45 Low frequency accelerometer data, Run 1170

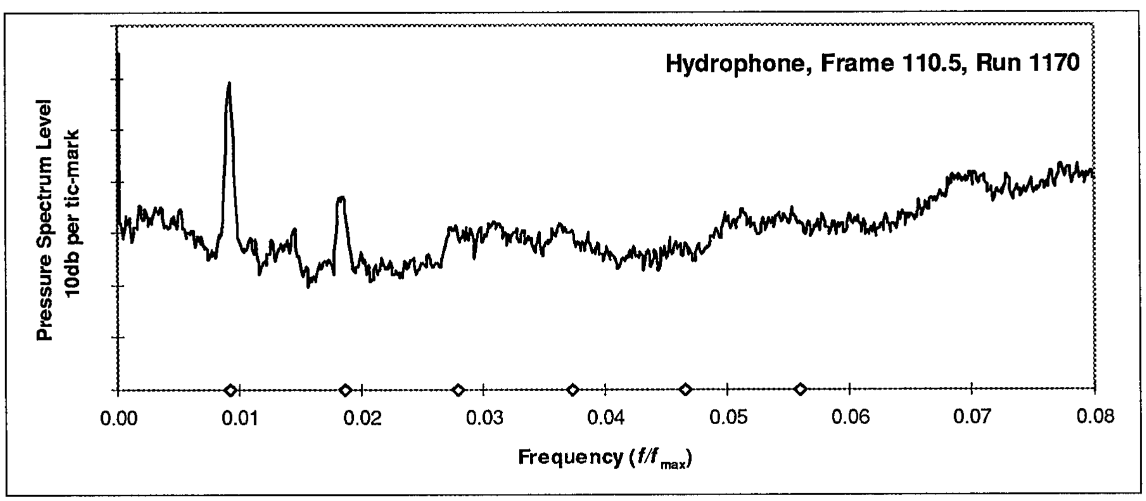

Figure 46 Low frequency hydrophone data, Run 1170

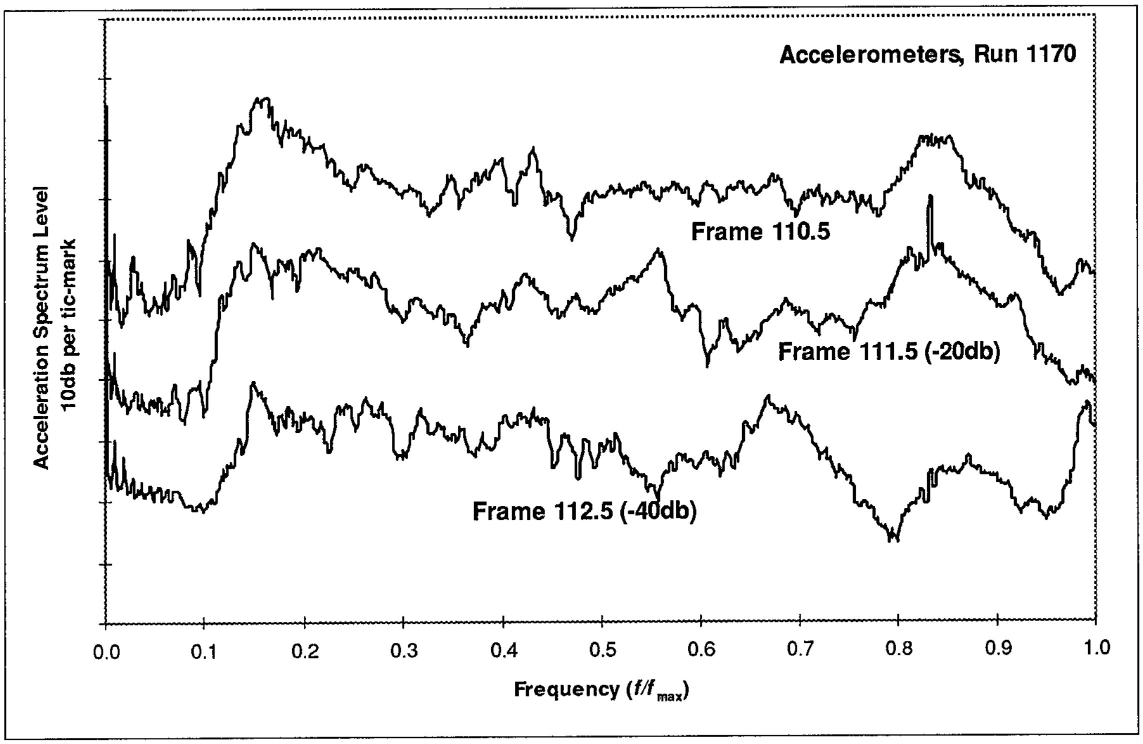

Figure 47 High frequency accelerometer data, Run 1170

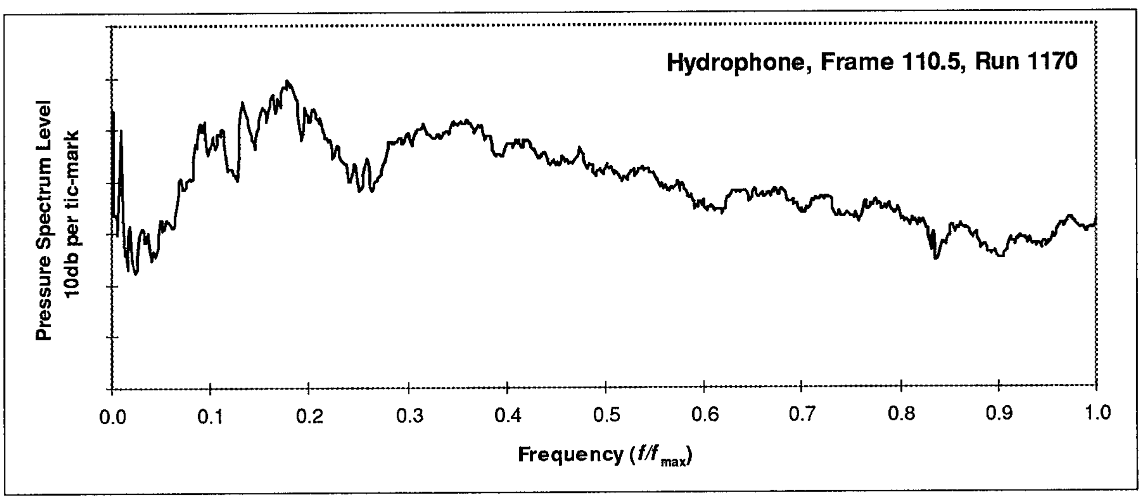

Figure 48 High frequency hydrophone data, Run 1170

3.9 Run 1180

Table 11 presents the measured test conditions during Run 1180.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.87	0.01
Port shaft power, Pp/Pt_{1200}	0.32	-
Starboard shaft power, Ps/Pt_{1200}	0.32	-
Port revolutions, $Np/Navg_{1200}$	0.87	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.87	0.01

Table 11 Conditions for Run 1180

The leading edge vortex and sheet cavitation were seen consistently in this condition on all blades. The sheet extended down some blades to the 0.8 radius fraction. The sheet cavities were larger and less separated than in Run 1170, as shown in Figure 49. The vortex cavitation always burst into a cloud of bubbles, as seen in Figure 50. Also the vortex cavitation from previous blades burst in the wake peak near the rudder. Up to two vortices from preceding blades were observed at close to top-dead-centre. An arrow points out the furthest downstream vortex in Figure 49.

Figure 51 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 52 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers at frames 110.5 and 111.5 showed lines up to, and including, 3×BR. At frame 112.5 only the lines up to 2×BR were clearly visible. The broadband noise had risen to obscure other lines. The hydrophone also showed lines up to, and including, 3×BR as well as a line at 5×BR. Any line at 4×BR was not apparent.

Figure 53 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 54 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All accelerometer spectral levels increased by about 2db from Run 1170. The hydrophone signal increased by about 5db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 2db in the frequency band from $f/f_{max} = 0.3$ to 1.0.

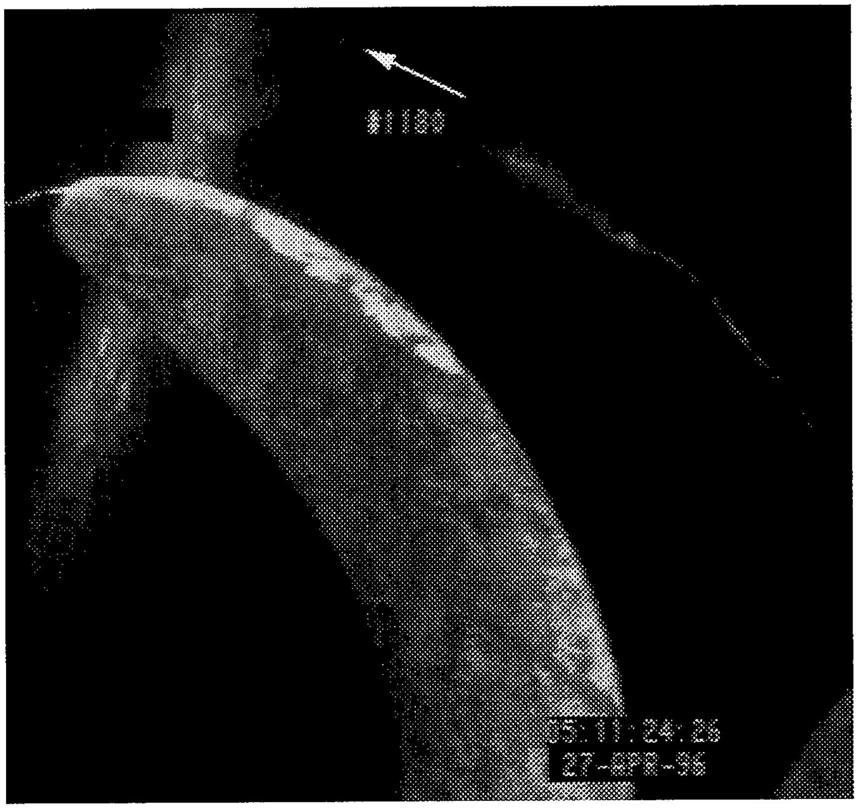

Figure 49 Propeller cavitation, looking aft, Run 1180

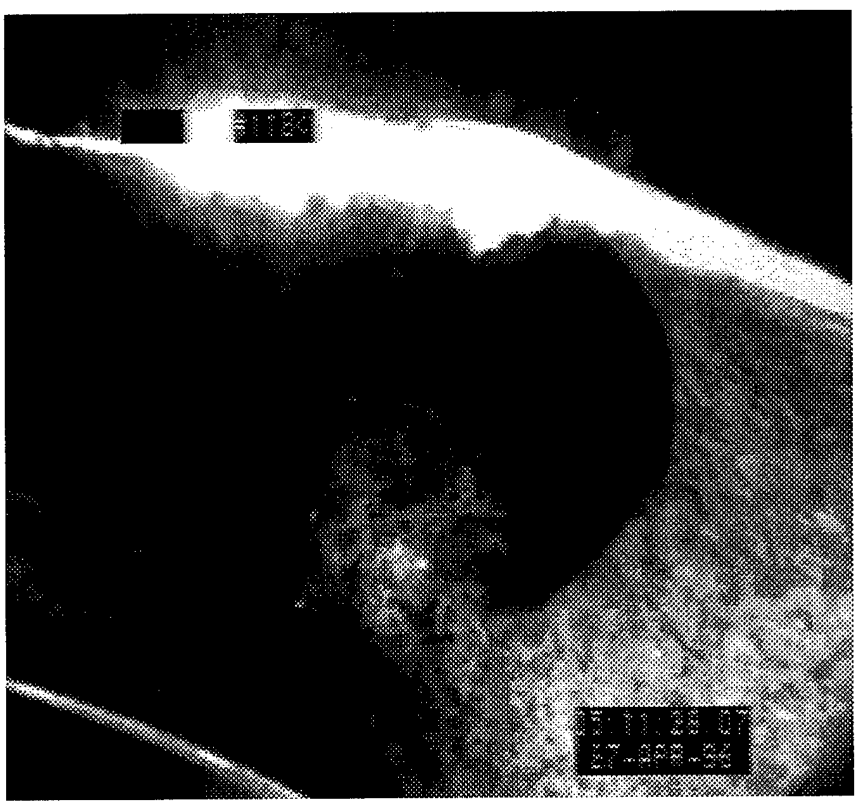

Figure 50 Propeller cavitation, view from above, Run 1180

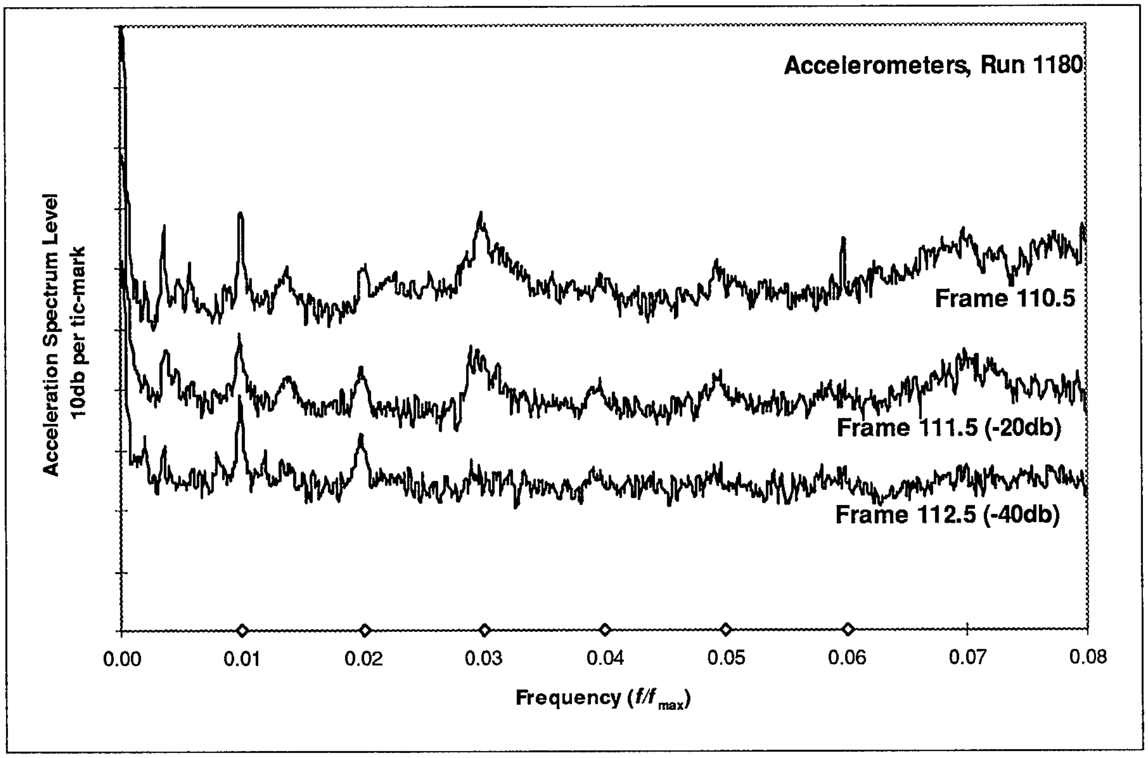

Figure 51 Low frequency accelerometer data, Run 1180

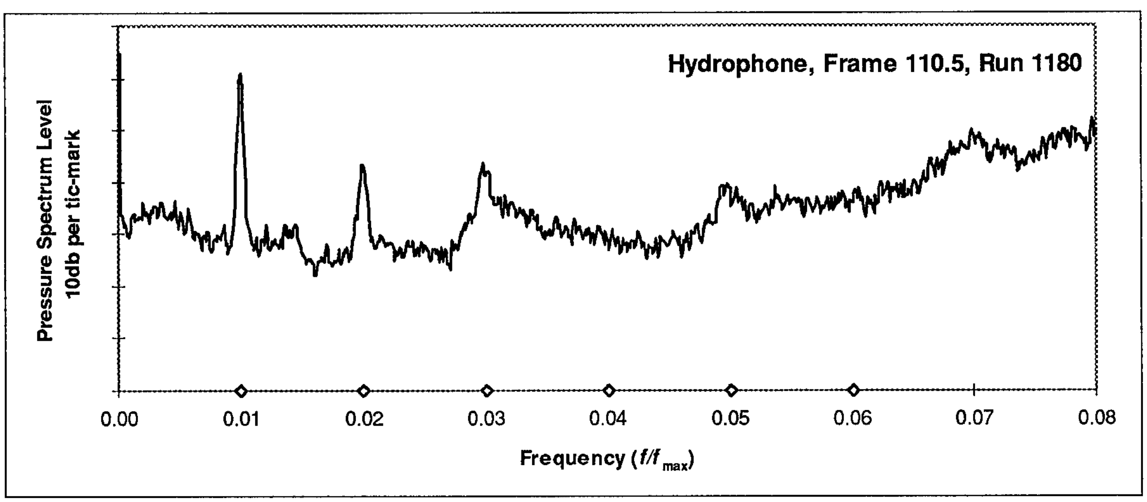

Figure 52 Low frequency hydrophone data, Run 1180

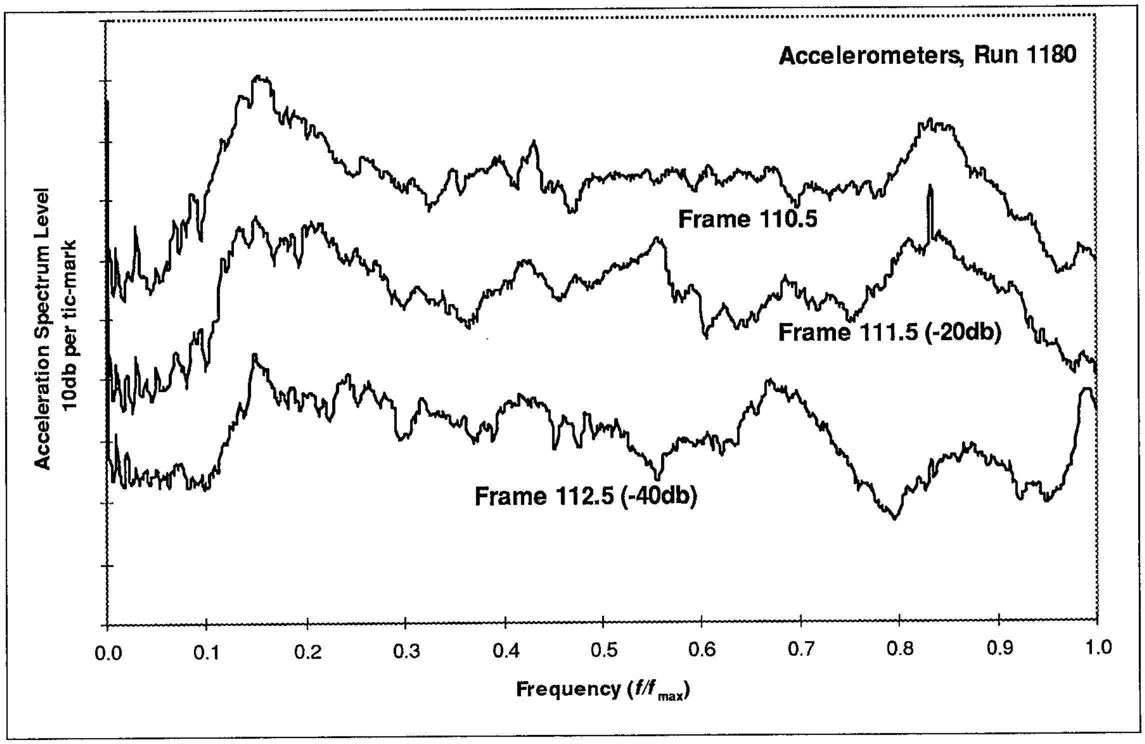

Figure 53 High frequency accelerometer data, Run 1180

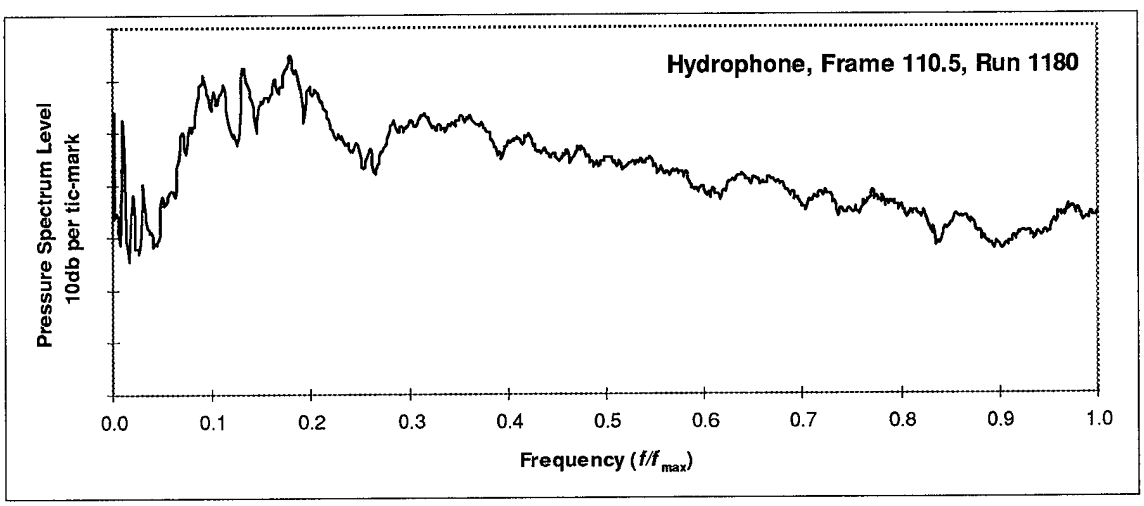

Figure 54 High frequency hydrophone data, Run 1180

3.10 Run 1190

Table 12 presents the measured test conditions during Run 1190.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	0.93	0.02
Port shaft power, Pp/Pt_{1200}	0.42	-
Starboard shaft power, Ps/Pt_{1200}	0.42	-
Port revolutions, $Np/Navg_{1200}$	0.94	0.01
Starboard revolutions, $Ns/Navg_{1200}$	0.93	0.01

Table 12 Conditions for Run 1190

The leading edge vortex and sheet cavitation were seen consistently in this condition on all blades. By comparison with Run 1180, the sheet extended farther across the chord. The vortex cavitation arose from a complex combination of leading edge vortices and sheet as seen in Figure 55. After forming, this cavity would quickly burst. Also the vortex cavitation from previous blades burst in the wake peak near the rudder. Such a vortex can be seen bursting in Figure 55. At this condition a very intermittent hub vortex was occasionally observed as shown by the arrow in Figure 56.

Figure 57 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 58 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers showed lines up to, and including, 3×BR. The hydrophone clearly showed lines up to, and including, 4×BR. The broadband levels had risen to obscure the line at 5×BR seen in Run 1180.

Figure 59 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 60 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All spectral levels increased by about 3db from Run 1180, across the entire analysis frequency band.

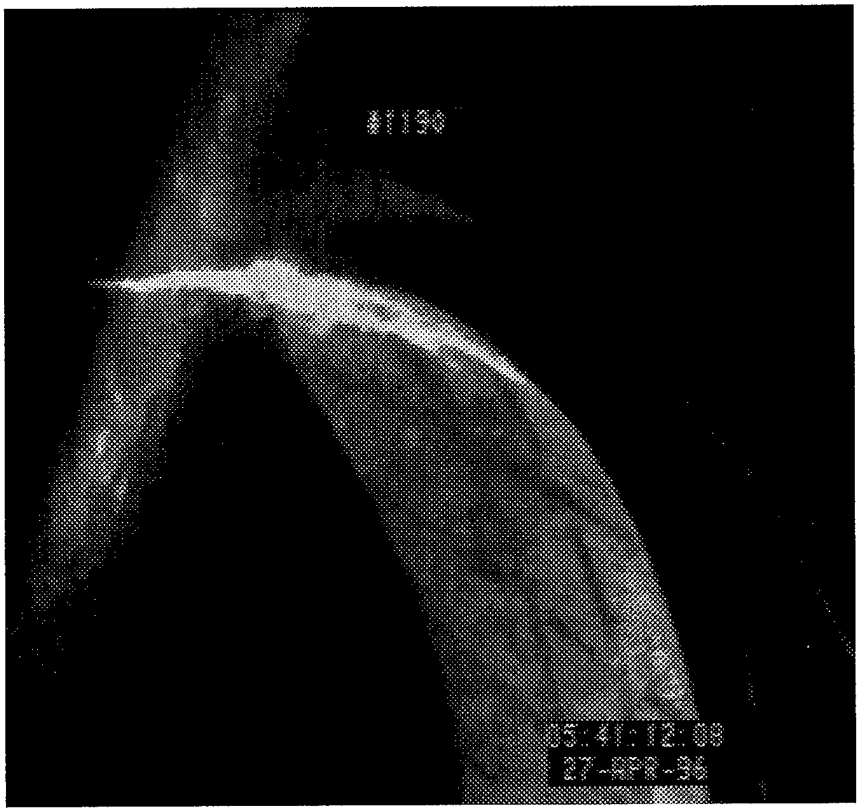

Figure 55 Propeller cavitation, looking aft, Run 1190

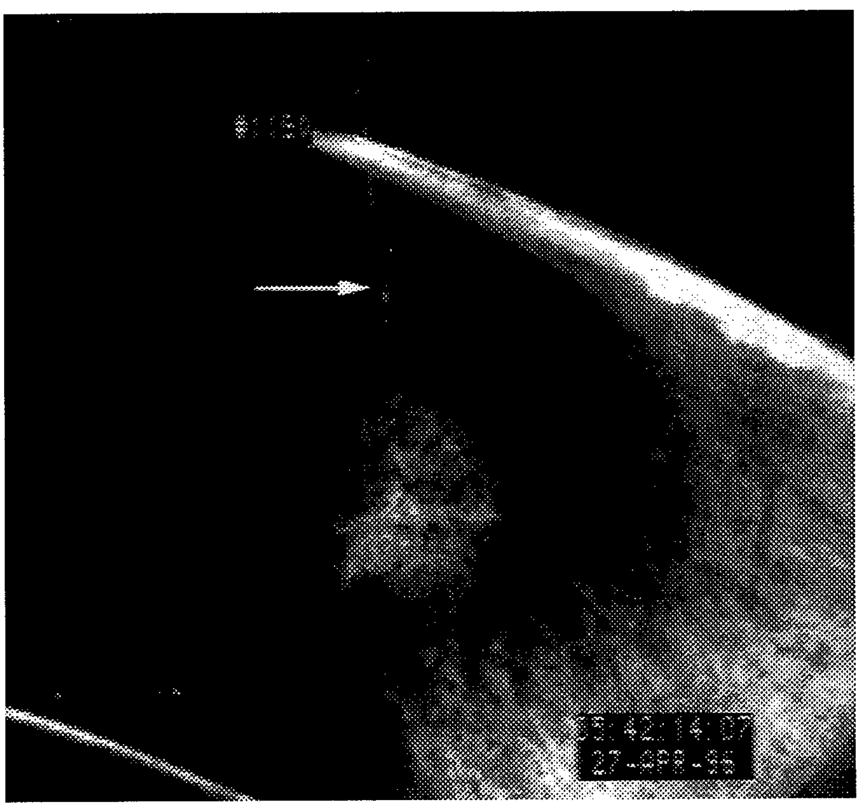

Figure 56 Propeller cavitation, view from above, Run 1190

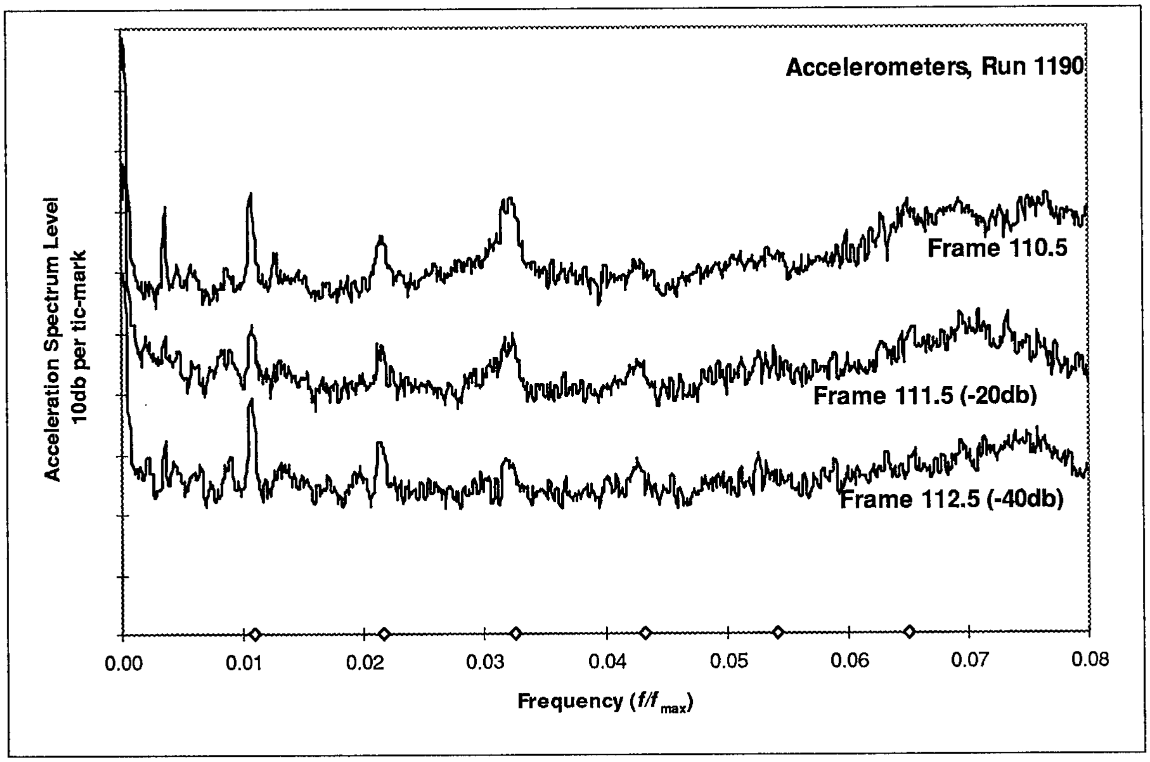

Figure 57 Low frequency accelerometer data, Run 1190

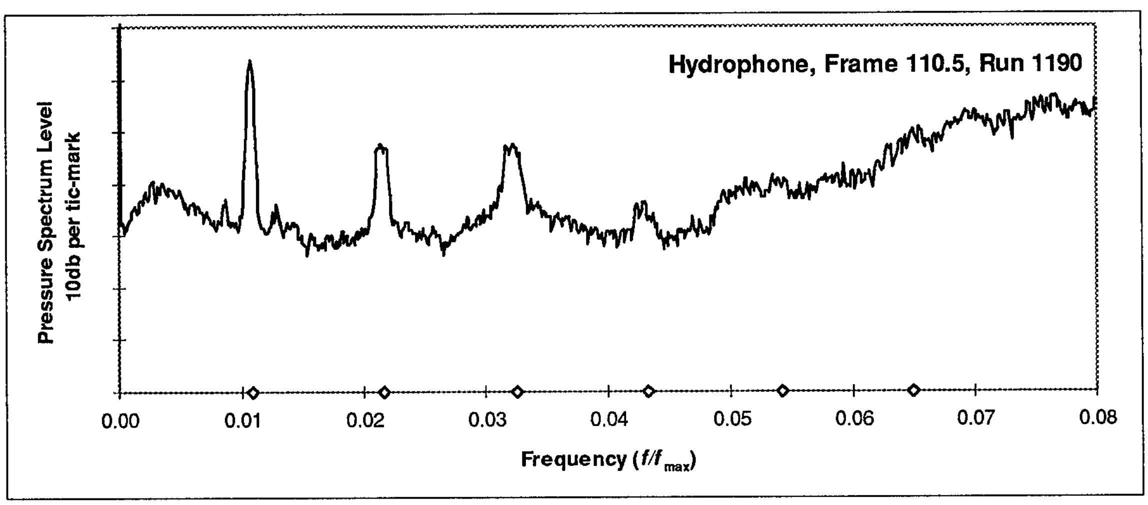

Figure 58 Low frequency hydrophone data, Run 1190

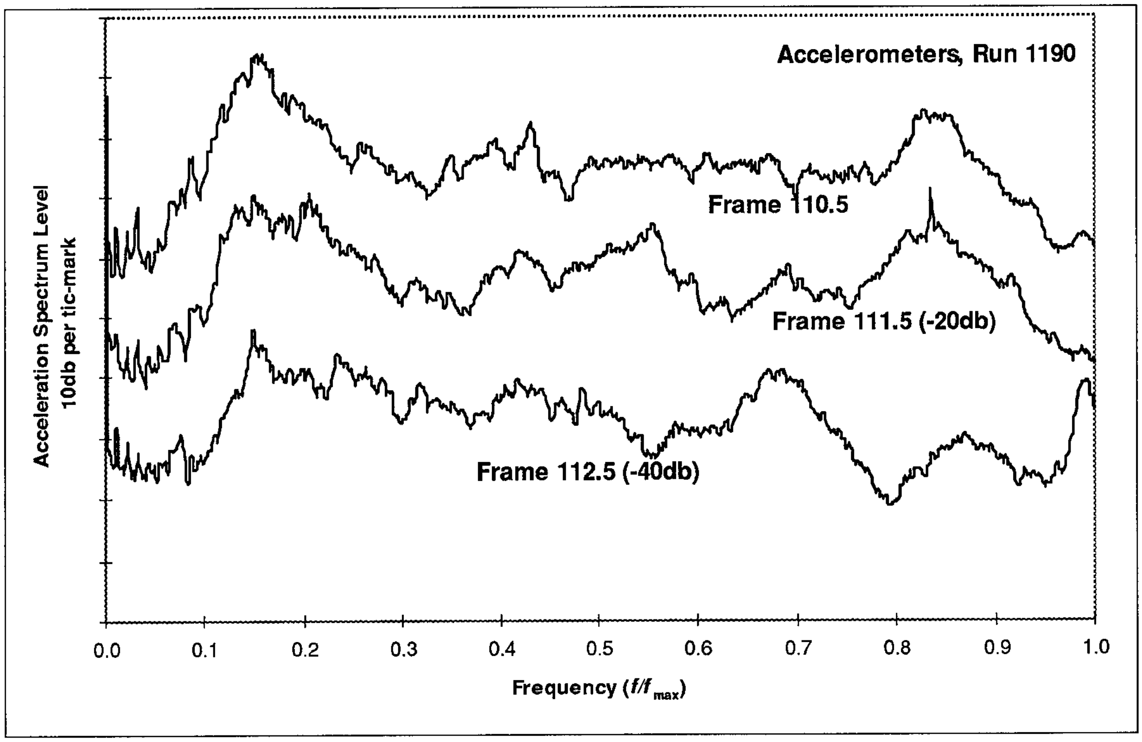

Figure 59 High frequency accelerometer data, Run 1190

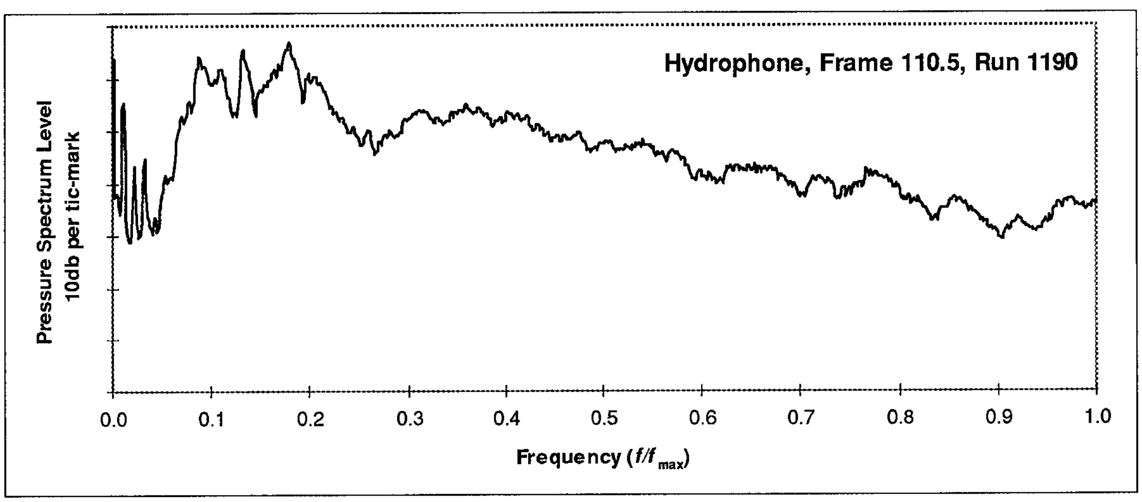

Figure 60 High frequency hydrophone data, Run 1190

3.11 Run 1200

Table 13 presents the measured test conditions during Run 1200.

	Mean	Standard deviation
Ship speed, Vs/Vs_{1200}	1.00	0.02
Port shaft power, Pp/Pt_{1200}	0.49	-
Starboard shaft power, Ps/Pt_{1200}	0.51	-
Port revolutions, $Np/Navg_{1200}$	1.00	0.01
Starboard revolutions, $Ns/Navg_{1200}$	1.00	0.01

Table 13 Conditions for Run 1200

The leading edge vortex and sheet cavitation were seen consistently on all blades at this operating condition. By comparison with Run 1190, the sheet extended farther across the chord, as seen in Figure 61. Also, in contrast with the mainly cloudy appearance of the sheet seen at lower speeds, more of the sheet exhibited a transparent, glass-like appearance. The vortex cavitation from previous blades burst in the wake peak near the rudder. A particularly spectacular vortex burst can be seen in Figure 61. At this condition an intermittent hub vortex was observed, as seen in Figure 62.

Figure 63 presents the low frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 64 presents the low frequency pressure spectrum level data from the hydrophone at frame 110.5.

The accelerometers and hydrophone spectra showed lines up to, and including, 6×BR. The line at 6×BR was the least distinct in most cases. The higher harmonic accelerometer lines were least apparent for the accelerometer at frame 112.5.

Figure 65 presents the high frequency acceleration spectrum level data from the three accelerometers at frames 110.5, 111.5 and 112.5. Figure 66 presents the high frequency pressure spectrum level data from the hydrophone at frame 110.5.

All accelerometer spectral levels increased by about 2db from Run 1190. The hydrophone signal increased by about 3db in the frequency band from $f/f_{max} = 0$ to 0.3 and by about 1db in the frequency band from $f/f_{max} = 0.3$ to 1.0.

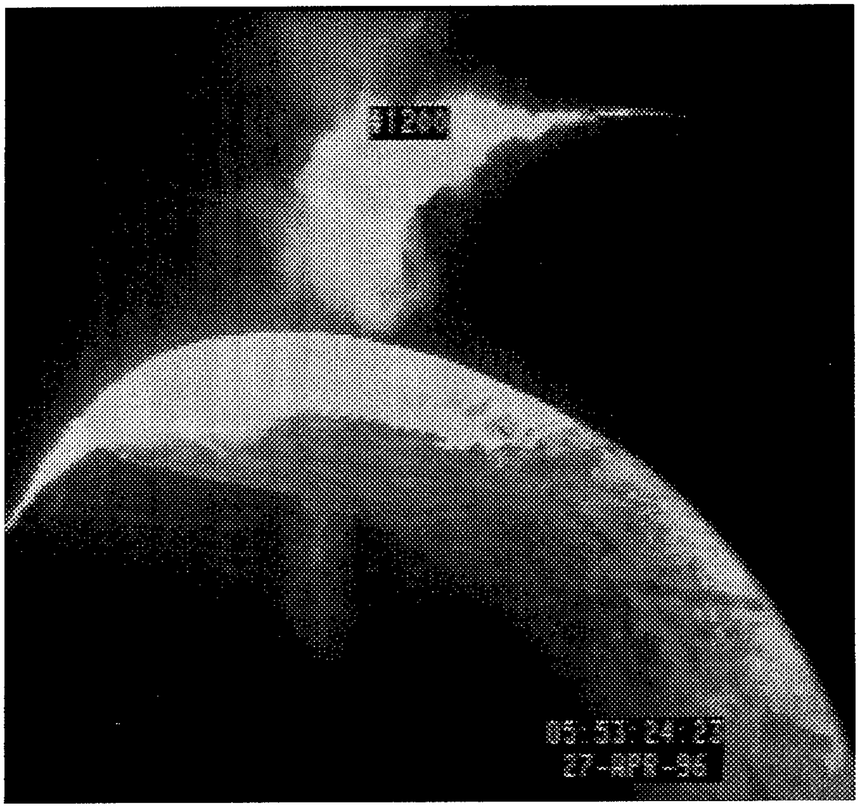

Figure 61 Propeller cavitation, looking aft, Run 1200

Figure 62 Propeller cavitation, view from above, Run 1200

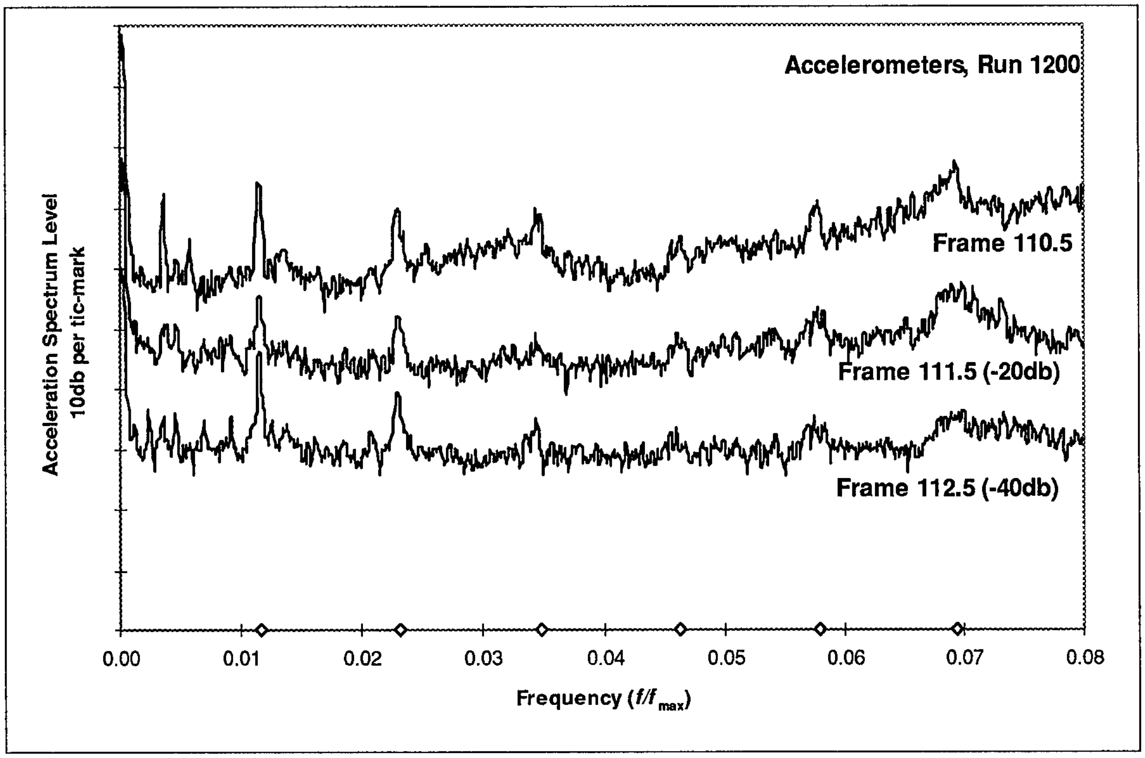

Figure 63 Low frequency accelerometer data, Run 1200

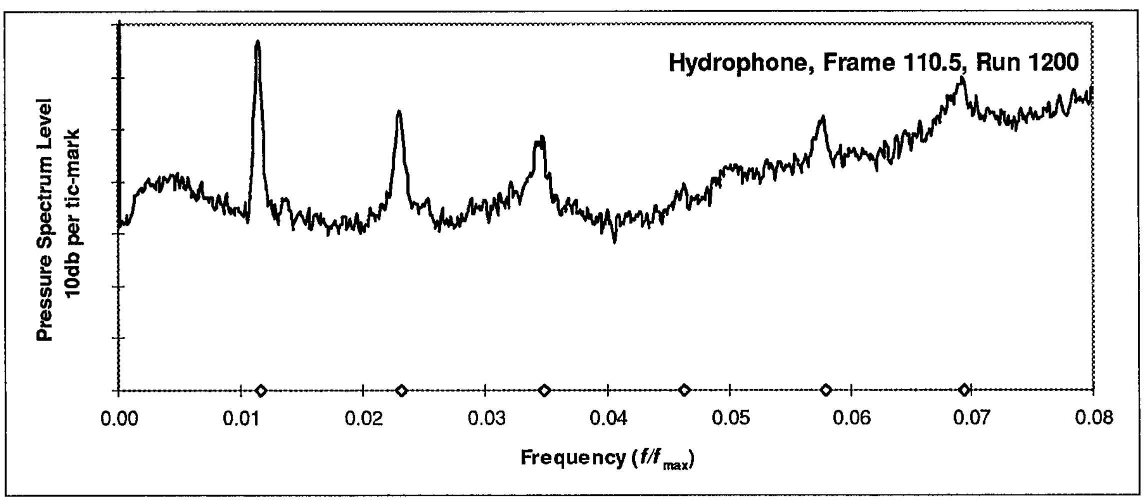

Figure 64 Low frequency hydrophone data, Run 1200

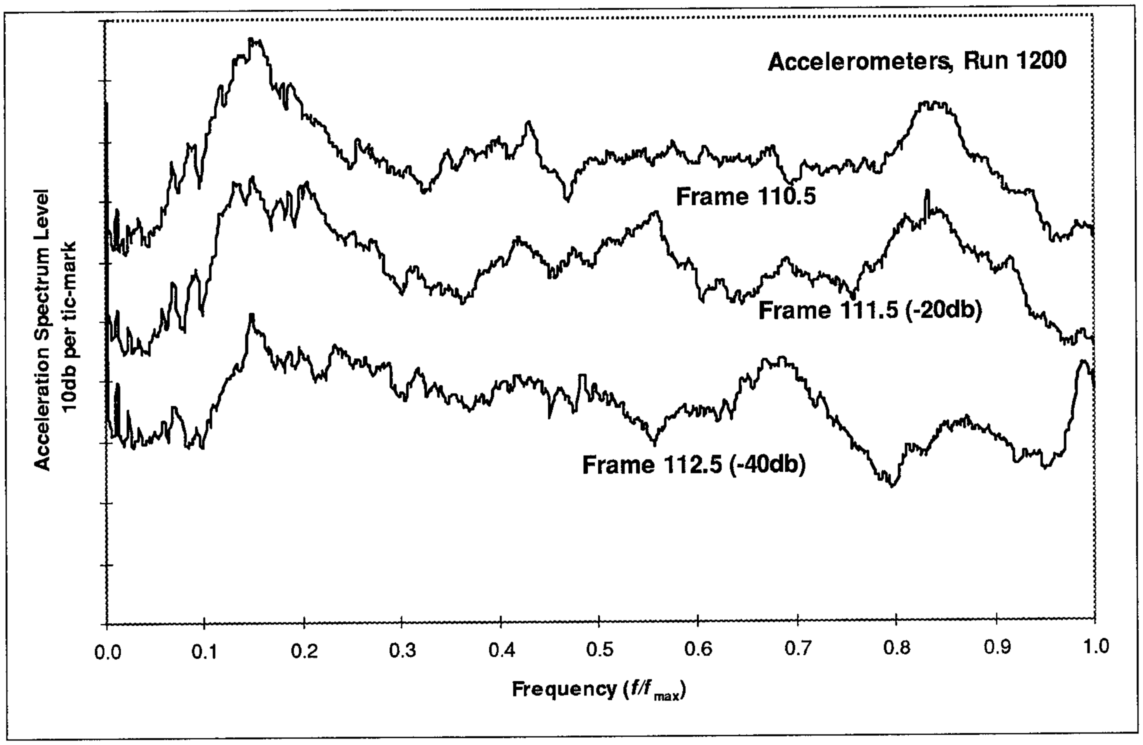

Figure 65 High frequency accelerometer data, Run 1200

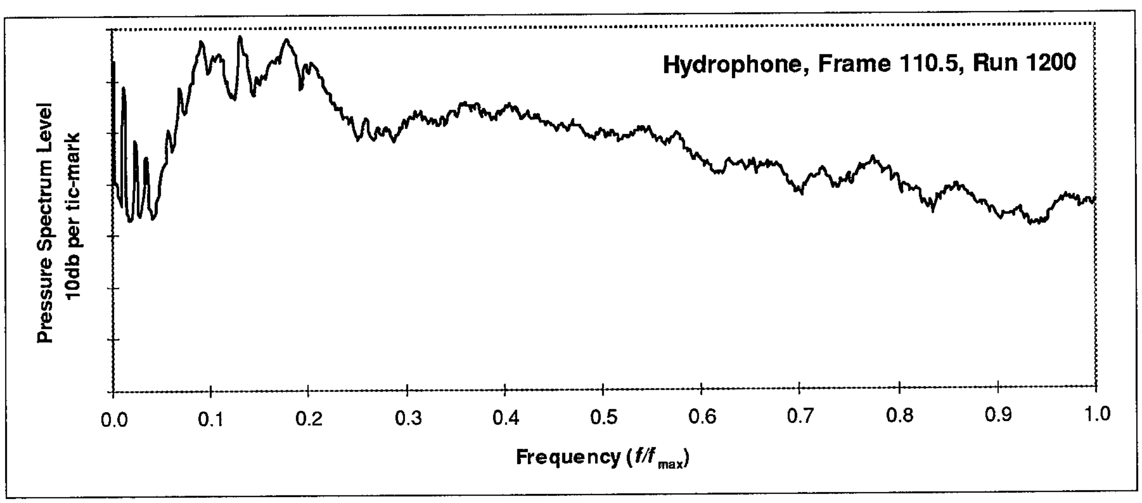

Figure 66 High frequency hydrophone data, Run 1200

3.12 Accelerating Runs 1210 to 1222

The accelerating runs were conducted in daylight without the aid of strobe-lights. All these runs showed much more cavitation than the steady speed runs. Among the accelerating runs the cavitation features were similar to varying degrees. Vast quantities of cavitation bubbles were shed from the tips in all cases. All cases showed hub vortices of varying strength. Propeller-hull vortices were also observed running from the hull to the vicinity of the propeller hub. These propeller-hull vortices were most pronounced in the cases of full ahead acceleration. All that was largely as expected. No analysis of the accelerometer or hydrophone data has been attempted.

4. Discussion of Results

It is not possible to determine the hull pressures from these data. The accelerations and hydrophone pressures are a direct result of the hull pressures and it is assumed that large responses on these sensors reflect large hull excitation pressures. These sensors respond also to other vibration sources on the ship. In the analysis of the spectral data, attention has been paid to discount lines that may be due to other sources.

In examining the low frequency spectra it is natural to compare the ratios of the spectral levels at the different harmonics of blade rate. In doing so, readers are reminded that a 6db difference represents a factor of two in the pressure or acceleration amplitude.

In the hydrophone data, the blade rate peak dominated all other peaks in the spectra, usually by more than 12db. In Run 1200 the line at 6×BR rose to within 9db of the blade rate. In the accelerometer data, the blade rate peak generally dominated most other peaks in the spectra. In several runs (1160, 1180, 1190 and 1200) the line at 3×BR rose to similar levels as blade rate and in Run 1200 the line at 6×BR was 3db greater than blade rate.

These differences in response between the accelerometers and the hydrophone make it difficult to estimate the relative levels of the harmonics in the hull pressures. Such an analysis was not conducted on the data.

The hydrophone signal responded most strongly to the cavitation and was chosen for some additional inspection. All the hydrophone data in the low frequency band (f/f_{max} = 0 to 0.08) was plotted on one graph in Figure 67. The spectra have been superimposed, with each run's data separated by a 20db increment. This format shows clearly the harmonics of blade rate and the various noise signals that could be confused with the harmonics.

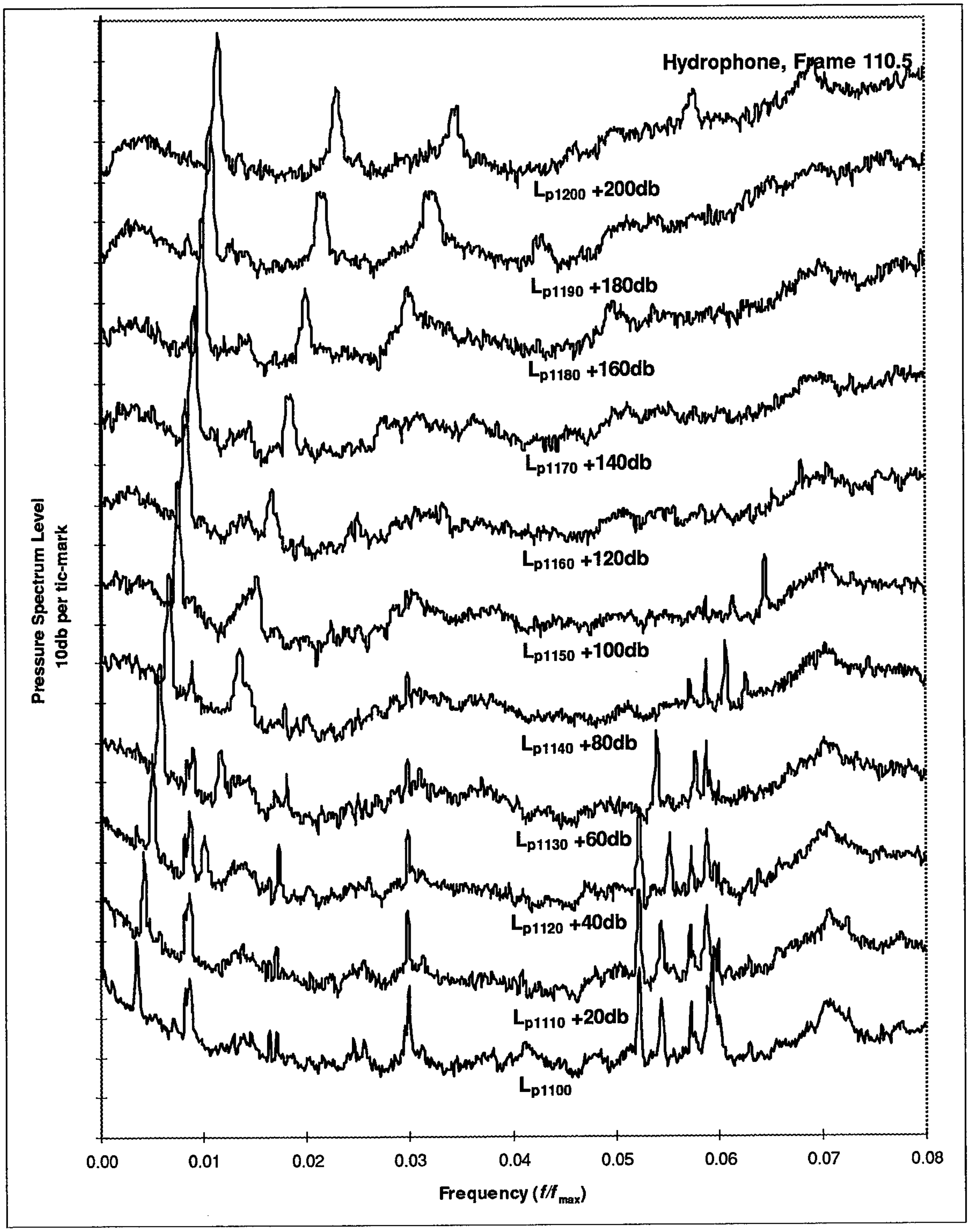

Figure 67 All hydrophone low frequency spectra

The high frequency spectra have also been examined in some detail. In Figure 68 all the high frequency spectra (in the band f/f_{max} = 0 to 1.0) from the hydrophone have been presented. As with Figure 67, the spectra have been superimposed, with each run's data separated by a 20db increment.

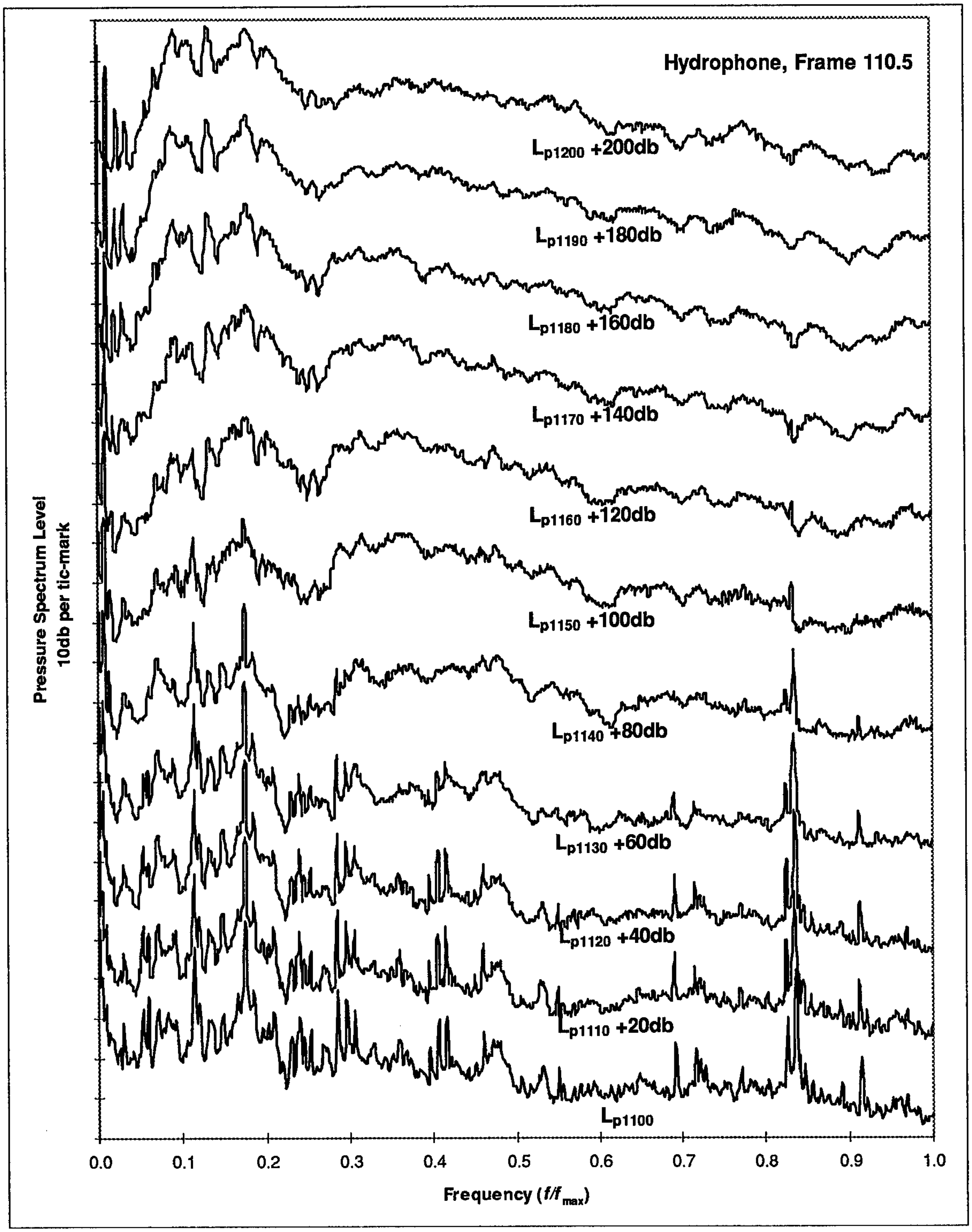

Figure 68 All hydrophone high frequency spectra

Close inspection of the rate of increase of the pressure spectrum with ship speed showed that the data fell into two categories, roughly above and below $f/f_{max} = 0.3$. Figure 68 shows the relatively large increases of levels in the $f/f_{max} = 0.3$ to 1.0 band between Runs 1120 and 1160. In the $f/f_{max} = 0$ to 0.3 band, the largest level increases were between Runs 1140 and 1170. The increases in level were noted above in Section 3.

It was noted from the high frequency accelerometer data that the accelerometer at frame 112.5 responded differently from the other two accelerometers, especially above $f/f_{max} = 0.5$. This could imply that the accelerometer was not performing correctly, or, more likely, that its response was very dependent on the local structure. Frame 112.5 is very close to the rudder stock and the ship structure there is more massive. Also, the leading edge of the rudder is very close to that accelerometer.

One object of gathering the data was to add to our general knowledge of the relationship between propeller cavitation and the harmonics of blade rate in the hull excitation. Hence, an attempt was made to correlate the response of the sensors to the observed cavitation. Table 14 summarizes the main features of the cavitation observed on the various runs.

Run No.	Leading Edge Vortex Cavitation	Sheet Cavitation	Hub Vortex Cavitation
1100			
1110			
1120	Very intermittent		
1130	Intermittent, also from preceding blade		
1140	Intermittent, occasional bursting, also from preceding blade	Very intermittent	
1150	Consistent, usually bursting. Preceding blade: occasional bursting	Intermittent, at .95R	
1160	Consistent, usually bursting. Preceding blade: frequent bursting	Consistent, .95R to .9R, in separated areas	
1170	Consistent, usually bursting. Preceding blade: frequent bursting	Consistent, 1.0R to .85R, in separated areas	
1180	Consistent, always bursting. Preceding blades: always bursting	Consistent, 1.0R to .8R, areas larger and less separated	
1190	Consistent, always bursting. Preceding blades: always bursting	Consistent, 1.0R to .8R, in one larger area	Very intermittent
1200	Consistent, always bursting. Preceding blades: always bursting	Consistent, 1.0R to .8R, in one even larger area	Intermittent

Table 14 Summary of Observed Cavitation

The hydrophone pressure spectra for each run are presented in Figure 69 with the frequency presented in terms of blade rates. This form permits ready comparison of all the blade rate harmonics from the various runs. Most of the analysis of the data was based on this hydrophone data, but the accelerometer responses were checked for consistency with the hydrophone data.

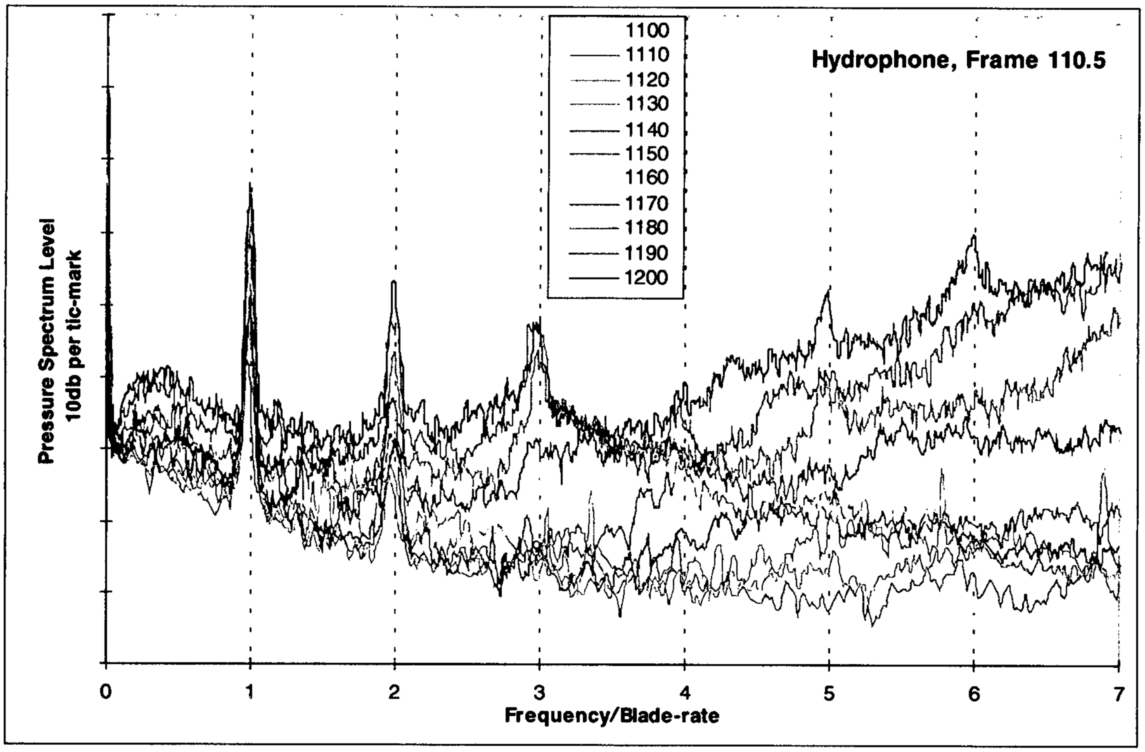

Figure 69 All hydrophone spectra, with frequency normalized by blade-rate

A comparison of the cavitation data of Table 14 with the spectra indicates that there may be some correlation between cavitation and blade rate harmonic lines in the hull excitation:

- When cavitation was first intermittently detected (Run 1120) both hydrophone and accelerometer signals were affected. For the hydrophone, the blade rate line increased and 2×BR appeared. Also, the blade rate line appeared in the accelerometer signal.
- When sheet cavitation was first detected and the leading edge vortex cavitation from the blade in the wake peak was first seen to burst (Run 1140) the accelerometers picked up a line at 2×BR. The response of the hydrophone was different, as described below.
- When the trailing vortices from previous blades are first seen to burst close to the rudder (Run 1150) both the hydrophone and the accelerometers showed an increase in spectral level at around 4×BR.
- The first, very intermittent, appearance of a hub vortex in Run 1190 gave rise to a line at 4×BR in the hydrophone signal.

There are, however, some features of the data that indicate that any correlation will not be simple and would likely depend on the amount, or frequency of occurrence of cavitation. These are:

- Sheet cavitation was first detected and the leading edge vortex cavitation from the blade in the wake peak was first seen to burst in Run 1140. No higher harmonics arose in the hydrophone signal due to these new forms of cavitation.
- There was no new cavitation observed in Run 1180, although a line at 5×BR was then detectable in the hydrophone signal.
- The first, very intermittent, appearance of a hub vortex in Run 1190 did not give rise to any more harmonics in the accelerometers' signals.
- The introduction of the 5×BR line in the accelerometer spectra, and the 6×BR line to all the spectra was not accompanied by any new cavitation. There was just more of the existing types of cavitation.

From the broadband data the principal points noted about the increases in spectral level are:

- The higher frequencies (f/f_{max} = 0.3 to 1.0) increased most substantially when sheet cavitation began (Run 1140).
- The lowest frequencies (f/f_{max} = 0 to 0.3) increased most substantially when the trailing vortices from previous blades are first seen to burst (Run 1150).

5. Conclusions and Recommendations

The trial conducted on QUEST did not use a hull pressure transducer. Instead, hull accelerations and hydrophone readings were taken. There was some limited correlation between the appearance of the different forms of cavitation and the appearance of specific harmonics in the hull excitation. It was not possible to unambiguously associate the presence of specific harmonics with any particular form of cavitation. This result likely applies to hull pressures as well.

The hydrophone data received the most detailed analysis of any sensor. Further analysis of the data is possible. Also, the data from the accelerometers could be analyzed in more detail. It is however recommended that such analysis be postponed until the way forward for this work is clarified by the other work of the "PRES" Working Group.

The results here apply to QUEST, which has neither a hull nor a propeller that is typical of known problem ships. It would not be correct to extrapolate the results from this single data set to those classes of ships. A similar trial on a problem ship would reveal if the above conclusions are more widely applicable, or otherwise.

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The NSMB Co-operative Research Ships organization is investigating various aspects of hull excitation from highly skewed propellers. As part of this effort DREA measured hull excitations and made concurrent cavitation observations onboard CFAV QUEST. Results from these are presented and discussed. Varying amounts of sheet, leading edge vortex, tip vortex and hub vortex cavitation were observed. Bursting of the vortex cavitation was prominent in many cases. As ship speed and the amount of cavitation increased, so did the level of the higher harmonics of blade rate in the hull excitation spectra. There was some limited correlation between the appearance of the different forms of cavitation and the appearance of specific harmonics in the hull excitation. There was also data that indicated that no simple correlation would be possible. For instance, the harmonics at five and six times blade rate depended on the amount rather than the nature of the cavitation.

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