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PITCH REDUCTION OF SHIPS BY MEANS OF ACTUATED FLAPS OPERATING IN THE WAKE OF A DUCTED PROPELLER

by

Alvin Gersten

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PITCH REDUCTION OF SHIPS BY MEANS OF ACTUATED FLAPS OPERATING IN THE WAKE OF A DUCTED PROPELLER

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ABSTRACT

The feasibility of reducing the pitching motions of a ship by actuating flaps mounted in the wake of a ducted propeller has been investigated by means of model tests. The results of this study are presented and the pitch reduction attainable in State 5 and 6 seas is discussed. It is indicated that with a flap system of acceptable size installed, the pitch reduction achieved does not justify the added design complexities. Evaluations are made of the effect of the flaps on heave, of the force required to drive the flaps, and of the lift produced. Data obtained from sinusoidal excitation of the model (either by waves or flap oscillation) have been presented in graphs, and records containing random signals (from irregular wave tests) have been analyzed statistically and the results presented in tabular form.

ADMINISTRATIVE INFORMATION

The study reported herein was performed at the request of the Bureau of Ships as Task 1712 of Project No. S-F013 02 04. The request was made in Bureau of Ships letters Serial 442-047 of 12 June 1962 and Serial 442-164 of 9 August 1963.

INTRODUCTION

A number of undesirable phenomena are associated with severe ship motions; foremost among these are slamming, propeller emergence, discomfort of personnel, and the shipping of green water. Much research effort has been devoted to devising methods of reducing motions, particularly in the rolling and pitching modes. For pitch reduction, passive bow fins and passive or controllable stern-mounted fins have received the most attention.[1-5] The results of full-scale trials and model tests reveal that transverse hull vibration often occurs when passive bow-fins are utilized. Consequently, these devices have never achieved acceptability and no permanent shipboard installations have been made. Since the ship pitching

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[1] References are listed on page 60.

axis is aft of midship, fixed stern-mounted fins have a relatively small angle of attack compared to bow fins and therefore produce smaller moments to reduce pitch. As a result, they are of less practical interest than the other two devices mentioned above.

In July, 1958, the Eastern Research Group (ERG) submitted a proposal[6] for pitch quenching to the Bureau of Ships. They proposed to investigate the feasibility of reducing pitch by deflection of a propelling jet. A contract was subsequently awarded and the results of an experimental study carried out by the Davidson Laboratory of the Stevens Institute of Technology under subcontract to ERG were published in January 1962.[7] The program consisted of model tests in regular waves to compare the pitching motion of the DE 1006 when fitted with a conventional propeller, and when equipped with a ducted propeller (pumpjet) with various configurations of activated flaps. The largest flaps tested had a total area of 245 sq ft.* When operating with these flaps at a speed of approximately 16 knots in regular waves of length equal to ship length and steepness $\left(\frac{\text{wave height}}{\text{wave length}}\right)$ equal to 1:48, a pitch reduction of 64 percent was obtained. A reduction of 36 percent was obtained when operating at the same conditions as above except for a change in wave steepness to 1:24.

ERG, again under contract to the Bureau of Ships, designed and manufactured a flapped pumpjet for a 1:19.52 scale model of the AGDE-1. A ducted propeller is to be installed on an AGDE-1 prototype which is presently under construction. It was planned to incorporate flaps on the pumpjet if such a system proved significantly effective during model tests in random waves. Therefore, the Bureau of Ships requested the Taylor Model Basin to utilize this pumpjet and an existing model of the AGDE-1 to evaluate the potentialities of the flapped pumpjet for pitch reduction in irregular waves. A test program was subsequently established at the Model Basin and carried out at the Maneuvering and Seakeeping Facilities (MASK). Preliminary results were presented to the Bureau of Ships in letter form shortly after these tests were completed.

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*All dimensions, speeds, frequencies, etc. given in this report will be for the full-scale ship unless otherwise noted.

TEST PROGRAM

MODEL AND PROTOTYPE

The model utilized in this test program was a 1:19.52 scale representation of the destroyer escort AGDE-1 (TMB Model 4881-1). The AGDE-1 lines are shown in Figure 1, and the particulars of the ship and model are presented in Table 1. During the tests with the pumpjet installed, a portion of the stern was hollowed out to provide space for a force gage, as shown in Figure 2. This space was free flooding, and to compensate for the loss of displacement, the model weight was decreased by 10 lb. The longitudinal radius of gyration (0.28 of the length between perpendiculars) was the same for all tests and was determined by oscillating the model in yaw about its center of gravity as a bifilar pendulum. Photographs of the model with a conventional propeller and with pumpjet installed are shown in Figures 3 and 4, respectively.

FLAP CONFIGURATIONS

The total areas[*] (in square feet) of the flaps used during these experiments were as follows:

Middle Flap A	26.4
Middle Flap B	42.8
Middle Flap C	95.8
Flaps in Pumpjet Shroud	41.2[**]

Plan views of the various flap configurations are shown in Figure 5. Each of the middle flaps had a symmetrical foil cross section with maximum thickness of 0.68 ft; the cross section of the shroud flaps was the same as that of the shroud itself. The arrangement of the flap system can be seen in Figures 4a and 4b; there Middle Flaps B and C, respectively, are installed together with the flaps in the shroud.

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[*] Including both port and starboard for middle flaps and top and bottom for flaps in the shroud.

[**] Projected area.

TEST PROCEDURE

General Aspects

The schedule of experiments can be divided into four phases as follows:

Phase 1: Tests in regular and random waves with a *conventional propeller installed.* These experiments were carried out to characterize the pitching of the vessel with thrust provided by a standard nonducted-type propulsive device.

Experiments were first carried out at zero speed in regular waves. Examination of the pitch unit response as a function of wave frequency revealed that the zero speed curve has two peaks of approximately the same magnitude. The maxima occur at frequencies corresponding to wave length to ship length ratios of about 1.0 and 1.6. It was desired to carry out all future tests in wave conditions which induce appreciable pitch since the reduction of small pitching motions is of no particular consequence. Therefore, the synchronous speed of the model in pitch for waves of length equal to 1.25 times the model length (a compromise between 1.0 and 1.6) was selected for future testing. Specifically, this speed was 3.7 knots model scale (16.3 knots full scale). In addition, regular wave tests were made at 5.0 knots model scale (22.1 knots full scale) since this speed represents an estimate of the upper limit attainable by this vessel in a State 5 sea. Tests in irregular waves were also conducted at model speeds equivalent to 0, 16.3 and 22.1 knots full scale.

Phase 2: Calm water tests with the flapped pumpjet installed. During these tests, the *flaps* in the shroud were *oscillated sinusoidally,* both alone and in conjunction with each of the middle flaps *to induce pitching motions.* This phase provided an estimate of the magnitude of the force required to drive the flaps at various frequencies. This information was required for the selection of a flap-actuating device to be utilized in the Phase 4 tests. In addition, by providing a measure of the pitching motion induced by the various flap configurations, these tests enabled a determination of the minimum size flaps that could be expected to significantly reduce pitch in a seaway. This follows from the fact that the flap inducing the largest motions will, if actuated properly, also reduce motions most effectively when the vessel is excited by wave action. During each test at 16.3 or 22.1 knots, the flaps were oscillated at a constant frequency and amplitude; the nominal values are listed in Table 2.

Phase 3: Tests in random waves with the pumpjet installed. The flaps in the shroud were positioned in the periphery of the shroud and locked; no middle flap was employed. These experiments provided a reference with which the pitching motions of Phase 4 could be compared.

Phase 4: Tests in random waves during which the pumpjet was in operation and a feedback control system was used to position the flaps automatically. In conjunction with the Phase 3 tests, these experiments enabled an evaluation of the effectiveness of the servomechanism-controlled flaps to reduce pitch. Middle Flap C, the largest of those examined during the induced-motion tests, was employed in this phase along with the flaps in the shroud. They were free to move through ± 34 deg. The ship speeds were 16.3 and 22.1 knots.

All wave tests were conducted in head seas. Free oscillation tests in calm water were performed to provide information on the natural period and damping characteristics of the vessel in pitch. It was important to maintain a constant natural period since for fixed model form and displacement, this implies a constant moment of inertia. It was essential that the latter not be altered so that comparisons of the forced model motions obtained in the various test phases would be meaningful. The free oscillation tests in water provided a check on the results obtained by oscillation of the model in air as a bifilar pendulum (see page 3). The damped natural pitch period of the ship during each of the test phases is listed below together with the method of determination.

Period, sec	Method
Phase 1: 6.27	Free oscillation in calm water
Phase 2: 6.25	Location of peak in plot of induced pitch as a function of frequency*
Phase 3: 6.36	Free oscillation in calm water
Phase 4: 6.36	Free oscillation in calm water

Wave Conditions

Phase 1: The regular waves employed for this test phase had the dimensions given in Table 3. The energy density spectra of the irregular waves generated are presented in Figure 6. The Neumann spectrum which best approximates that of the waves produced in the basin is shown for comparison in Figure 6a. It is representative of a moderate State 6 sea. Although there are differences in the energy distributions of the two spectra, the total energy (which is proportional to the area under the curves) is approximately the same. The area under the energy density spectrum is represented by E. It should be noted that the relationship between the mean-squared value of a random variable and the E value (as defined by St. Denis and Pierson) is given by E = 2 x mean-squared value. Figure 6b shows the wave energy density as encountered by the ship traveling at 16.3 and 22.1 knots.

Phases 3 and 4: The two tank-generated wave systems utilized in these phases are represented by the energy spectra shown in Figure 7. Here again, the Neumann spectra which approximate the test spectra are presented for reference. Spectrum B approximates a middle State 5 sea, and Spectrum C is comparable to a moderate State 6 sea. Figure 7b shows the wave spectra of encounter. In the frequency of encounter domain, both spectra contain a considerable amount of energy at the pitch natural frequency.

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*This is actually the "resonant" period or period of maximum forced amplitude. It is close to the natural period for small values of damping.

The irregular waves were obtained by means of a magnetic tape program that effected a random change in the wave frequency and height. Since the program was of approximately 15-min duration (model time) and the basin length is limited (360 ft), it was not possible to conduct an uninterrupted test. Therefore, the procedure was to start the wave program and, with the wavemaker continuously generating waves, to make a series of passes down the tank for the duration of the tape program. This usually resulted in about eight samplings, each containing approximately 15 cycles of the variables. The spectra presented in Figures 6 and 7 were computed by placing 40 wave records (made during 40 passes down the tank) end-to-end and analyzing them as one continuous record. The individual runs were made with various sections of the tape program on the line, some of which overlapped. Therefore, Figures 6 and 7 approximate the wave systems encountered during any single series of approximately eight passes through the basin.

Measured Variables

The following variables were measured during these experiments:

Phase 1:
- a. pitch
- b. heave
- c. bow acceleration
- d. wave height
- e. model speed

Phase 2:
- a. pitch
- b. heave
- c. bow acceleration
- d. flap actuating force
- e. flap angle
- f. force on block gage[*]
- g. total lift force

Phase 3: Same as Phase 1

Phase 4: Same as Phase 2 with the addition of wave height

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[*] See next section for discussion.

INSTRUMENTATION FOR DATA RECORDING, FLAP OSCILLATION, AND PROPULSION

The transducers listed in Table 4 were used in the various phases of this investigation. All transducer signals were amplified and recorded on Sanborn chart recorders. For the tests in irregular waves, the signals were also recorded on magnetic tape so that electronic computation of root-mean-square (rms) values could be performed.

Phase 1: Propulsive force was provided by a model of the design propeller (TMB propeller 4016). The prototype propeller has five blades, a diameter of 15 ft 0 in. and a pitch (at 0.7 of the radius) of 15 ft 8 5/8 in. The propulsion shaft of the model was driven by a 5-hp, shunt-wound, direct-current motor.

Phase 2: For these and all subsequent tests, the pumpjet shown in Figures 2 and 4 was installed on the model. It can be seen in Figure 2 that the pumpjet was attached by brackets to a force-measuring transducer (block gage) which was bolted to the model. The block gage was sensitive only to forces acting in the direction of the arrow. The rod which actuates the flaps was instrumented with strain gages to record the force required to move the flaps. The sum of the block gage and strain gage outputs was obtained electrically. This signal is proportional to the total force acting on the model perpendicular to the propeller shaft. Since the shaft was inclined only 4 deg from the baseline, the above force was essentially the total vertical force acting on the model.

The model flaps were oscillated sinusoidally by a 5-hp, direct-current motor exactly like the propulsion motor. The motor was connected to the flap push rod through a speed-reducing gear box (9:1 gear ratio) and a Scotch yoke. A standard TMB revolution counter pickup, consisting of a slotted copper disk (mounted on the shaft between the gear box and Scotch yoke) and two iron core induction coils mounted adjacent to the disk, was utilized in conjunction with a pulse counter. This provided a reading of the flap oscillation frequency. The direct-current motor speed could be adjusted to produce any desired flap frequency. Once set, this frequency was maintained by means of a tachometer generator feedback system. The amplitude of flap oscillation was set prior to each run by adjusting the stroke of the Scotch yoke. A potentiometer was mounted near the top of the flap push rod and was actuated through a linkage system, duplicating that used at the bottom of the push rod to oscillate the flaps. Thus, a continuous record of flap angle was obtained. Figure 8 shows the general layout of the equipment employed in this test phase. A sample of the records obtained on the Sanborn recorder is presented in Figure 9a.

Phase 3: The motions, wave height, and model speed were recorded by the transducers indicated in Table 4.

Phase 4: During these experiments, the largest middle flap (i.e., Flap C) and the flaps in the shroud were actuated in hard-over to hard-over fashion by a torque motor driving a rack and pinion. The motor has a peak torque of 11 lb-ft and a rotor inertia of only 0.012 lb-ft $\sec^2$ (both model scale). The rotory position of the torque motor shaft, and therefore of the flaps, was automatically controlled by the closed loop servomechanism system shown in block diagram form in Figure 10. This diagram was taken from Reference 8 which also contains schematic diagrams of the electric drive and power supply. The servosystem employed pitch displacement and bow acceleration as basic signal inputs. An analogue computer was utilized to derive a pitch rate input and then to combine the three inputs by means of a standard summing circuit containing an operational amplifier. During pretest trial runs, the resistance in each leg of the summing circuit was asjusted to control the weighting factor for each input until the lift force supplied by the flaps opposed the pitching motion throughout most of the pitching cycle. An example of this kind of operation can be seen in the sample record presented in Figure 9b. The optimized system was responsive to pitch rate to a much greater degree than pitch displacement and bow acceleration. It also employed a high overall gain so that maximum flap angle was ordered even for relatively small pitching motions. Thus, the system "switched" on pitch rate to achieve maximum resistance to large motions.

The output of the computer (ordered flap angle) was fed to an error regulator serving as a comparator for the primary feedback signal which was proportional to flap angle. The error regulator also contains a preset reference voltage with which a voltage proportional to the power supply output current (secondary feedback) is compared, so that the latter is limited. If the secondary feedback exceeds the reference voltage, a diode switch is closed, and the secondary feedback subtracts from the computer output. The error regulator signal to the rectifier control circuitry is then decreased, causing the silicon controlled rectifiers to be on the line during a shorter portion of the alternating current cycle and thus decreasing the output of the power supply.

Figure 11 shows the location of the equipment in the model. The two cams mounted on the motor shaft actuated microswitches to cut off power to the motor when the flaps were at their maximum up or down position. Mechanical stops were also provided. A ganged assembly of two potentiometers is shown forward of the torque motor. The output of one potentiometer was recorded to provide a trace proportional to flap angle; the output of the other potentiometer was utilized as the feedback signal in the closed loop control system.

RESULTS AND DISCUSSION

PITCH

Magnitude

Phase 1: The results of the regular wave tests are plotted in Figure 12 as pitch unit response versus frequency of wave encounter. An unusual phenomenon occurs at zero speed in that there are two peaks in the curve. It is unlikely that wave reflections from the tank walls or beach produced this anomaly since the model was located in the middle of the 360 by 240-ft basin and records were made as soon as the first waves passed the model. At zero speed, maximum pitch usually tends to occur at frequencies corresponding to wave lengths of 1.0 to about 1.5 times the ship length, depending upon the hull form. At higher speeds, the dynamic characteristics of the system are more important and pitch maximizes at, or close to, the natural frequency. This process is in evidence in Figure 12.

Experiments were conducted in irregular waves whose energy density spectrum is presented in Figure 6. Full-scale rms values of pitch and wave height and the average of the highest one-tenth pitch double amplitudes and wave heights are presented in Tables 5 and 6 respectively. The average of the highest 10 percent double amplitudes were read directly from the Sanborn records. It can be seen in these tables that the pitch per unit wave height was greater at 16.3 knots than at either 0 or 22.1 knots.

Phase 2: Figures 13a through 13h show the results of the induced-motion tests conducted in calm water. It is evident that Middle Flap C operating in conjunction with the flaps in the shroud induced the largest pitching motions; therefore, this configuration was selected for irregular wave experiments with the servosystem functioning. All curves peak at or near a frequency of 0.16 cps (period of 6.25 sec) which indicates that this is the resonant frequency.

Figure 14 is a cross plot of Figure 13 made at a frequency of 0.16 cps. The abscissa represents the area of the middle flap (i.e., exclusive of the flap in the shroud). The induced pitch is reasonably linear with respect to flap area within the range tested even though part of the largest flap was encountering the flow in the wake of the propeller while the remainder (that which extended beyond the shroud) was operating at the relatively low forward speed of the model. Thus, an increase in induced pitch, and hence a greater reduction in pitch in a seaway, might be achieved by making the middle flap area greater than that of Flap C. This was not done, however, since the Bureau of Ships indicated that it would be difficult to operate a middle flap larger than Flap C on the AGDE-1. The principal deterring factor was the housing of such a large device and its associated hydraulic actuating system in the stern of the ship. Moreover, if the flap size were increased appreciably, the major portion of the flap would be outside the propeller wake, and the advantages of a mounting point aft of the pumpjet would be nullified.

Phase 3: Experiments were carried out in the wave systems described by the spectra in Figure 7. The rms values of pitch and wave height are presented in Table 7 where they are designated by a tabulation of "no" in the column entitled "flap oscillating." These, and all subsequent statistical values (such as rms and average of the highest one-tenth) are the averages of values obtained from many runs for a particular test condition; the repeatability of data obtained from the individual runs was quite good. Table 8 is a listing of the average of the highest one-tenth pitch double amplitudes and wave heights. Again, these results are designated by a "no" under the "flap oscillating" column.

Phase 4: The rms values designated by a "yes" in Table 7 were also obtained from measurements made in the wave systems represented in Figure 7. Middle Flap C and the flaps in the shroud were actuated. The average of the highest one-tenth pitching motions and wave heights with flaps oscillating is presented in Table 8.

A "percent reduction" column is included in these and subsequent tables. Some of the values tabulated therein are based on small changes in measured variables which are subject to some experimental error. As a result, only large variations in these percentages should be considered significant. Moreover, one should bear in mind that equal absolute changes in a variable yield different percentage changes for different initial values. This can be misleading. The best measure of flap effectiveness is the absolute change in motion per unit wave height.

If one neglects small differences, it can be stated on the basis of Tables 7 and 8 that for a given set of test conditions, the magnitude of both rms and highest 10 percent pitch per unit wave height are in close agreement. Consequently, for the same test conditions, both the absolute and percent reduction of unit pitch response given in one table are almost identical to their counterparts in the other table. This occurs because greater reduction in pitch motion per se was effected in the higher waves than in the lower ones. This may be explained by the fact that the servo-system oscillated the flaps through larger angles and in more of a square-wave fashion when the pitching motions tended to be large. The angle of attack of the flaps also increased as pitch increased since the flaps were (indirectly) attached to the hull. Appreciably greater forces were therefore produced which reduced the motion more effectively. It can be seen in Figure 9b that in Regions 1 where the pitching motion was relatively large, the flap motion approximated a square wave (with some overshoot). In Regions 2, however, where pitch was less severe, the flap angle trace was of smaller amplitude and the flap spent more time in transit between the maximum up and down positions. This variation in flap motion produces a corresponding variation in the total lift force.

Since a comparison of the results in Table 7 with those in Table 8 indicates that the pitch reductions achieved in the tests were approximately proportional to wave height for a given test condition, one might be inclined to use these results to predict reductions in more severe seas. It should be pointed out that the system is inherently nonlinear. For example, the lift force will not generally increase proportionately with wave height, and neither therefore will the resulting pitch reductions. The reader is therefore cautioned not to extrapolate these results to predict pitch reduction in seaways more severe than those employed in this study.

If one considers either rms or the highest 10 percent pitch, it can be seen that for a given speed, the absolute and percent reduction in pitch per unit wave height is always less in Sea State C than in Sea State B. The flaps were generating somewhat greater forces in the higher sea state,* but these increased forces yielded no corresponding gain in the reduction of absolute pitch. This probably can be attributed to the fact that in the lower sea state, the lift forces are more often produced at frequencies close to the natural pitch frequency. An examination of Tables 7 and 8 reveals that for a given speed, the pitch per unit wave height without flaps operating is always greater in Sea State B than in Sea State C. This indicates that the former wave system contains a greater portion of its total energy at, or close to, pitch resonance. Since the flaps oscillate at the frequency of wave encounter, dynamic magnification of flap-induced model motions is greater in Wave System B. As a result, the smaller forces produced in Sea State B reduce pitch more than those occurring in Sea State C.

The wave spectra for 16.3 knots shown in Figure 7b corroborate the statements made above in that the maximum or near-maximum energy density levels of Spectrum B are located closer to the natural pitch frequency

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*This is shown in Tables 11 and 12 in which lift force is presented.

than are those of Spectrum C. Such confirmation is not extant for the 22.1-knot spectra. It must be emphasized, however, that these wave spectra are approximations of the actual spectra of encounter applicable in the individual test runs. Whereas the spectra in Figure 7b were obtained by applying a frequency transformation to the zero speed spectra of Figure 7a and are representative of essentially the entire wave program, the tests were conducted in waves generated by isolated segments of the wave program.

To summarize, the somewhat smaller lift forces generated by the flaps in Wave System B as compared to Wave System C were more effective in reducing pitch because they were applied to the hull at frequencies closer to resonance. Consequently, dynamic magnification played a greater role in the lower sea state. In a previous comparison of the reduction of rms pitch and the average of the one-tenth highest pitch, it was noted that the larger lift forces produced in the high waves resulted in a greater reduction of pitch. In that case, the forces were increased sufficiently to overcome any loss in magnification caused by a shift in predominant flap oscillation frequency away from resonance.

At a ship speed of 22.1 knots, the reduction in the average of the highest one-tenth pitch double amplitudes would be approximately 1.4 deg in either sea state. If it is assumed that the axis of rotation is two-thirds of the length between perpendiculars aft of the forward perpendicular (the point of minimum vertical motion is generally located in this vicinity for destroyer forms), this would result in a reduction of vertical motion at the forward perpendicular of roughly 6.4 ft. Thus, when large motions occur, the ship would, in effect, have the equivalent of 3.2 ft of additional freeboard to prevent shipping of green seas and 3.2 ft of additional draft at the bow to prevent forefoot emergence and severe slamming. Since the phase of the force generated by the flaps is adjustable, it is possible to utilize this force optimally to reduce motion at the bow or at any other location along the ship.

Damping

To determine the effect of the pumpjet on the pitch damping characteristics, the logarithmic decrement of the free oscillation records was analyzed for the model when equipped with the pumpjet and when fitted with the conventional propeller. The ratio of the damping coefficient $N_{\psi\psi}$ to the critical damping coefficient $(N_{\psi\psi})_c$ was then obtained for the two configurations. It was assumed in the analysis that the free-pitching oscillation of the model is described by

$$M_{\psi\psi} \ddot{\Psi} + N_{\psi\psi} \dot{\Psi} + B_{\psi\psi} \Psi = 0$$

where Ψ is the pitch angle at time t,

$M_{\psi\psi}$ is the virtual moment of inertia,

$N_{\psi\psi}$ is the damping coefficient, and

$B_{\psi\psi}$ is the restoring moment coefficient.

The analysis yielded the following results:

Configuration	$N_{\psi\psi}/(N_{\psi\psi})_c$
Conventional Propeller	0.24
Pumpjet (no flaps)	0.23

This indicates that even at excitation frequencies close to resonance, the amplification and hence the magnitude of the transfer function relating the pitching motion output and pitching moment input (due to wave action) would be essentially the same for both configurations.

FLAP-ACTUATING FORCE

Phase 2: Figures 15a through 15h present the force required to oscillate the flaps sinusoidally as a function of frequency of oscillation. It is interesting to note that this force is virtually independent of frequency over the range of frequencies examined. In addition, cross plots of actuating force versus flap angle (which are not presented here) reveal that these two parameters are linearly related within the range of angles investigated.

The dimensionless moment $(M/\rho V^2 S^{3/2})$ acting on an oscillating foil traveling through water is the same for model and full scale at the same Reynolds number $(R_N \overset{\Delta}{=} \rho V S^{1/2}/\mu)$ and Strouhal number $(S_N \overset{\Delta}{=} \omega S^{1/2}/V)$ only. In the above, ρ is the mass density of water, V is the free-stream velocity, S is a characteristic area, μ is the viscosity of water, and ω is the frequency of oscillation. During these tests, the Strouhal numbers were maintained equal, but the model Reynolds numbers were lower than those appropriate for the prototype. Therefore, the full-scale forces given in Figure 15 are approximate. Nevertheless, these forces, as well as those shown in subsequent figures and tables, should provide a useful estimate for prototype design.

Phase 4: Tables 9 and 10 are listings of the rms and average of the highest one-tenth flap-actuating forces, respectively. Although these forces were required to oscillate the flaps in hard-over to hard-over fashion, the average of the one-tenth highest single amplitudes was roughly the same as the force required to oscillate these flaps sinusoidally at an amplitude of 36 deg (see Figures 15g and 15h). The maximum actuating force measured during Phase 4 is ± 189 tons.

LIFT FORCE

Phase 2: The total lift force generated by the flaps and the pumpjet shroud was obtained by algebraically adding the output of the block gage and flap push-rod strain gages. These results are presented in Figures 16a through 16h. The lift shows the same tendency as the flap-actuating force in that it does not vary appreciably with frequency throughout the frequency range examined. Further, it too varies linearly with flap angle within the range of angles investigated.

Phase 4: The rms and average of the highest one-tenth lift forces measured during the irregular wave tests with the servosystem positioning the flaps are presented in Tables 11 and 12, respectively. The lift developed increases with speed for a given sea state and also increases with sea state for a given speed. The maximum lift force measured during

Phase 4 is ± 200 tons. This is an indication of the maximum load transmitted to the hull when operating the flaps hard-over to hard-over in seas up to a middle State 6.

HEAVE

Phase 2: Oscillation of the flaps had little effect on heave. For example, the largest induced heaving motion was ± 0.8 ft. This occurred at a speed of 22.1 knots with Middle Flap C oscillating in conjunction with the flaps in the shroud. The induced heave was significantly less for the other flap and speed conditions. Since inconsistencies exist in the heave curves, they are not presented here. These discrepancies are probably due to inaccuracies in the measurement of these small motions (in model scale) inasmuch as the equipment utilized was designed for much larger heave excursions.

Phase 3 and Phase 4: The heave measured in irregular waves is shown in Tables 13 and 14. Here too, it is apparent that oscillation of the flaps did not alter the magnitude of heave appreciably. It should be noted that except for the value listed in Table 14 at the higher speed in Sea State C, all percentages given indicate a decrease in unit heave response when the flaps are oscillated. This single case of heave increase is not unreasonable. Since the flap motion is controlled to reduce pitch, and heave and pitch are generally out of phase, the flaps could actually act to increase heave.

BOW ACCELERATION

Phase 2: The rigid body, vertical acceleration induced at Station 2 during the calm-water experiments is presented as a function of frequency in Figures 17a through 17h. The curves peak at a frequency only slightly greater than the resonant pitch frequency of 0.16 cps. For certain test conditions such as those represented by Figures 17a and 17d, a lower amplitude of flap oscillation appears to produce larger accelerations. This indicates that there may be some error in the measurement of these small accelerations and therefore the values shown are approximate.

Phase 3 and Phase 4: The rms values of bow acceleration $\ddot{\zeta}$ and the average of the highest one-tenth bow accelerations $\bar{\ddot{\zeta}}_{1/10}$ are presented in Tables 15 and 16, respectively. Each of these tables contains acceleration magnitudes measured (1) with Middle Flap C and the flaps in the shroud oscillating and (2) with no middle flap installed and the flaps in the shroud locked in the periphery of the shroud. The percent reduction achieved by operating the flaps is given. No reduction in the average of the highest one-tenth bow accelerations occurs at 22.1 knots in Sea State C (see Table 16) despite a 16.7-percent reduction in $\bar{\Psi}_{1/10}/\bar{h}_{1/10}$ at this test condition. This is due, at least in part, to the increase in the highest 10 percent heave which is brought about by flap actuation.

PHASE RELATIONSHIPS

The phases of pitch, bow acceleration, and bow immersion all referred to maximum downward flap angle are presented in Figures 18, 19, and 20, respectively. These results were obtained from the induced-motion tests in which the flaps were oscillated sinusoidally. The bow immersion was measured by mounting a capacitance-type probe on the model abreast of the forward perpendicular. Since induced heave was quite small, pitch and bow immersion are generally almost in phase.

WAKE DISTURBANCE DUE TO FLAP OSCILLATION

Visual observation during calm water and wave tests revealed that actuation of the flaps created a large flow disturbance in the wake of the vessel. The spouting of water was caused by upward deflection of the pumpjet wake. An example of this disturbance is shown in Figure 21 in which Middle Flap C and the flaps in the shroud were oscillated through ± 36 deg during Phase 2 experiments. In Figure 21a, the flaps are near their maximum downward position while in Figure 21b, they are at the peak of their upward swing. Apparently, it would be undesirable to operate the flaps when detection by other vessels is to be avoided.

CONCLUSIONS

The following are the principal findings of this investigation and, as stated, they apply to the full-scale ship. The flaps referred to are always Middle Flap C operating in conjunction with the flaps in the shroud.

1. At a speed of 22.1 knots, a reduction of approximately 1.4 deg in the average of the highest one-tenth pitch double amplitudes can be obtained in either a State 5 or 6 sea. This is equivalent to roughly a 3.2-ft reduction in the single amplitude of vertical motion at the forward perpendicular. To achieve this, it is necessary to oscillate flaps having a total area of 137 sq ft in hard-over to hard-over fashion. It would appear that complications involved in installing the flap system outweigh the gain made in terms of pitch reduction.

2. For a given set of test conditions (i.e., wave system and speed), the reduction in the average of the highest one-tenth pitch per unit wave height effected by automatically controlling the flaps is almost identical to the reduction of root-mean-square pitch per unit wave height. This is true because the pitch-quenching device performs more satisfactorily when the motions tend to be large and greater absolute reductions in pitch are achieved.

3. The reduction in pitch attained during these tests is generally not as great as that obtained by the Eastern Research Group[7*] during their regular wave tests. This is due to the fact that they used flaps which were much larger relative to the size of the ship (2.85 percent of the waterplane area as compared to 1.12 percent of the waterplane area in the present investigation).

4. Actuation of the flaps has only a small effect on heave.

5. For operation in seaways up to a State 6, the flap-actuating device must be capable of providing forces up to approximately ± 175 tons.

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[*] Cf. page 2.

6. The maximum moment about midships which the flaps can produce is approximately ± 35,000 ton-ft. The corresponding maximum load due to lift force transmitted to the hull at the pumpjet mounting point is ± 200 tons.

7. The difference in damping is negligible between the vessel with conventional propeller installed or pumpjet with no flaps installed.

8. Actuation of the flaps produces a large disturbance in the wake of the vessel which is undesirable from a ship quieting viewpoint.

RECOMMENDATION

The motion of the ship can be thought of as a superposition of wave-induced motion and flap-induced motion. Thus, the maximum pitch induced on a model traveling in calm water and excited at its resonant frequency by flaps moving in square-wave fashion is an upper limit of the pitch reduction which can be obtained in waves when utilizing an optimal control system. In practice, smaller reductions can be expected. In future studies then, it is recommended that only flap configurations capable of inducing in calm water motions comparable to the desired reductions be tested further in waves.

ACKNOWLEDGMENTS

The author wishes to thank Lt. Cmdr. H. Cox (USN) for his contributions to the design of the servomechanism which actuated the anti-pitch flaps and for optimizing the performance of this equipment during the tests. Thanks are also due to Messrs. P. M. Douglass Jr., S. E. Callanen, G. J. Norman, and H. E. Prucha for their outstanding work in expeditiously designing many of the electrical and mechanical devices used during these experiments.

The assistance of Messrs. S. R. Brovey, G. Rossignol, J. Kallio, and E. Wagley in reading and reducing the voluminous amount of data is gratefully acknowledged.

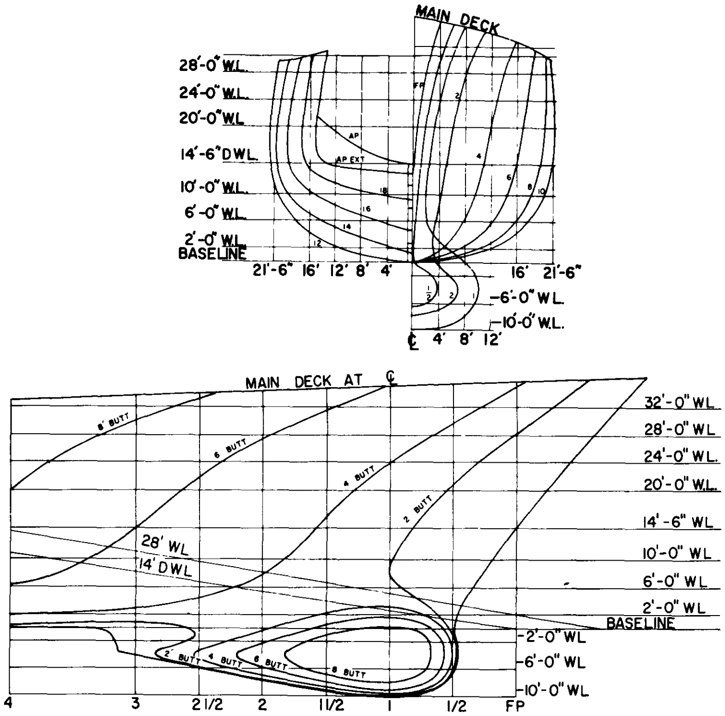

Figure 1 - Abbreviated Lines of the AGDE-1

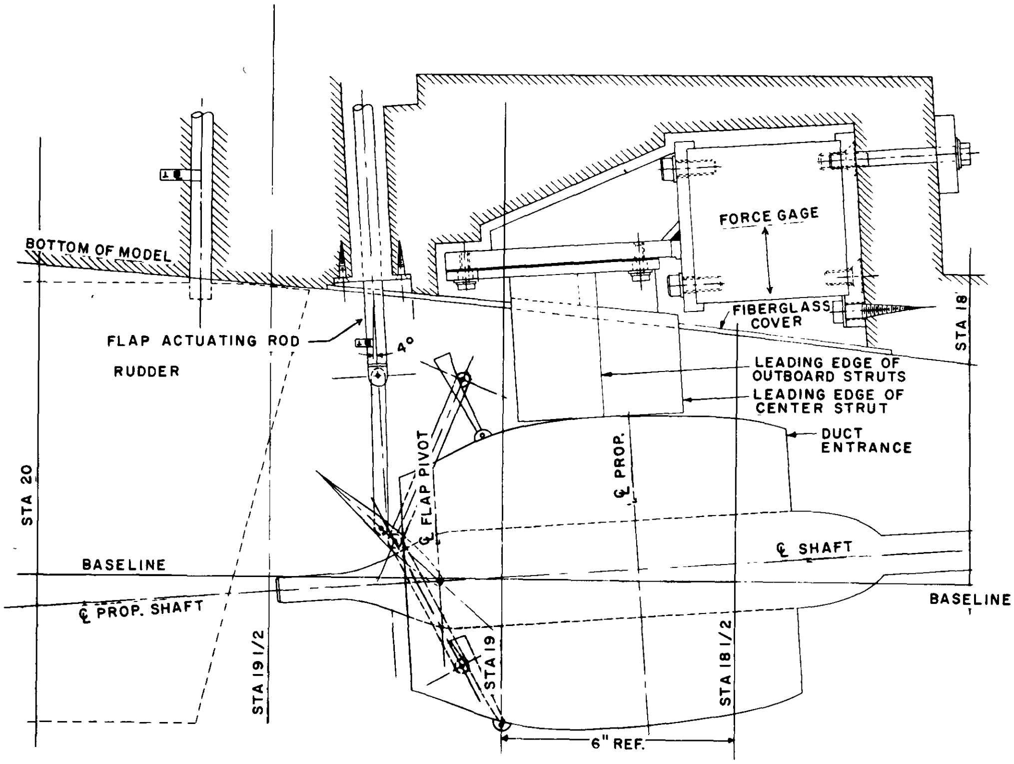

Figure 2 - Assembly of Pumpjet on Model

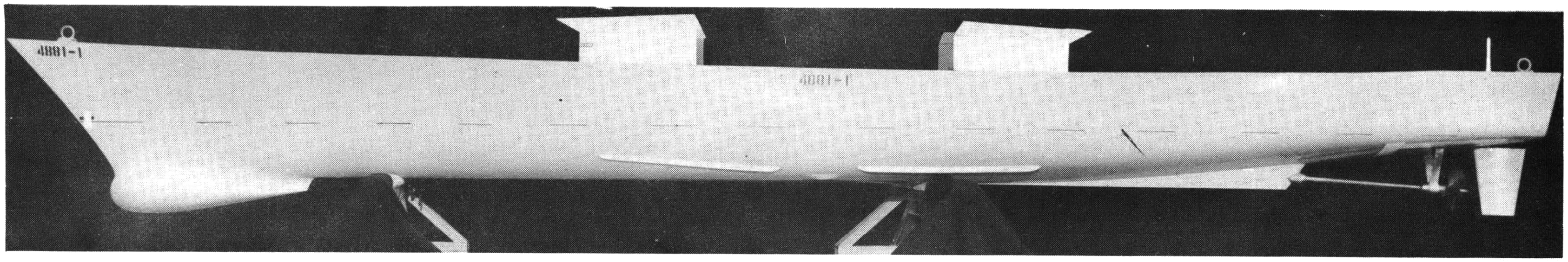

Figure 3 - Model with Conventional Propeller Installed

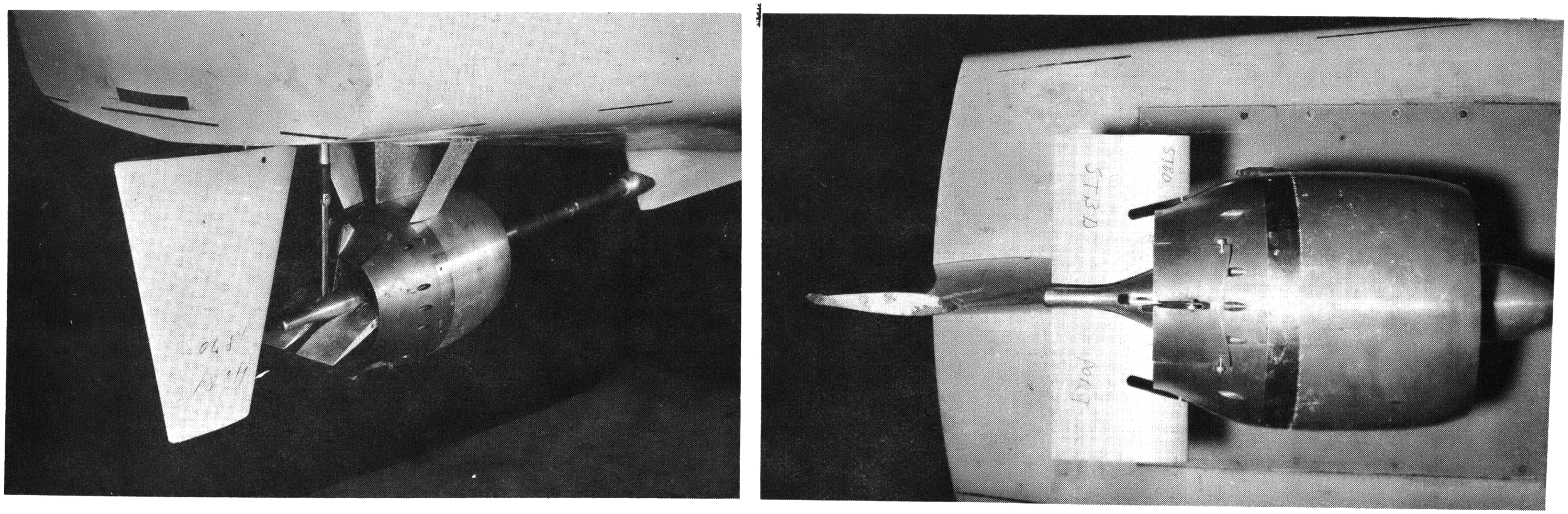

Figure 4 - Model with Flapped Pumpjet Installed

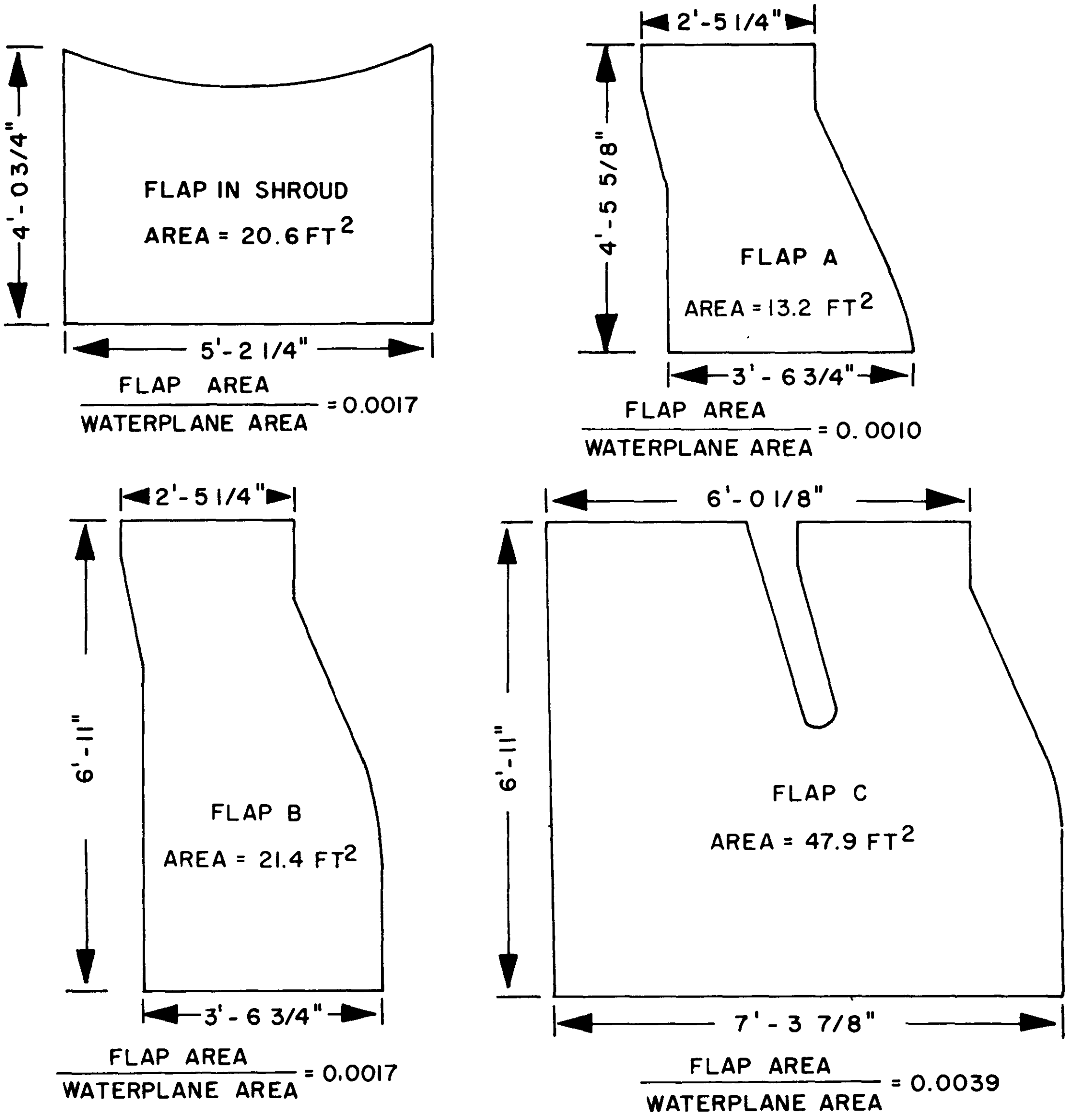

Figure 5 - Plan Views of Flaps A, B, C and Flaps in Shroud

Note: Flaps A, B, and C are Port Flaps

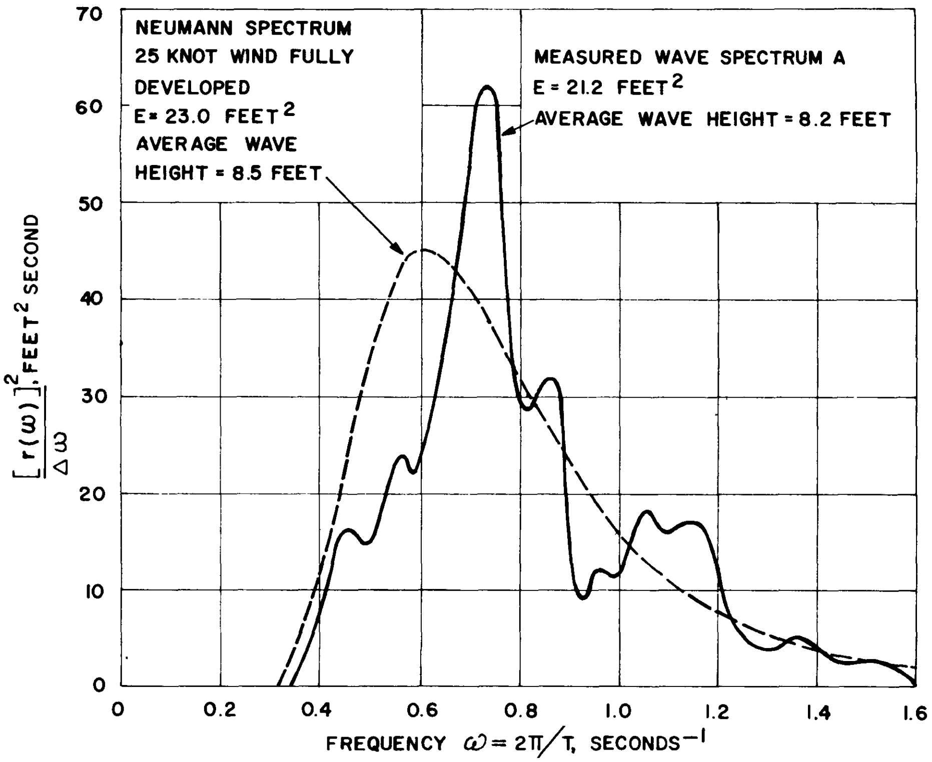

Figure 6a - Ship Speed of 0 Knots

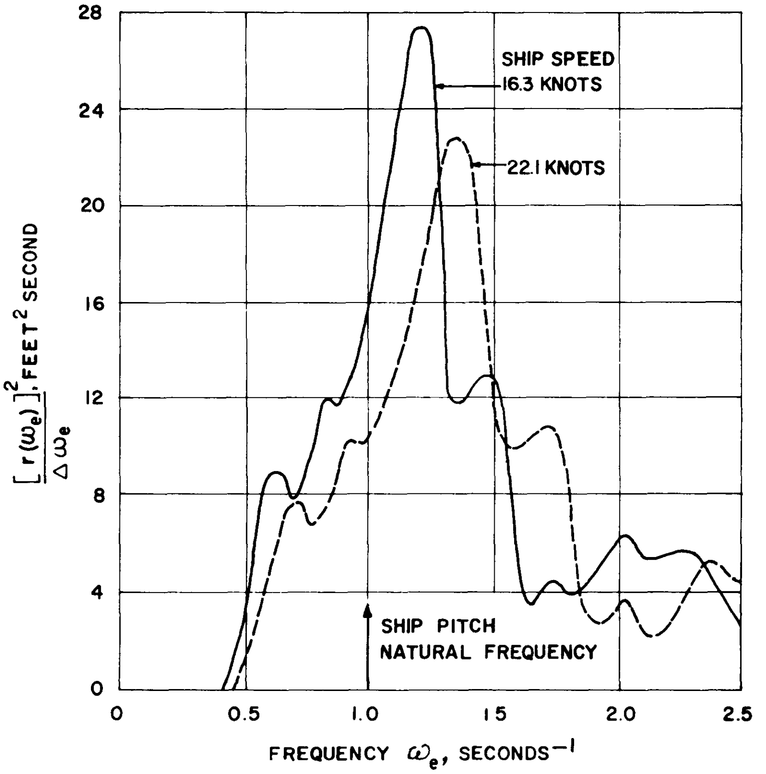

Figure 6b - Ship Speeds of 16.3 and 22.1 Knots

Figure 6 - Wave Spectrum A for Tests with Conventional Propeller (Phase 1)

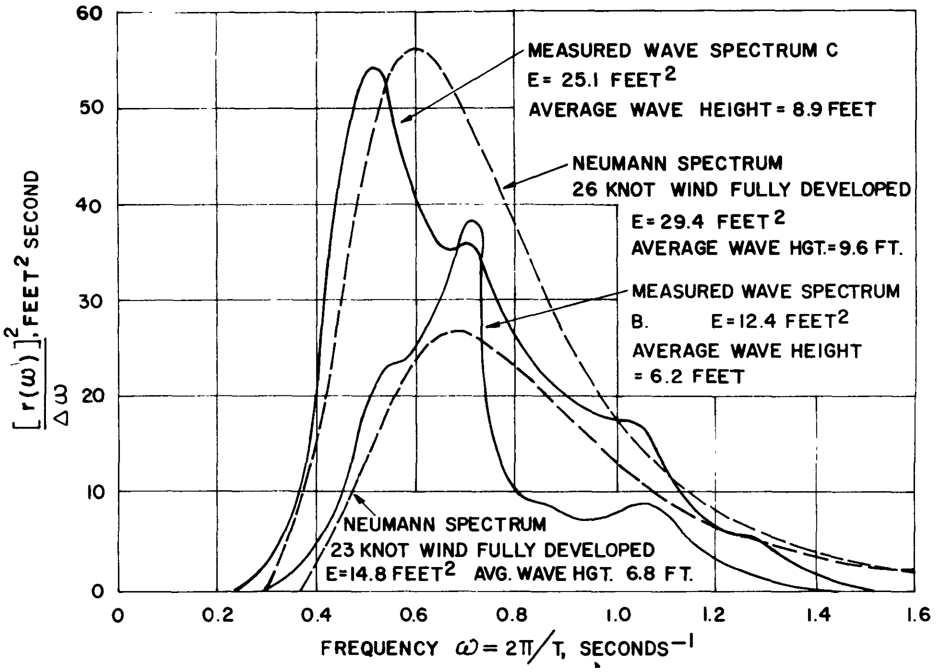

Figure 7a - Ship Speed of 0 Knots

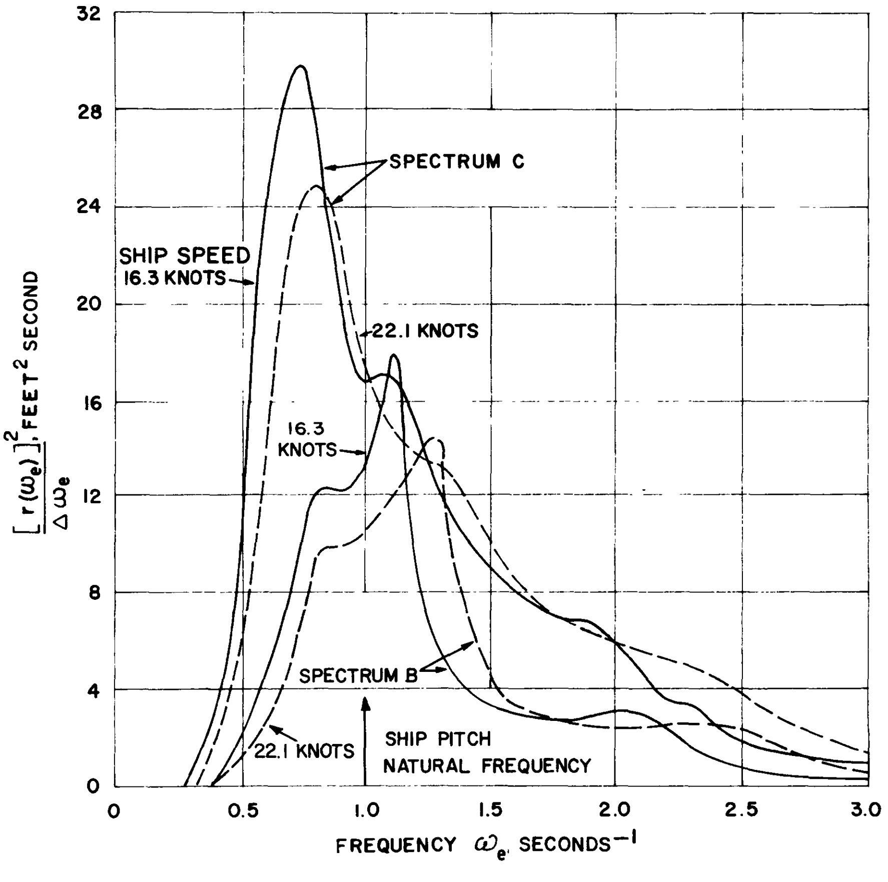

Figure 7b - Ship Speeds of 16.3 and 22.1 Knots

Figure 7 - Wave Spectra B and C for Phase 3 and Phase 4 Tests

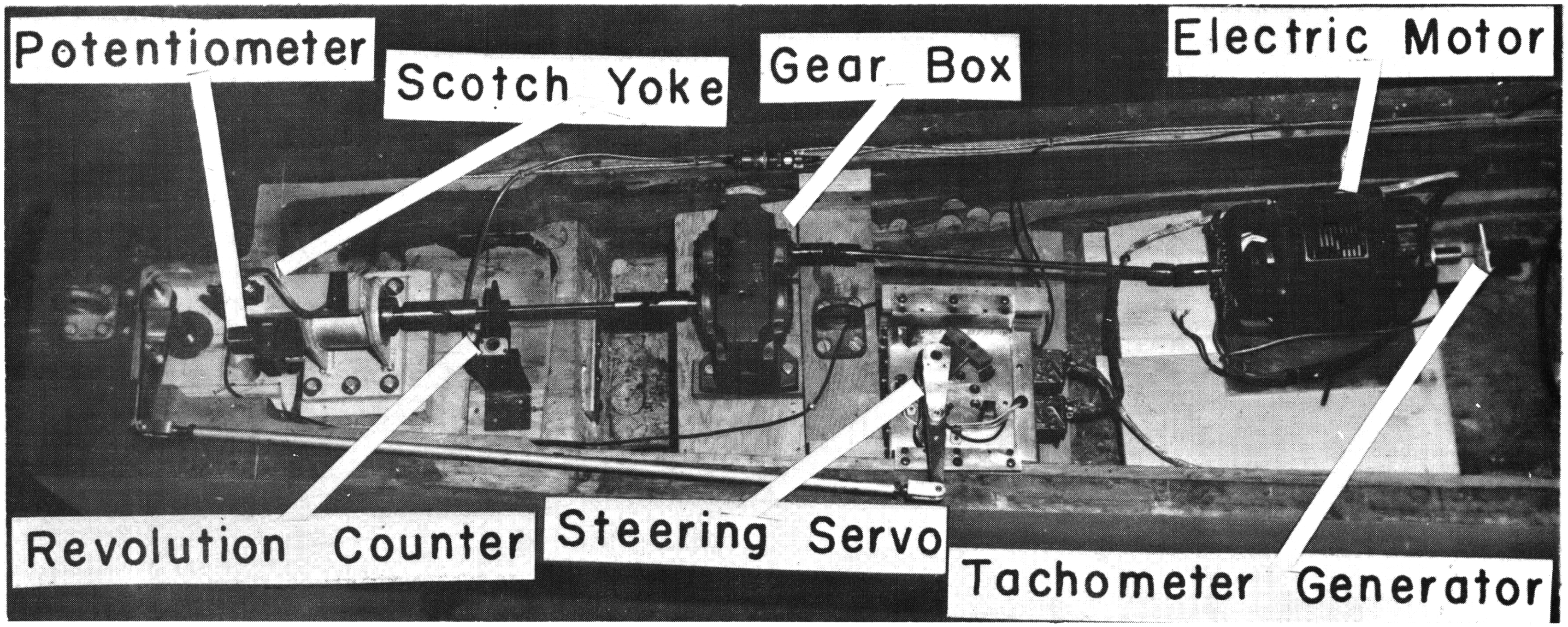

Figure 8 - Installation of Equipment for Phase 2 Tests

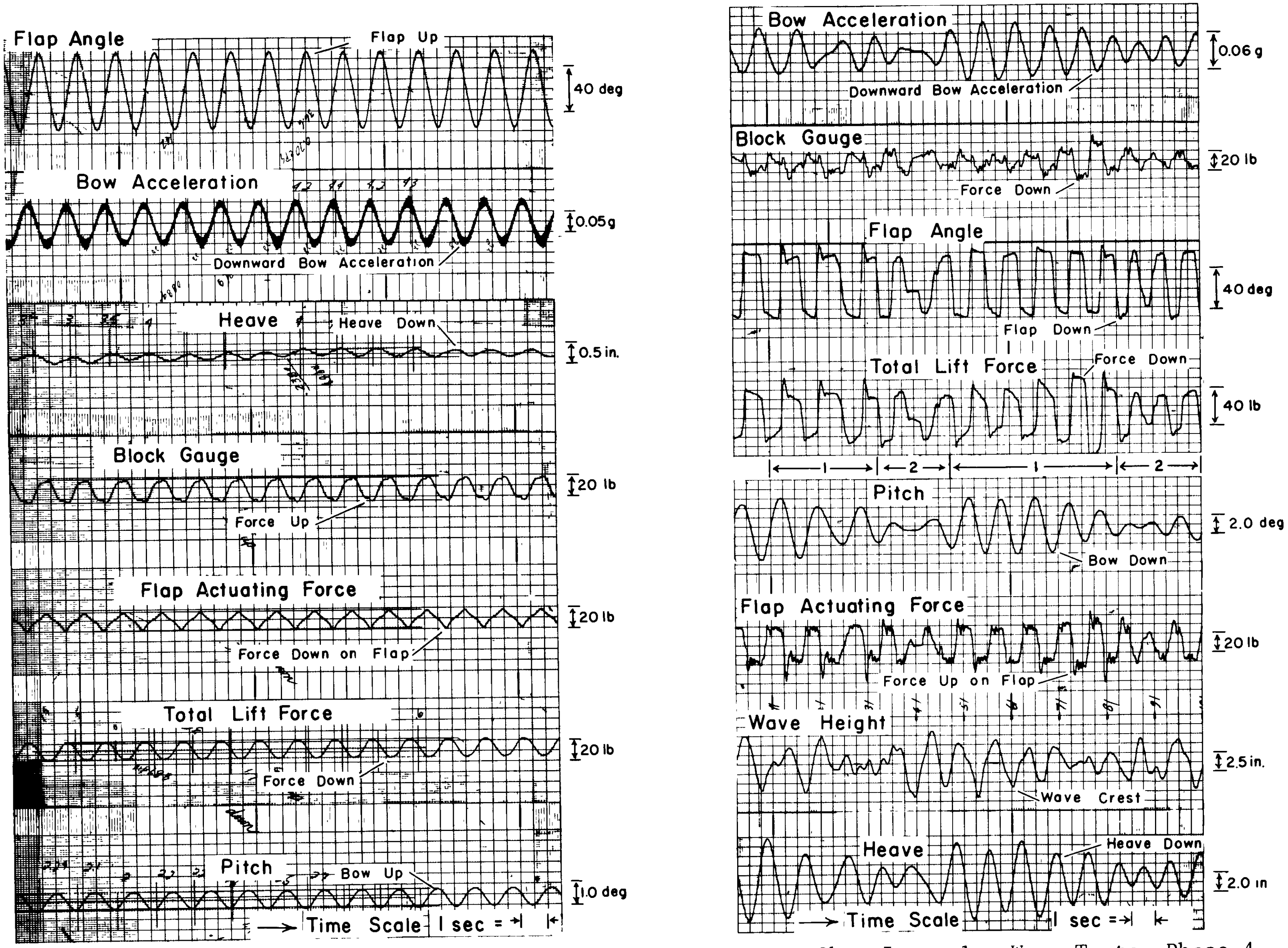

Figure 9a - Induced-Motion Tests, Phase 2

Figure 9b - Irregular Wave Tests, Phase 4

Figure 9 - Sample Sanborn Records

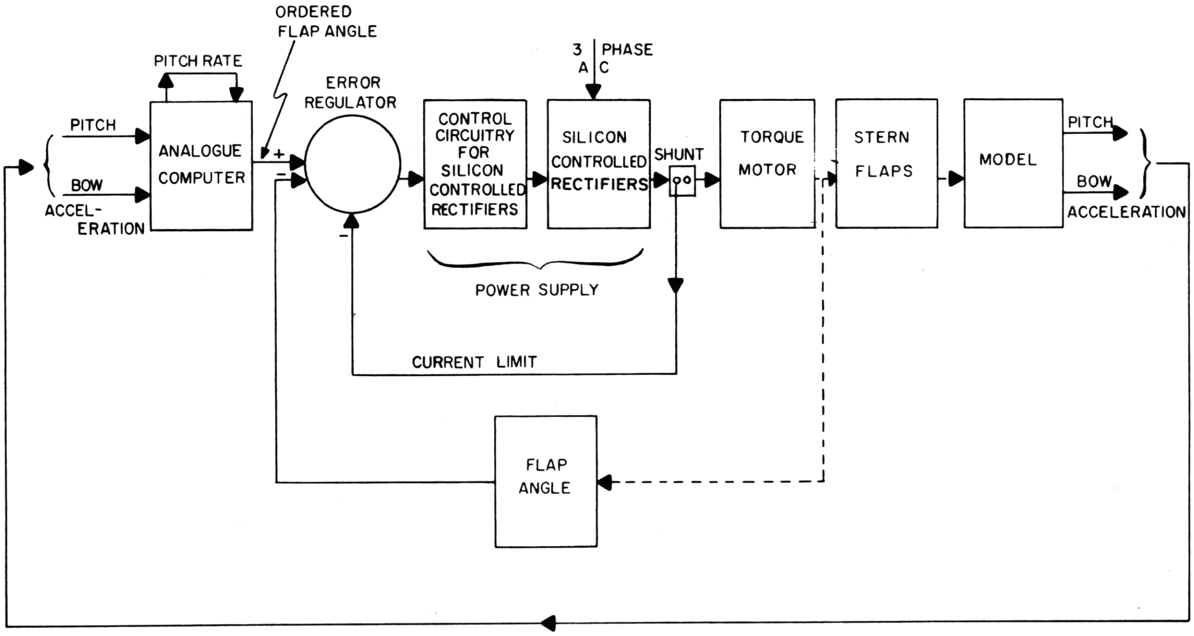

Figure 10 - Flap Control System

Note: Broken Lines Designate
Mechanical Connections

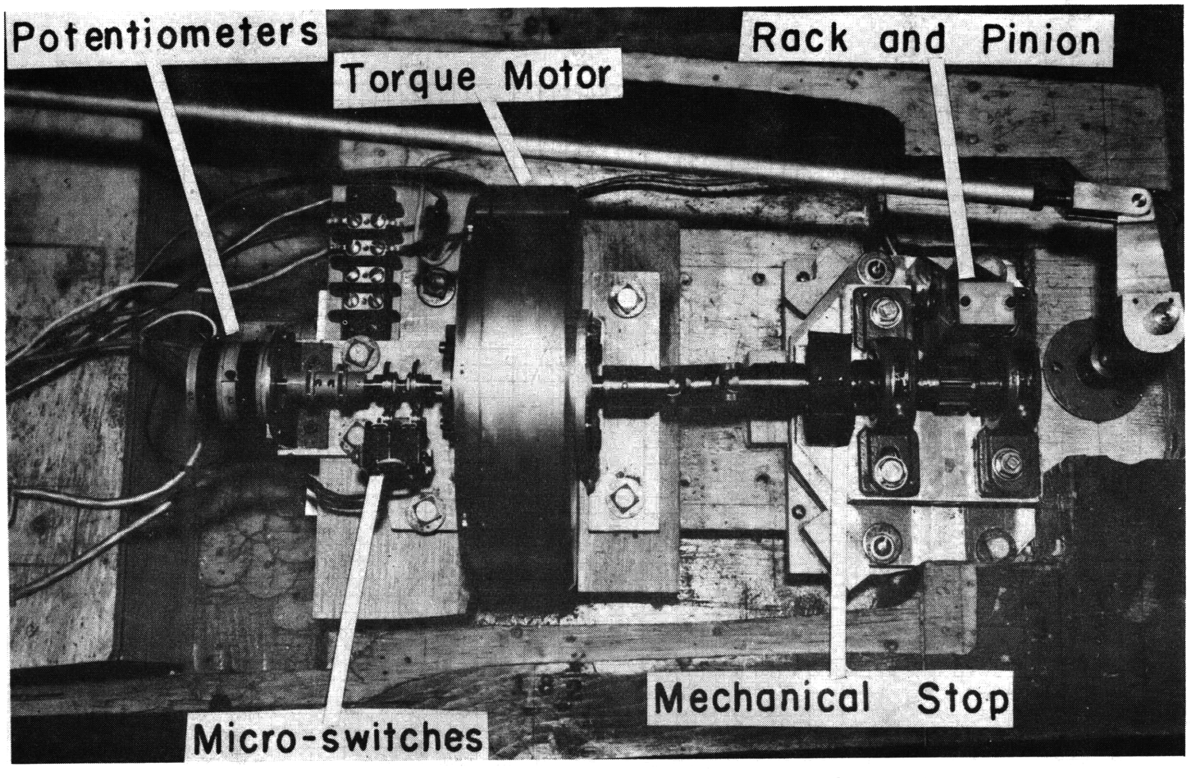

Figure 11 - Installation of Equipment for Phase 4 Tests

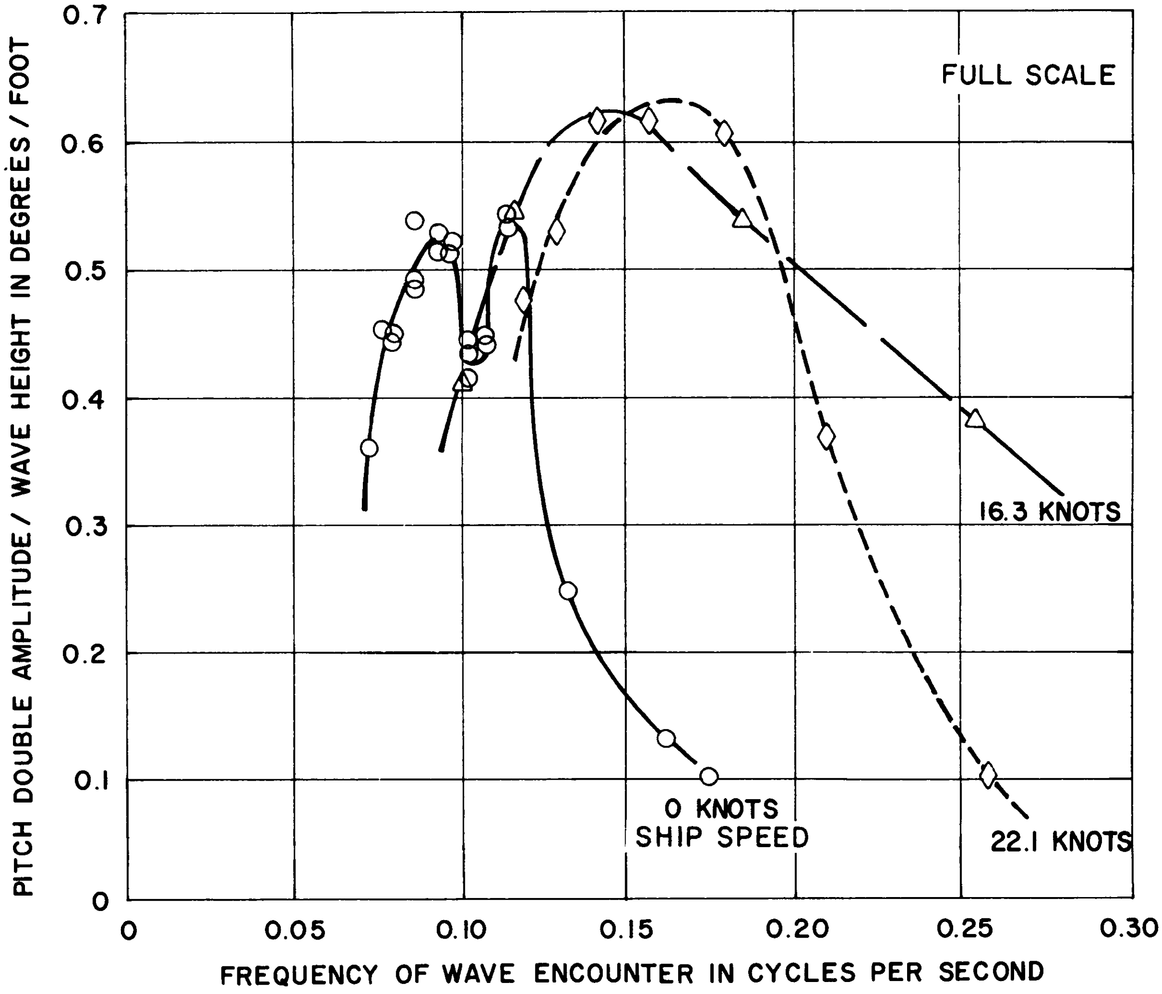

Figure 12 - Pitch Response in Regular Waves with Conventional Propeller Installed

Figure 13 - Induced Pitch in Calm Water as a Function of Frequency of Flap Oscillation

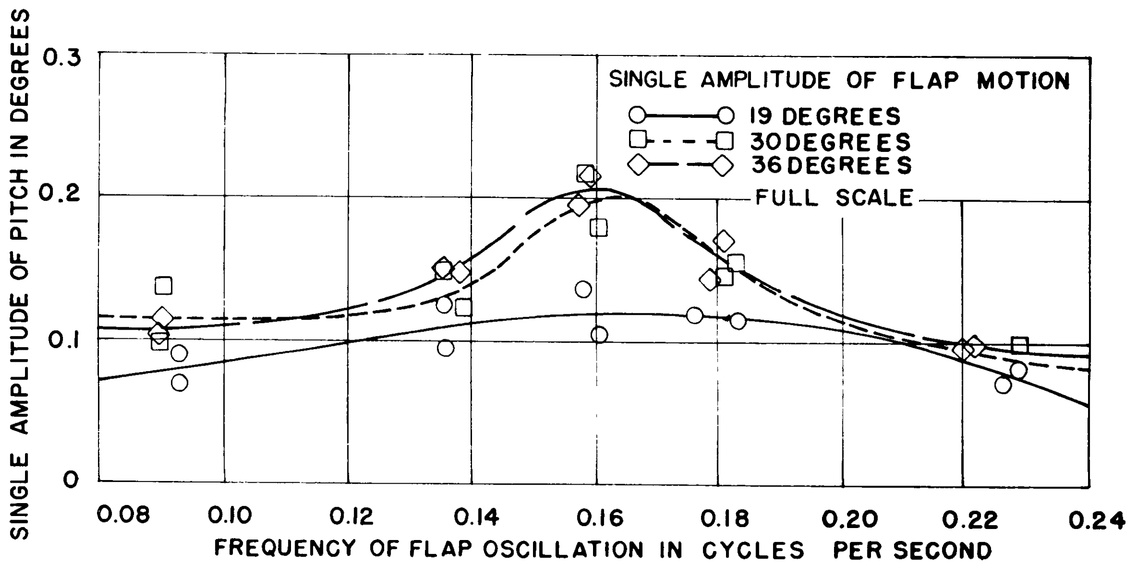

Figure 13a - Flaps in Shroud only, Ship Speed 16.3 Knots

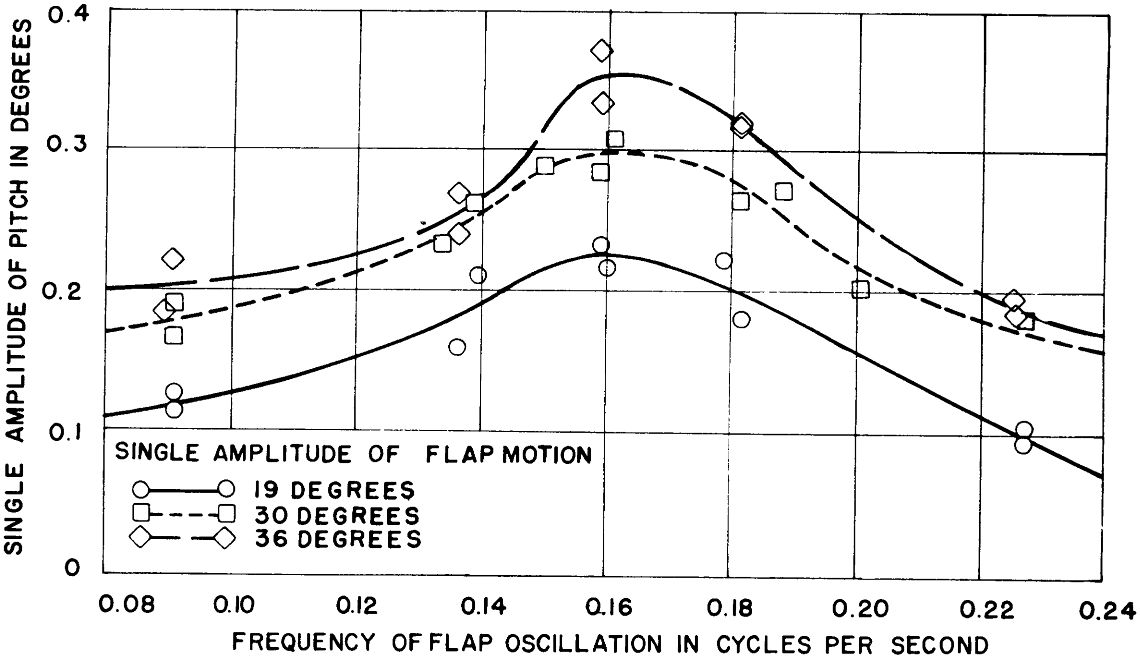

Figure 13b - Flaps in Shroud only, Ship Speed 22.1 Knots

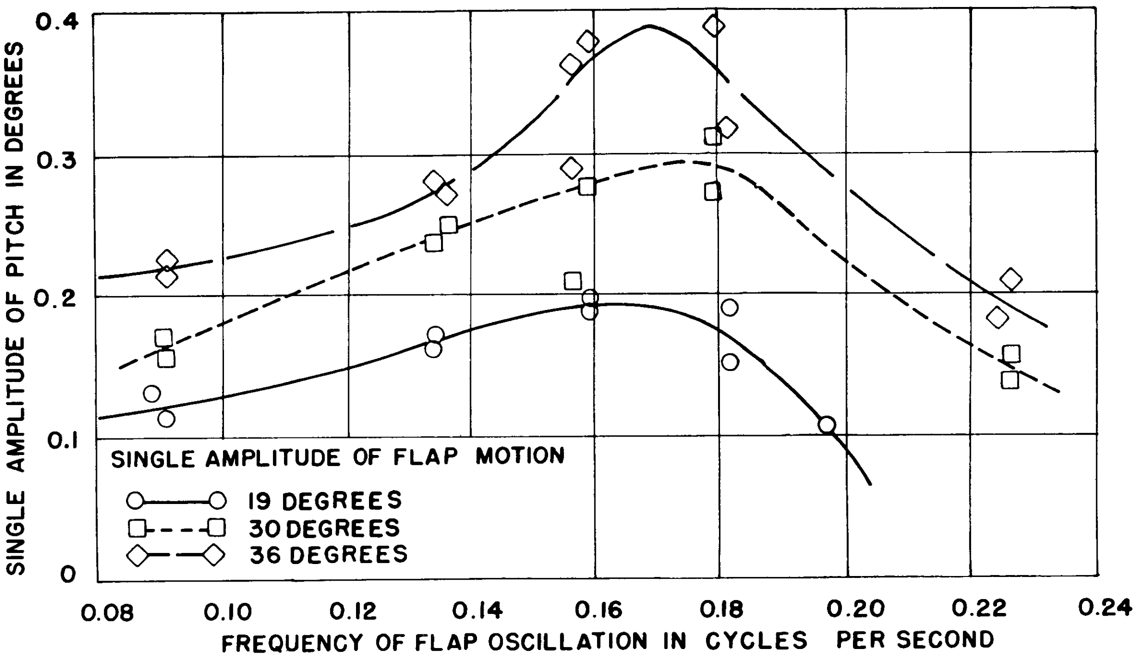

Figure 13c - Flap Configuration A Plus Flaps in Shroud,
Ship Speed 16.3 Knots

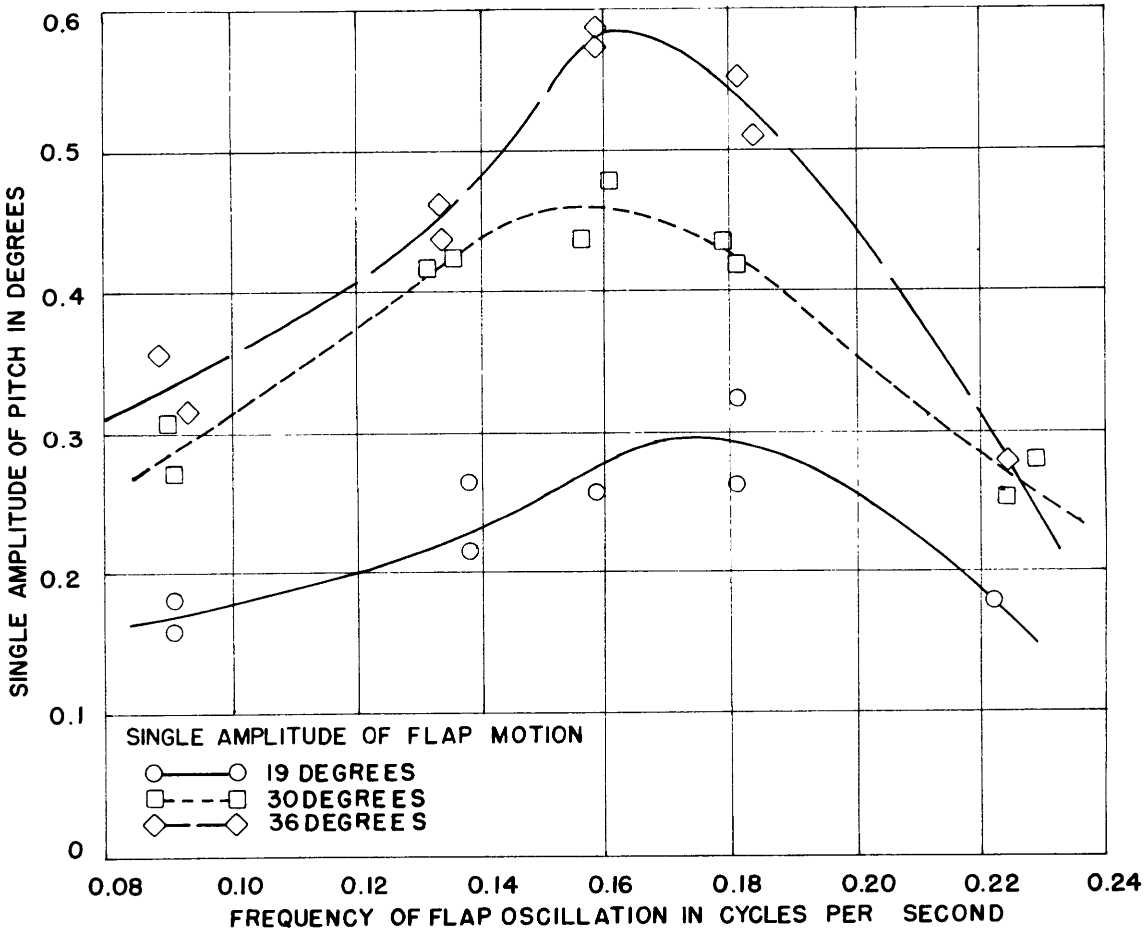

Figure 13d - Flap Configuration A Plus Flaps in Shroud,
Ship Speed 22.1 Knots

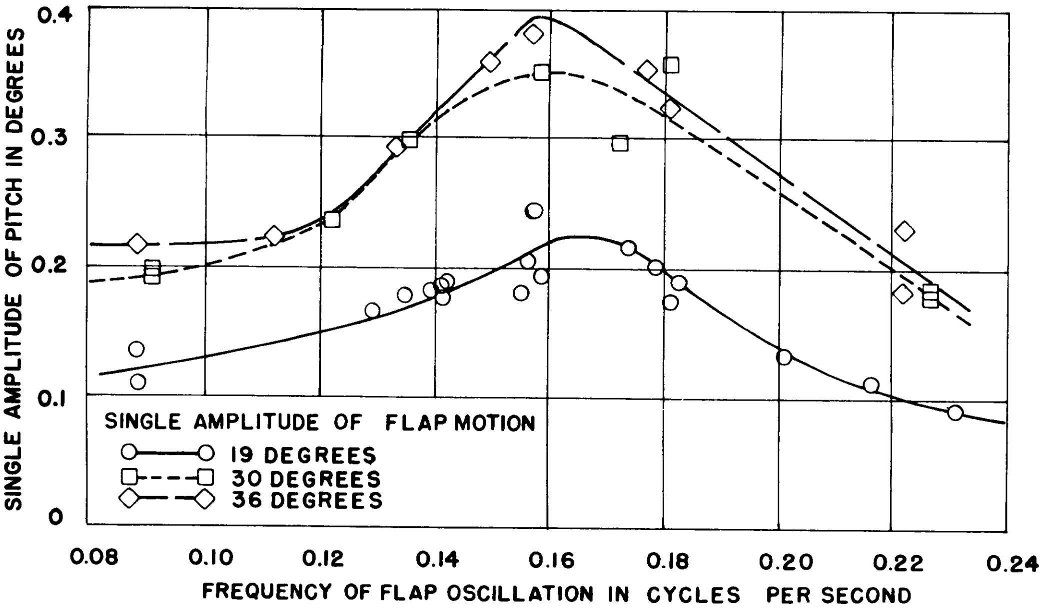

Figure 13e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

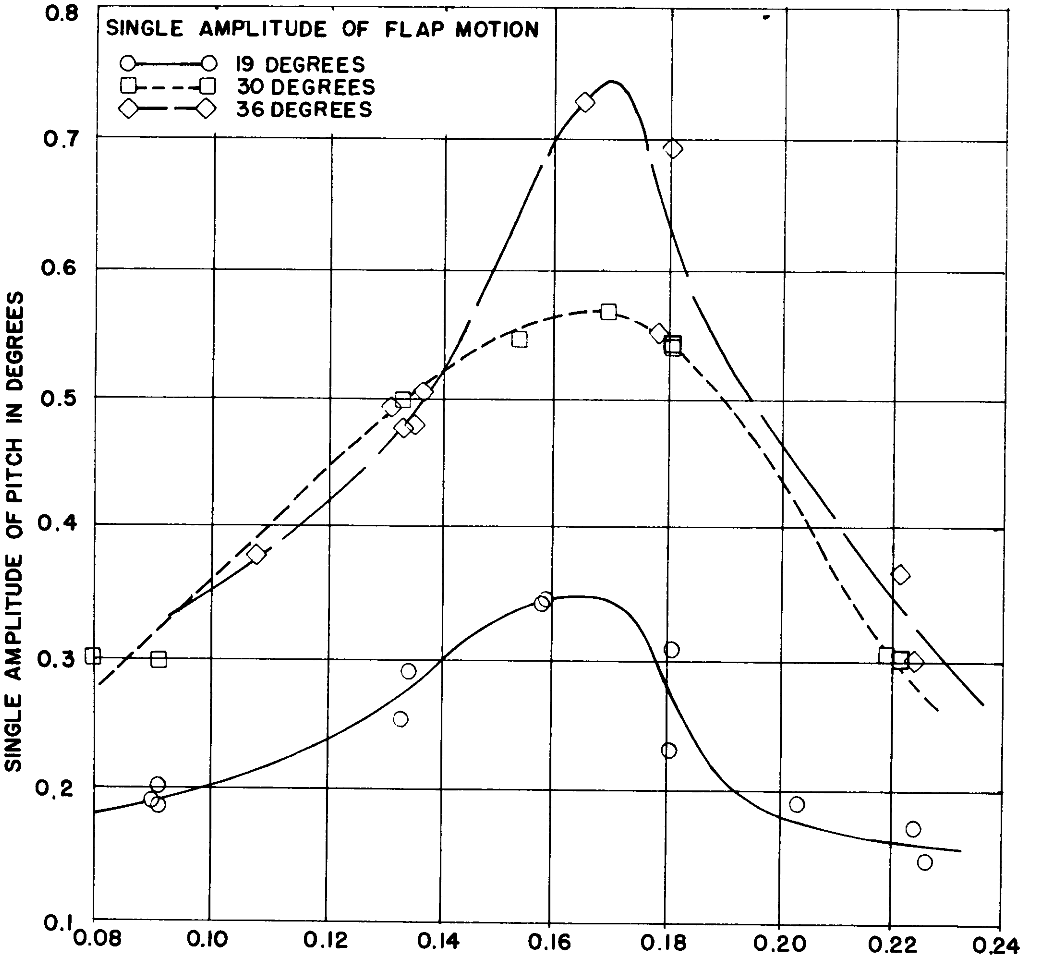

Figure 13f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

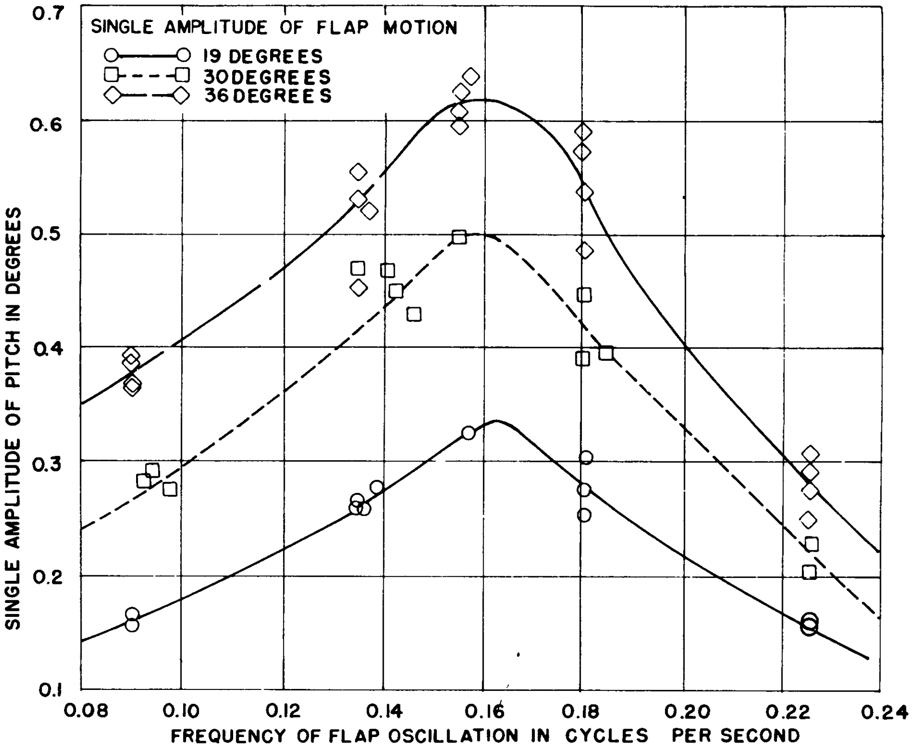

Figure 13g - Flap Configuration C Plus Flaps in Shroud, Ship Speed 16.3 Knots

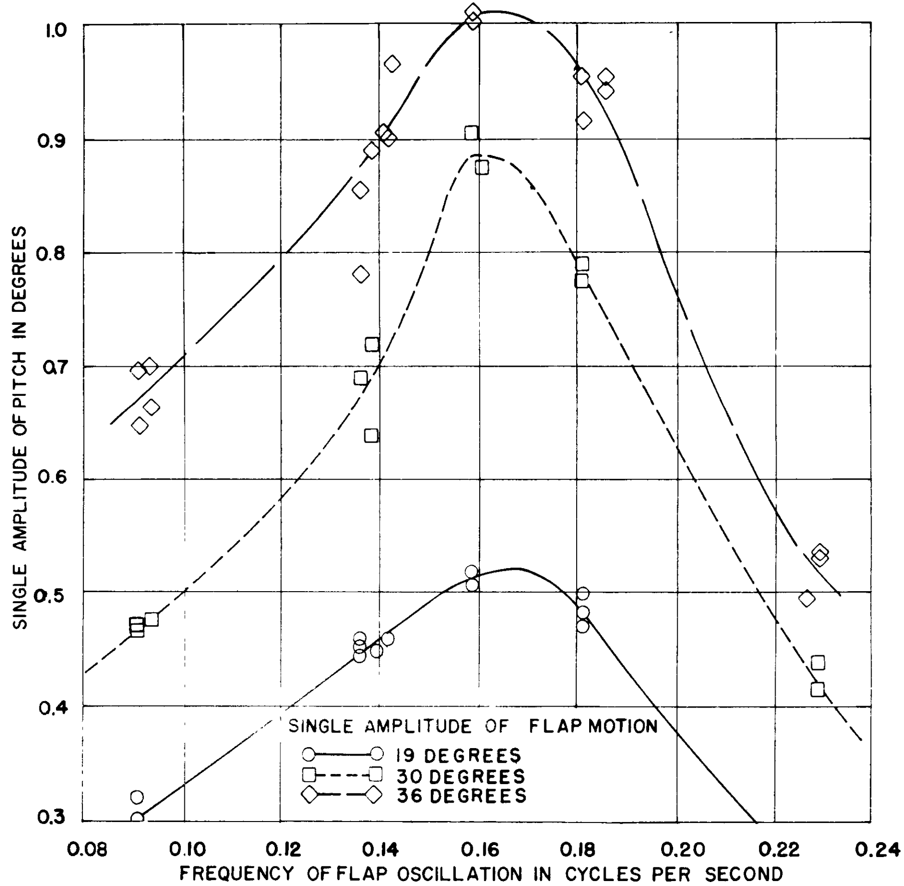

Figure 13h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

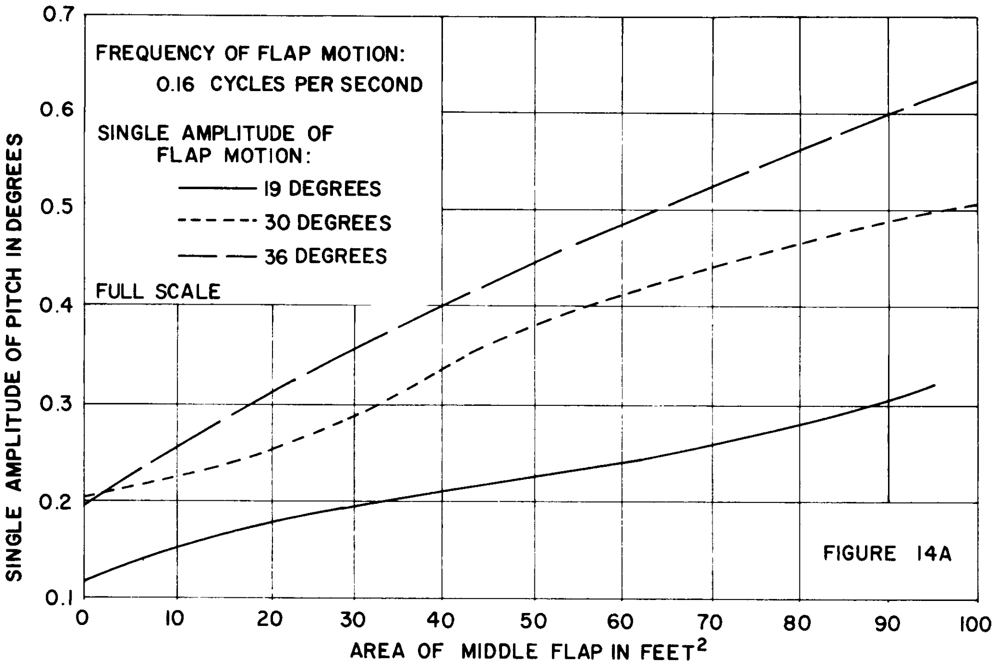

Figure 14a - Ship Speed 16.3 Knots

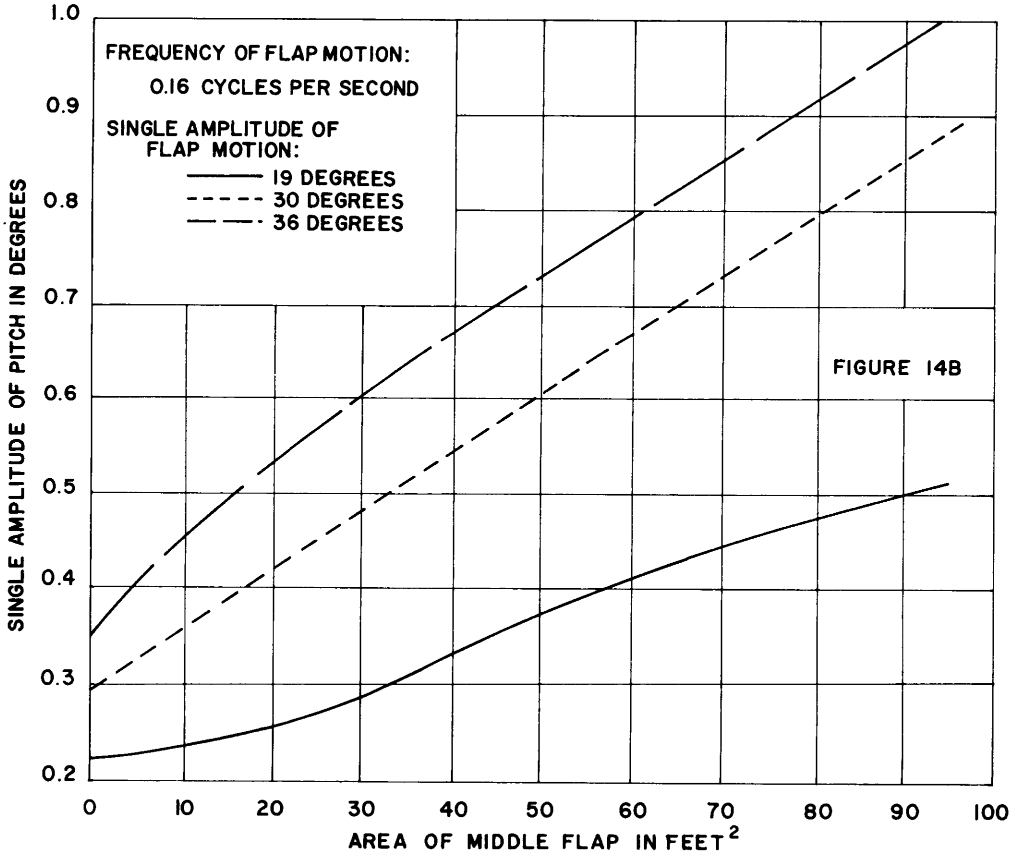

Figure 14b - Ship Speed 22.1 Knots

Figure 14 - Induced Pitch in Calm Water as a Function of Middle Flap Area

Figure 15 - Actuating Force for Sinusoidal Flap Oscillation in Calm Water

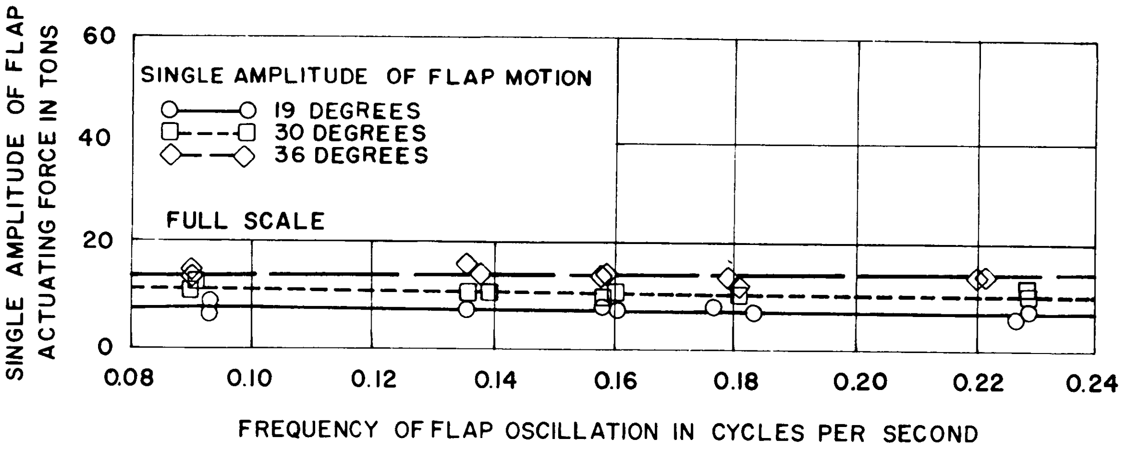

Figure 15a - Flaps in Shroud only, Ship Speed 16.3 Knots

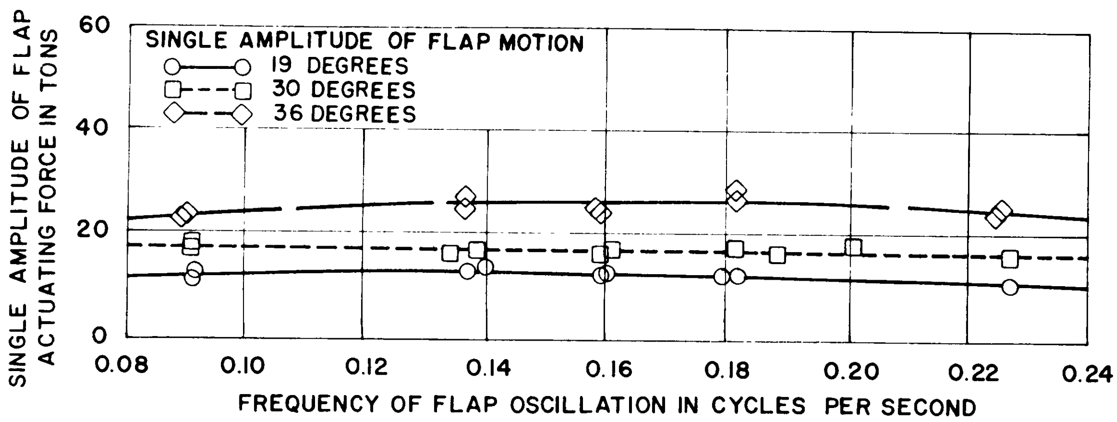

Figure 15b - Flaps in Shroud only, Ship Speed 22.1 Knots

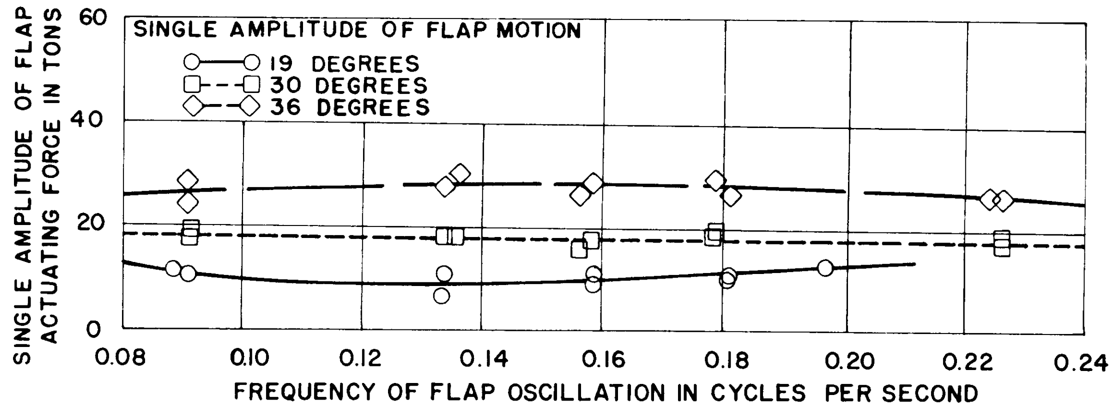

Figure 15c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

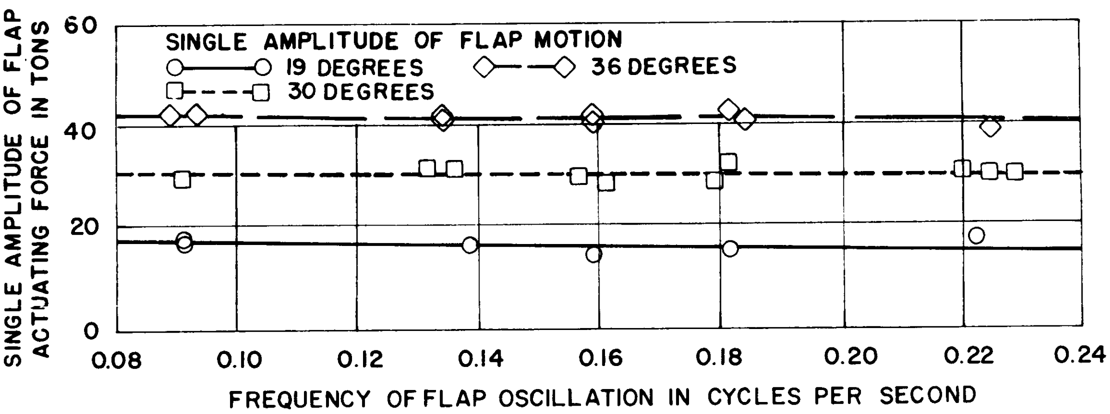

Figure 15d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

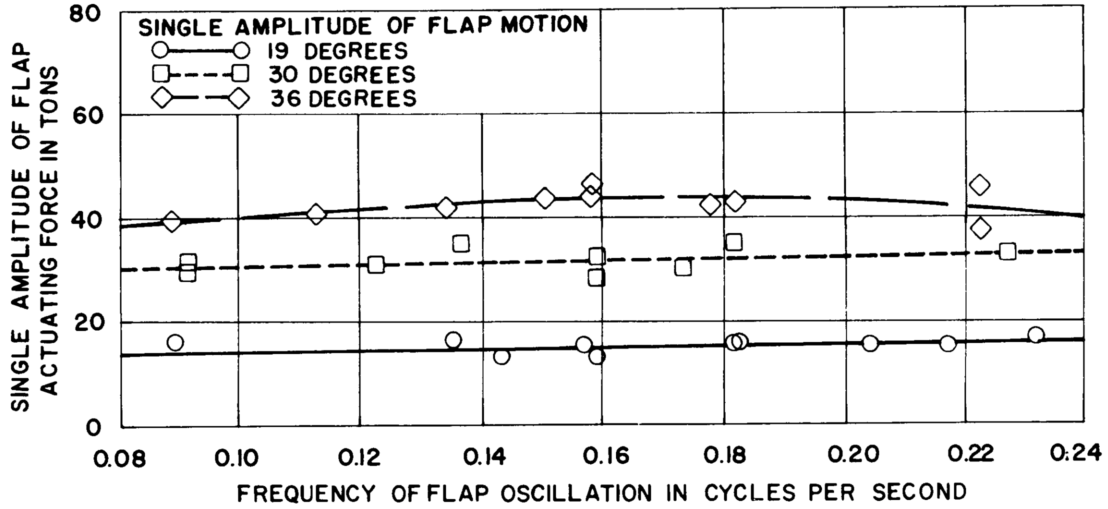

Figure 15e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

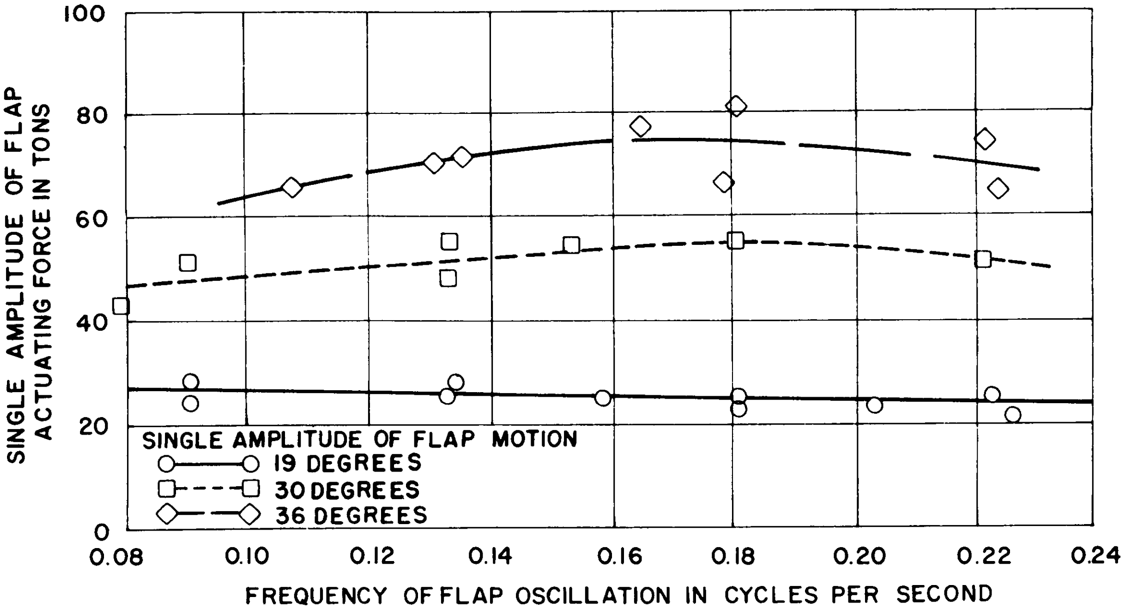

Figure 15f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

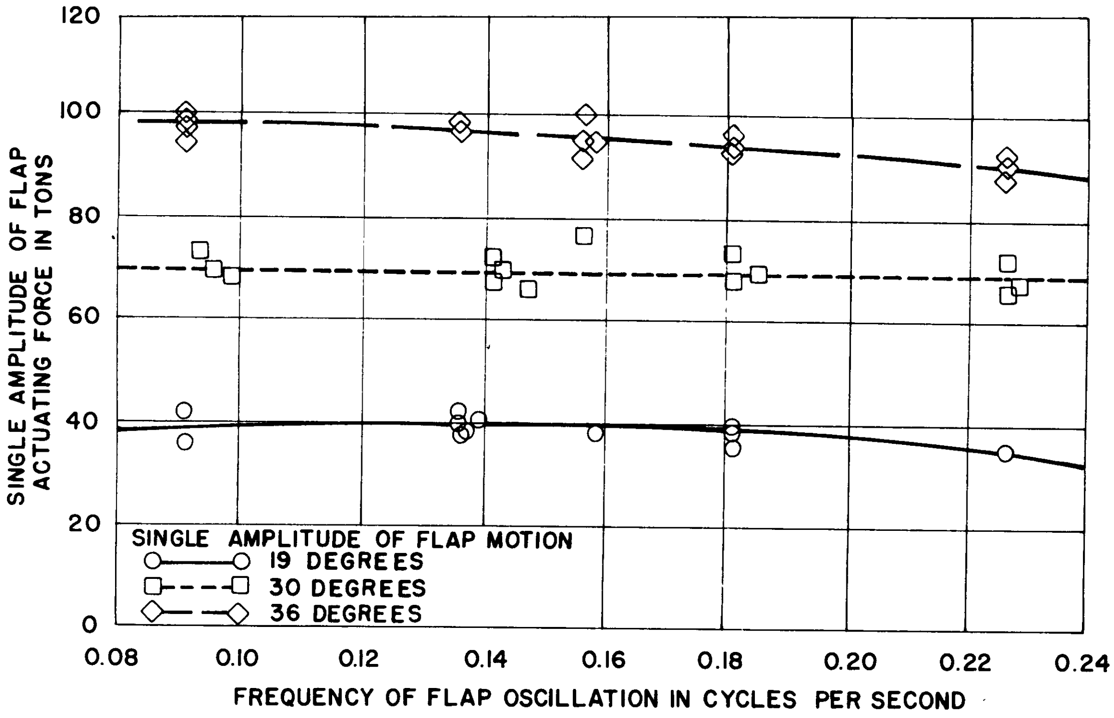

Figure 15g - Flap Configuration C Plus Flaps in Shroud, Ship Speed 16.3 Knots

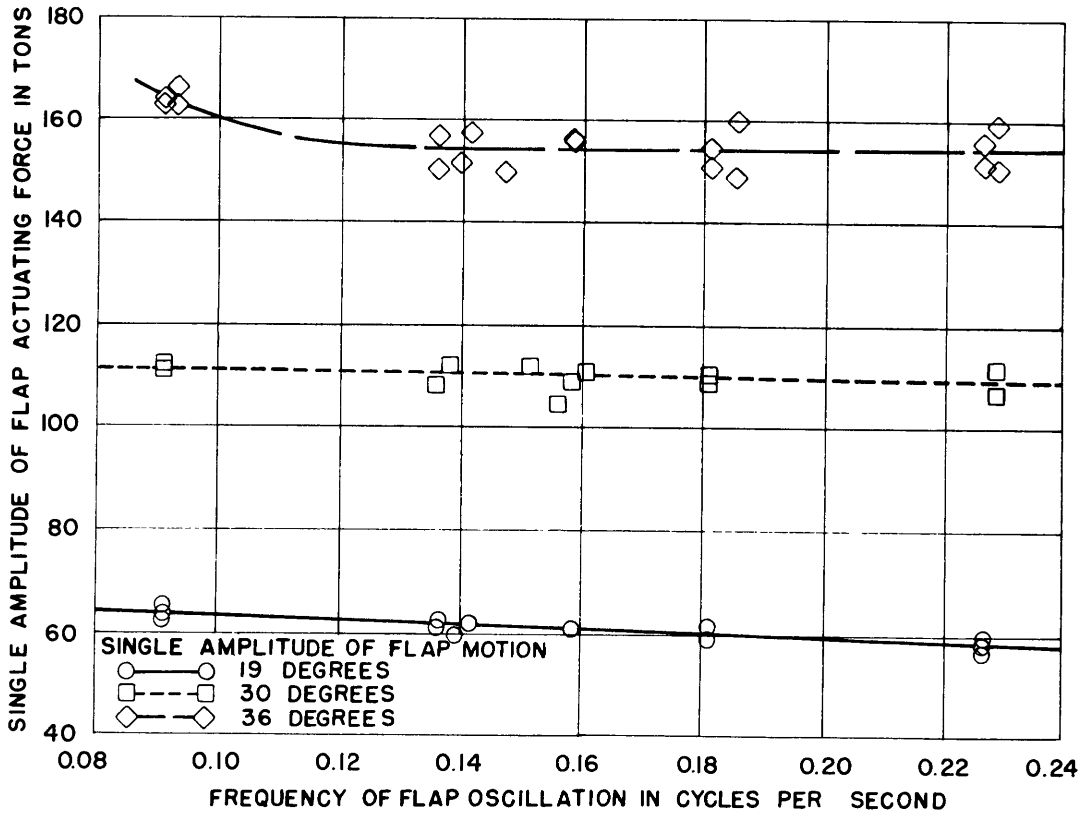

Figure 15h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

Figure 16 - Lift Force Produced during Sinusoidal Flap Oscillation in Calm Water

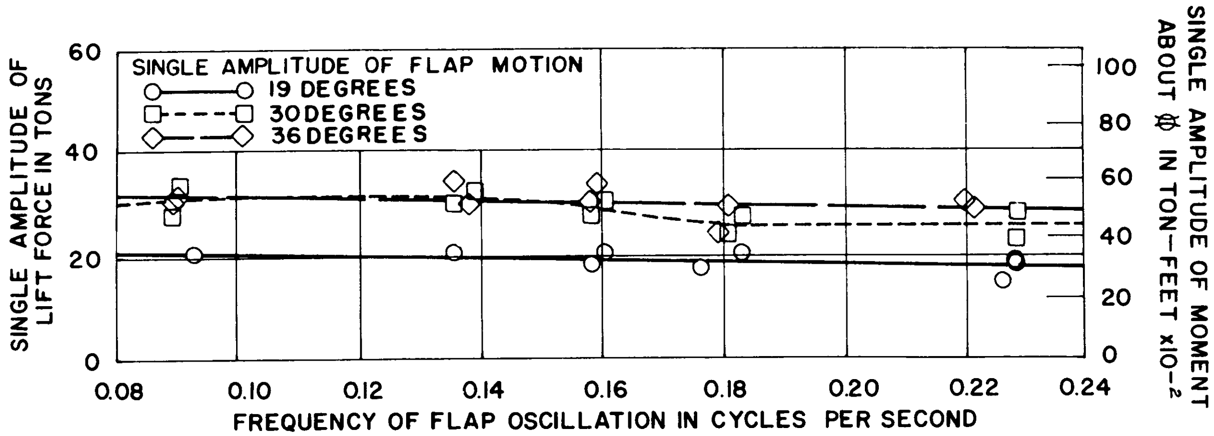

Figure 16a - Flaps in Shroud only, Ship Speed 16.3 Knots

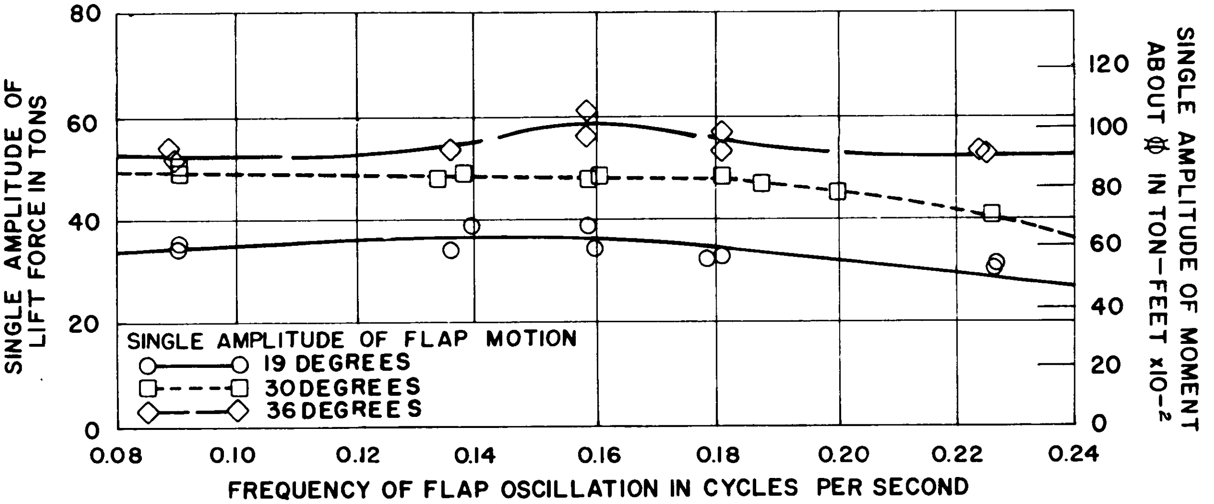

Figure 16b - Flaps in Shroud only, Ship Speed 22.1 Knots

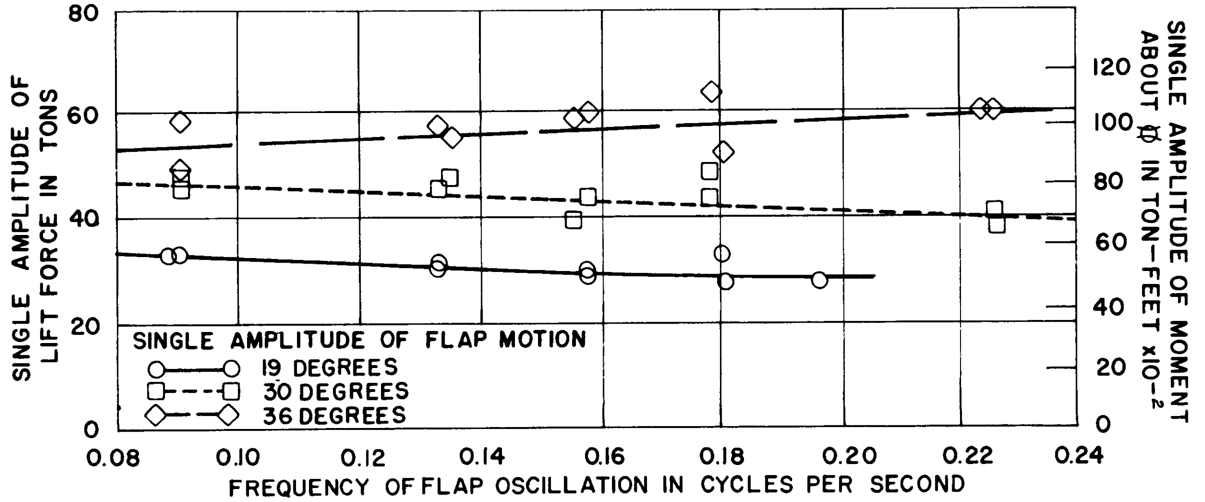

Figure 16c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

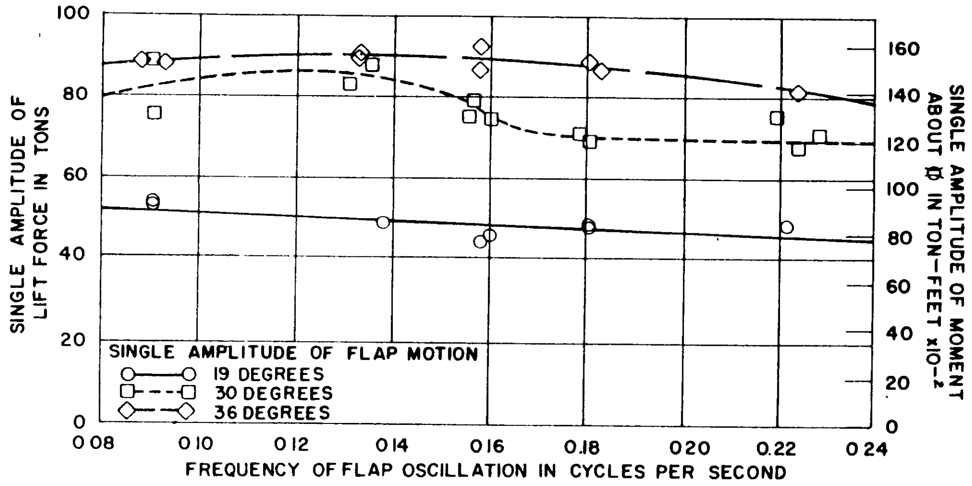

Figure 16d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

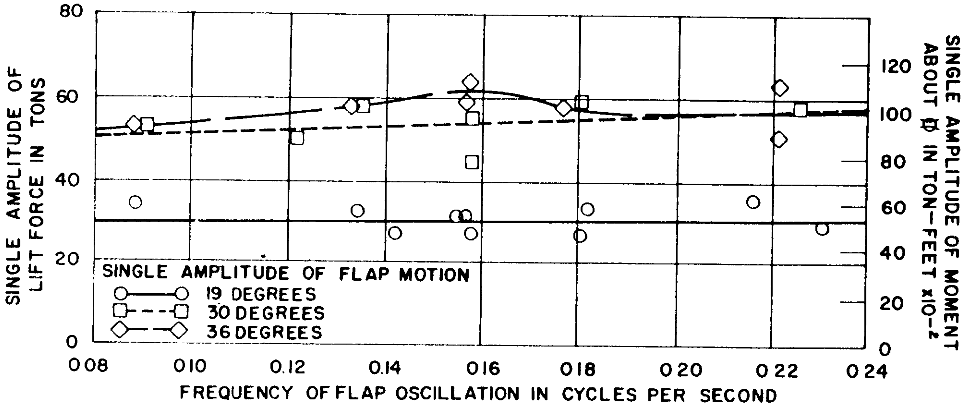

Figure 16e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

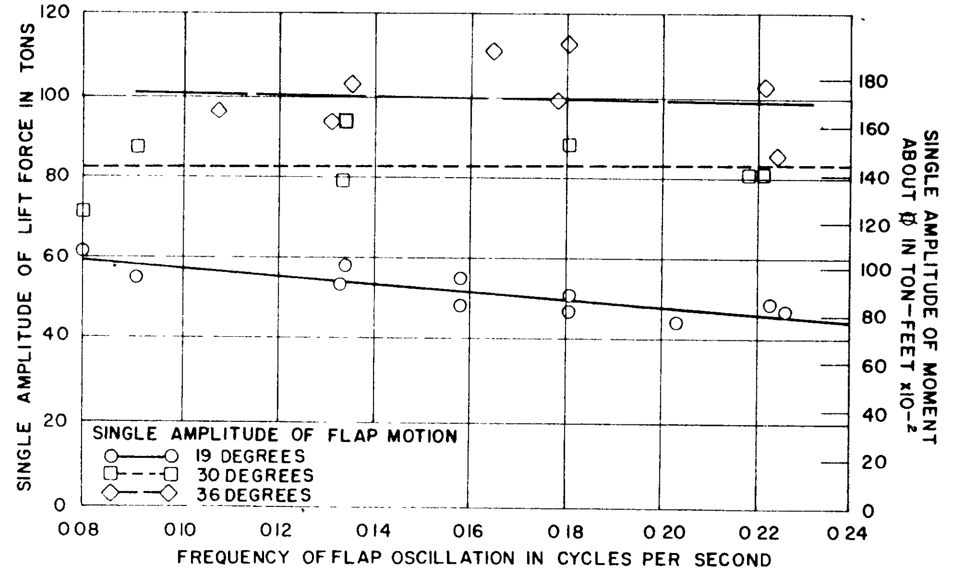

Figure 16f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

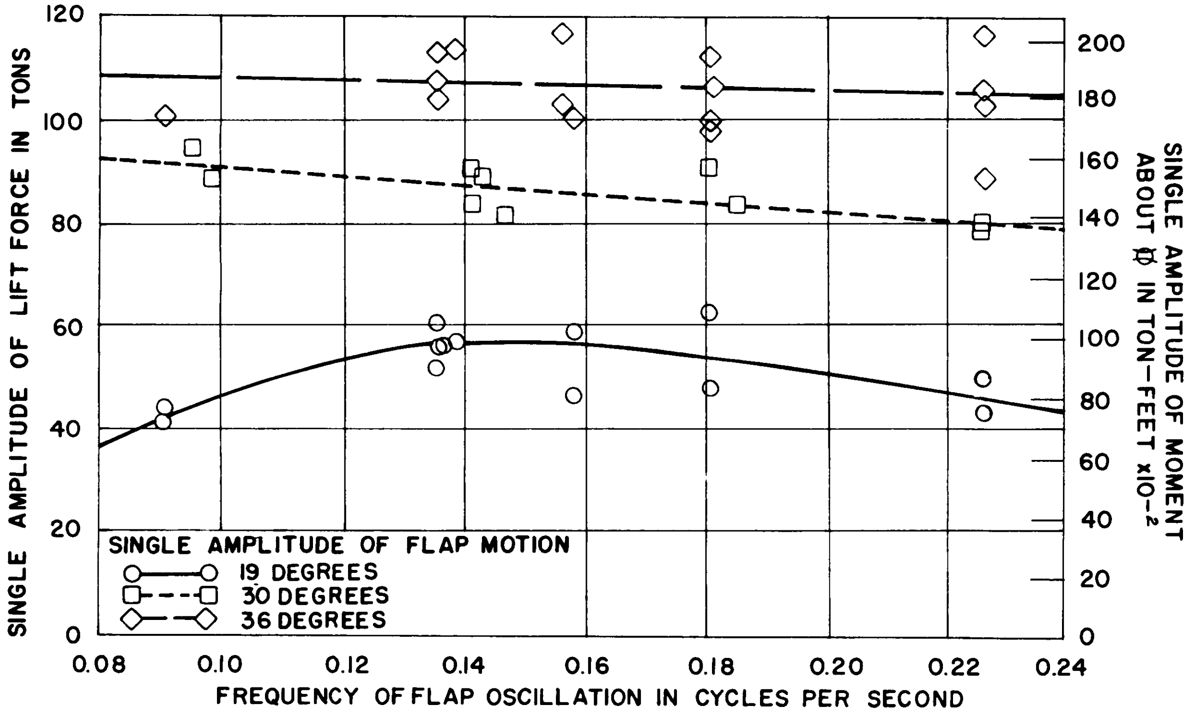

Figure 16g - Flap Configuration C Plus Flaps in Shrouds, Ship Speed 16.3 Knots

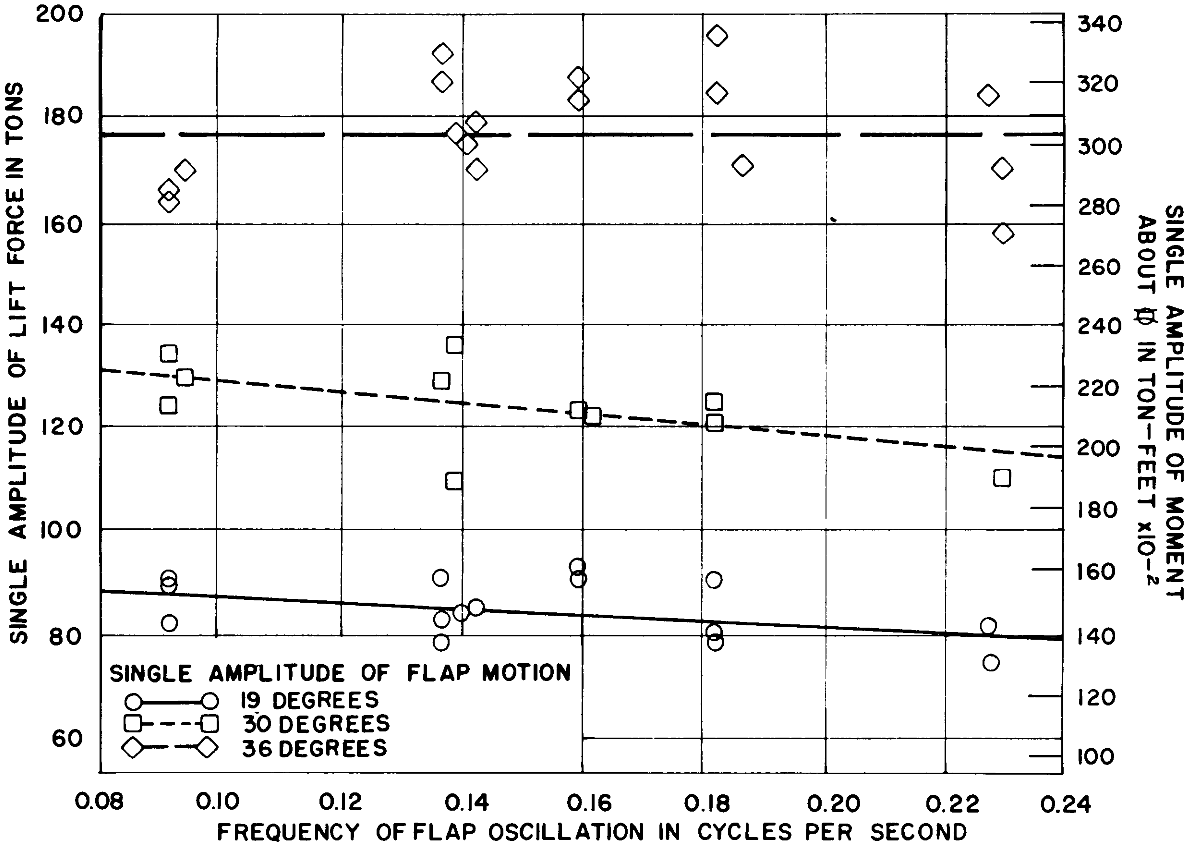

Figure 16h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

Figure 17 - Bow Acceleration Induced in Calm Water as a Function of Frequency of Flap Oscillation

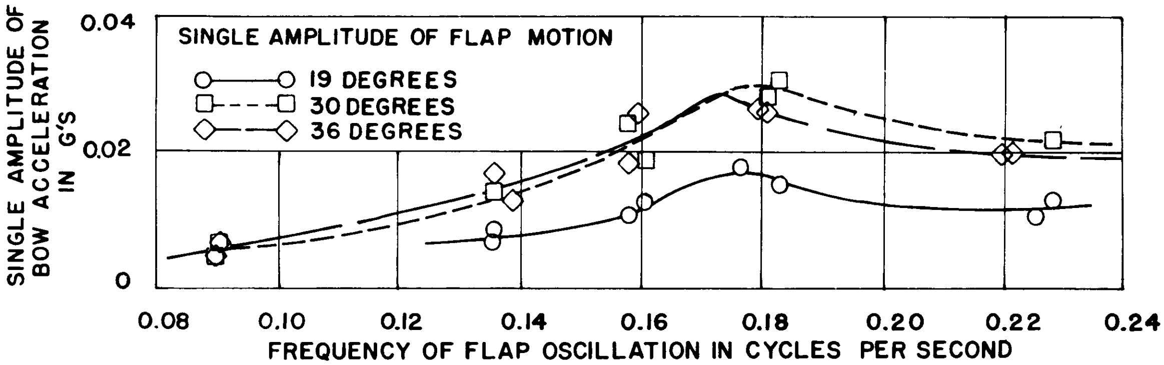

Figure 17a - Flaps in Shroud Only, Ship Speed 16.3 Knots

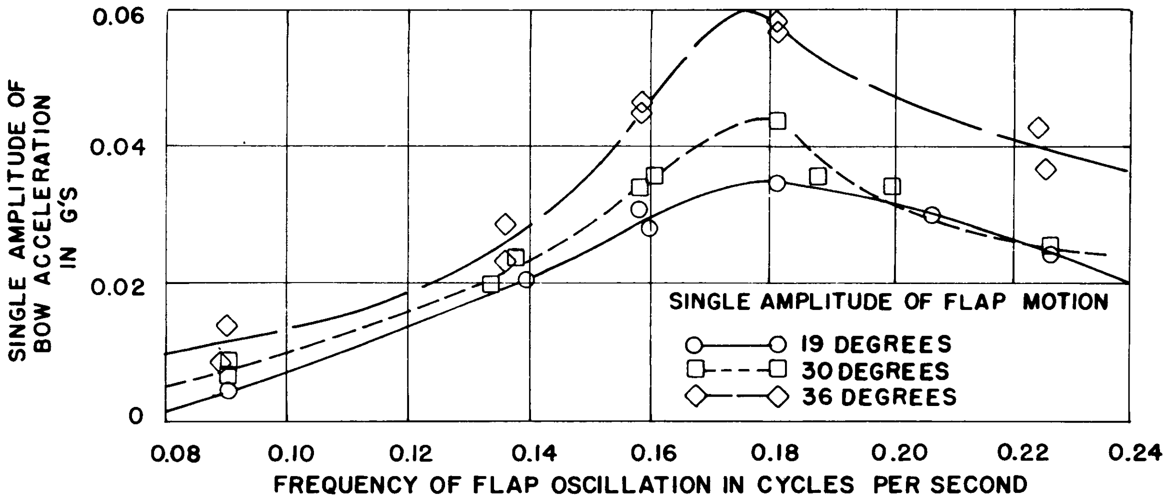

Figure 17b - Flaps in Shroud only, Ship Speed 22.1 Knots

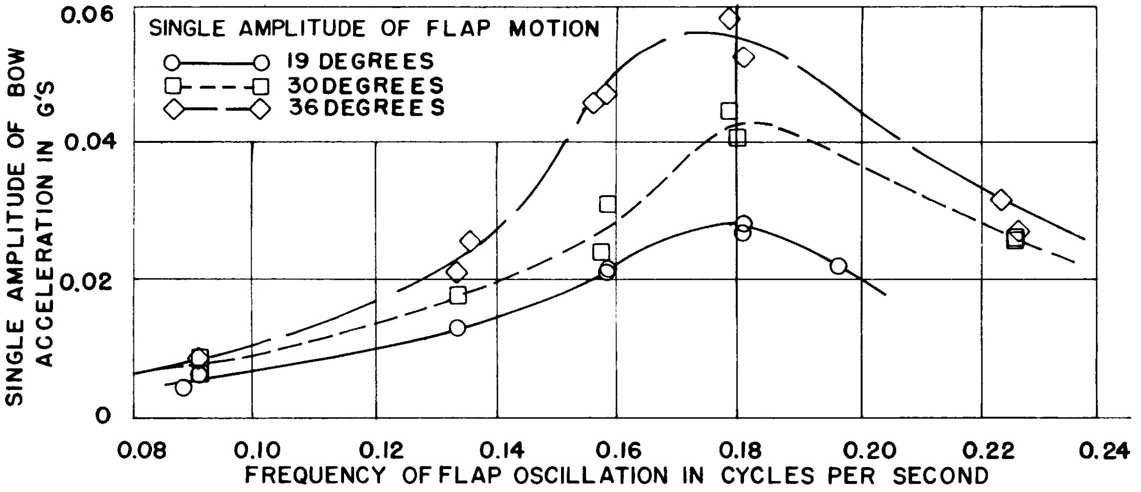

Figure 17c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

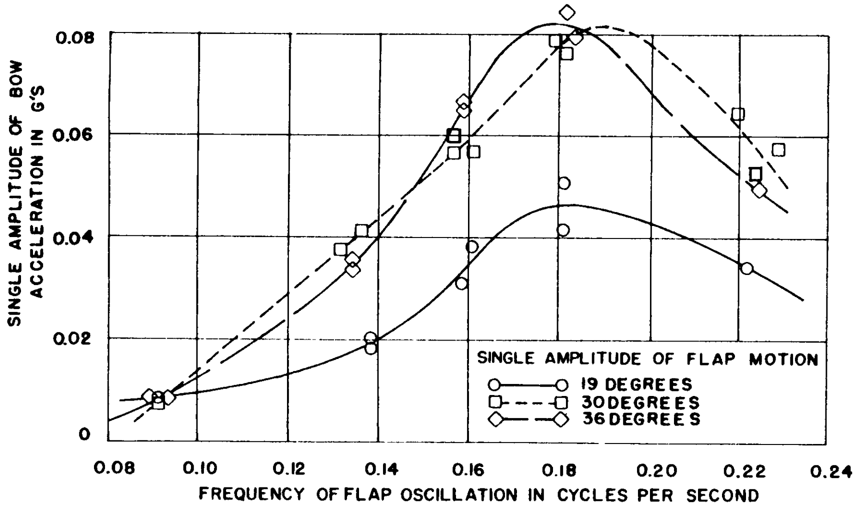

Figure 17d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

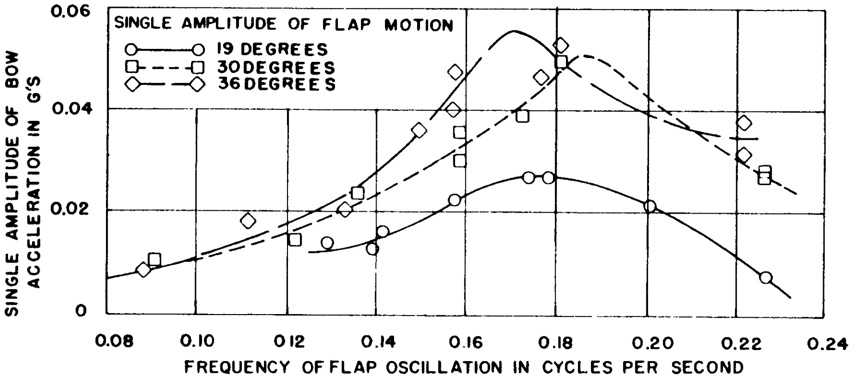

Figure 17e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

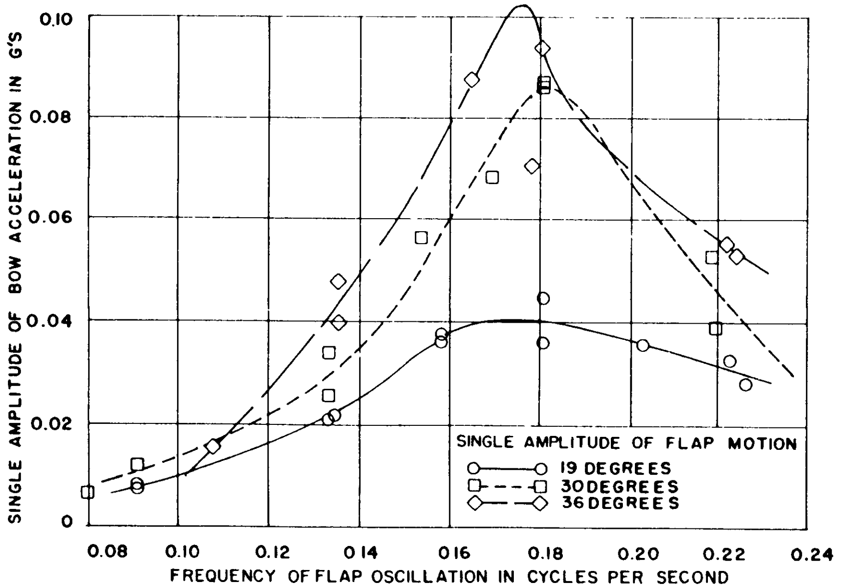

Figure 17f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

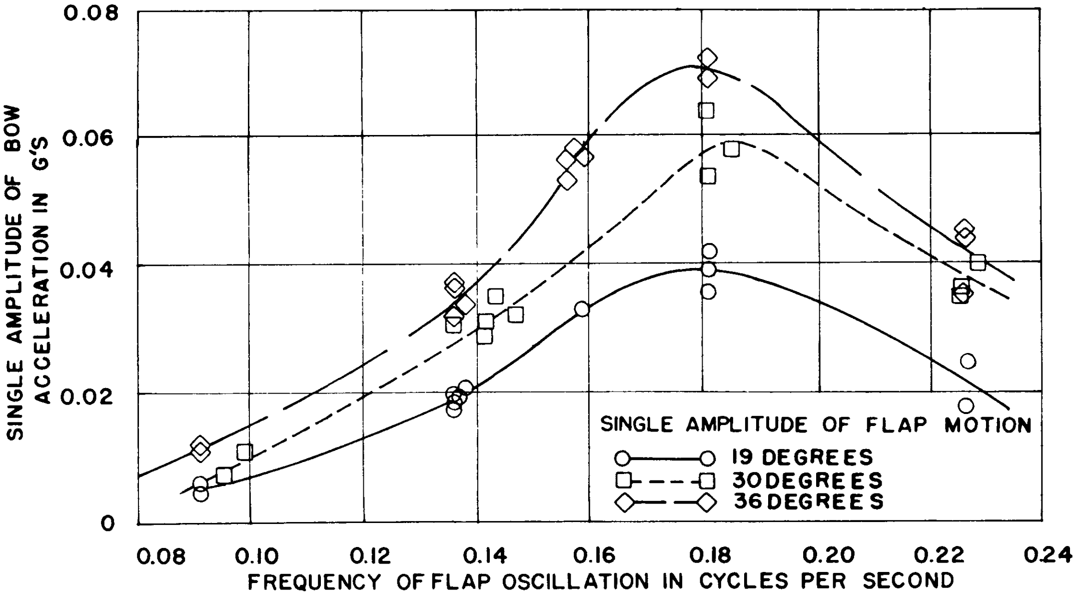

Figure 17g - Flap Configuration C Plus Flaps in Shroud, Ship Speed 16.3 Knots

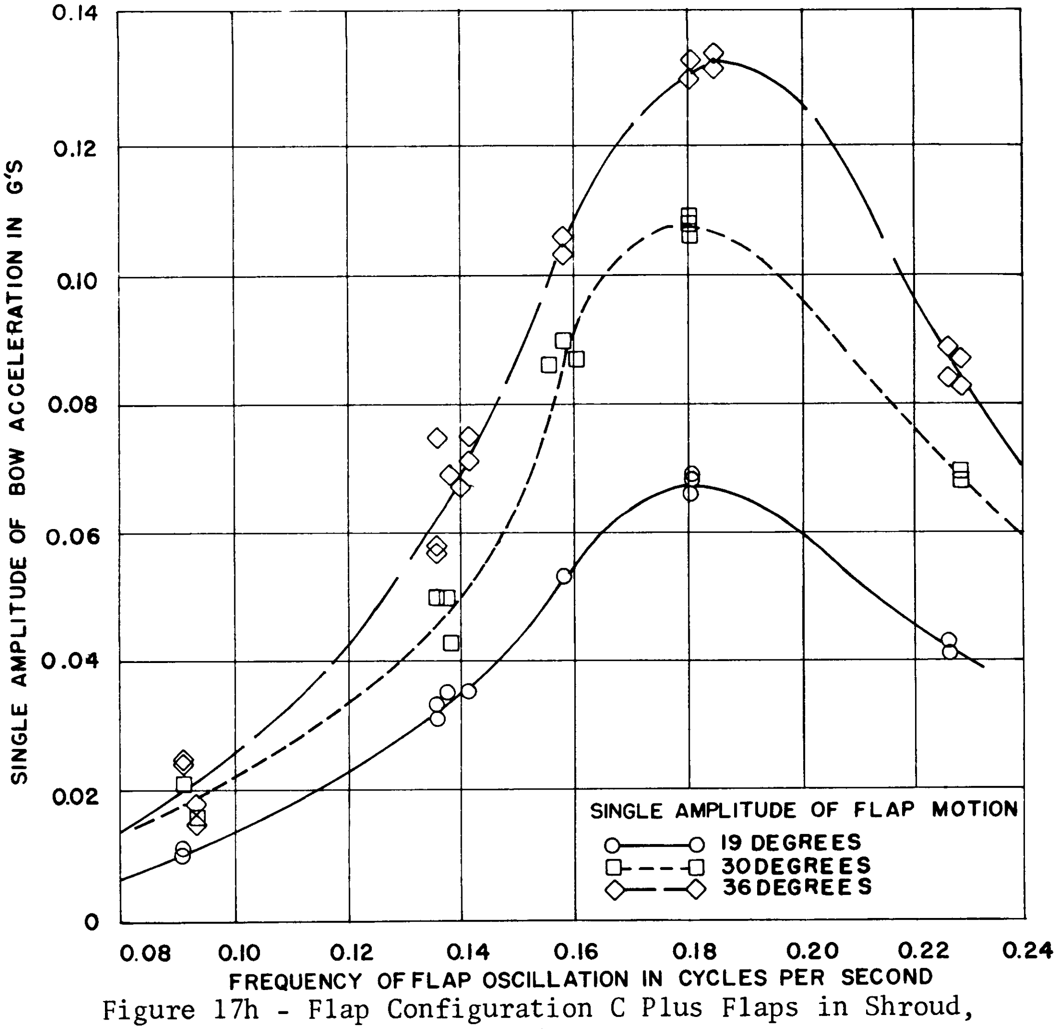

Figure 17h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

Figure 18 - Phase between Maximum Bow Down Pitch and Maximum Downward Flap Angle

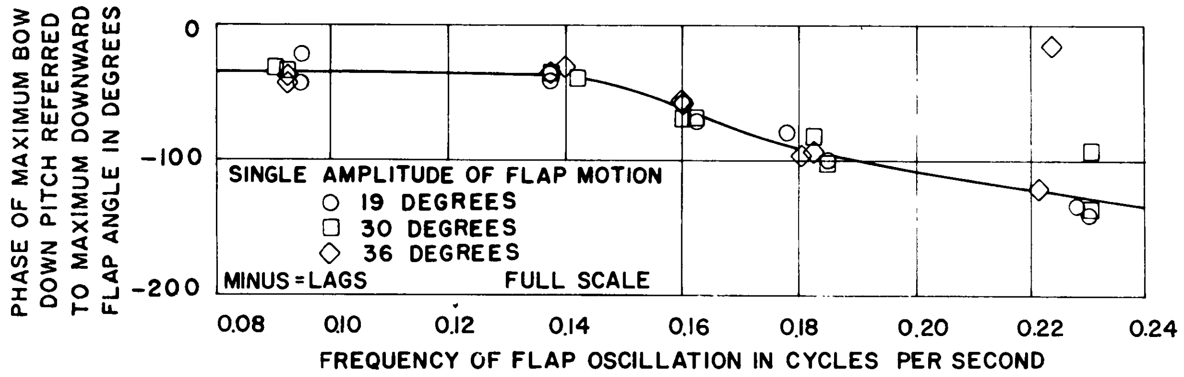

Figure 18a - Flaps in Shroud only, Ship Speed 16.3 Knots

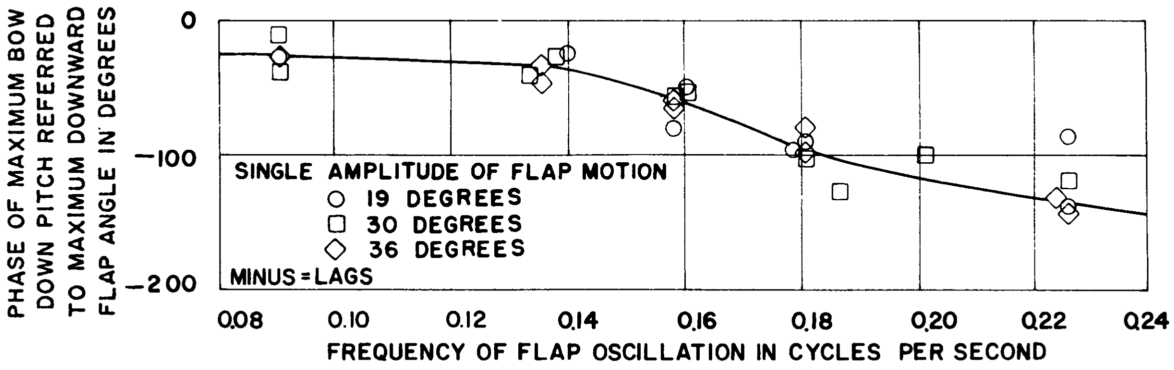

Figure 18b - Flaps in Shroud only, Ship Speed 22.1 Knots

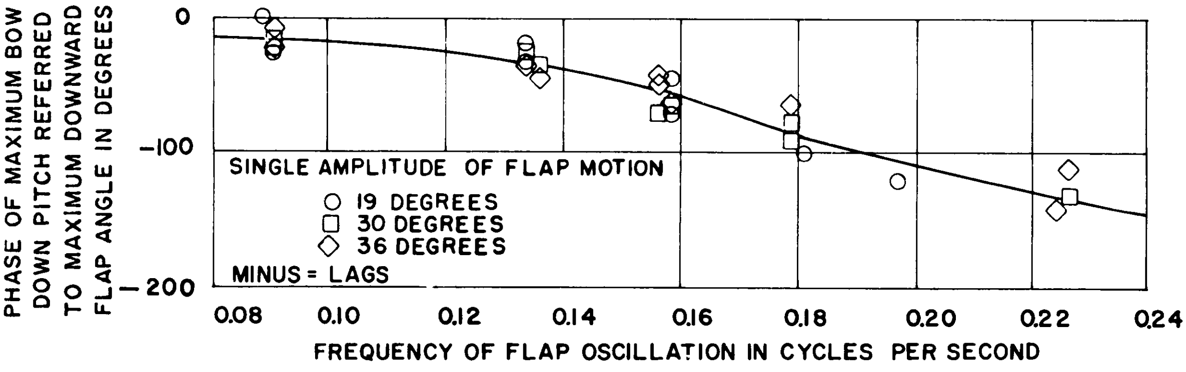

Figure 18c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

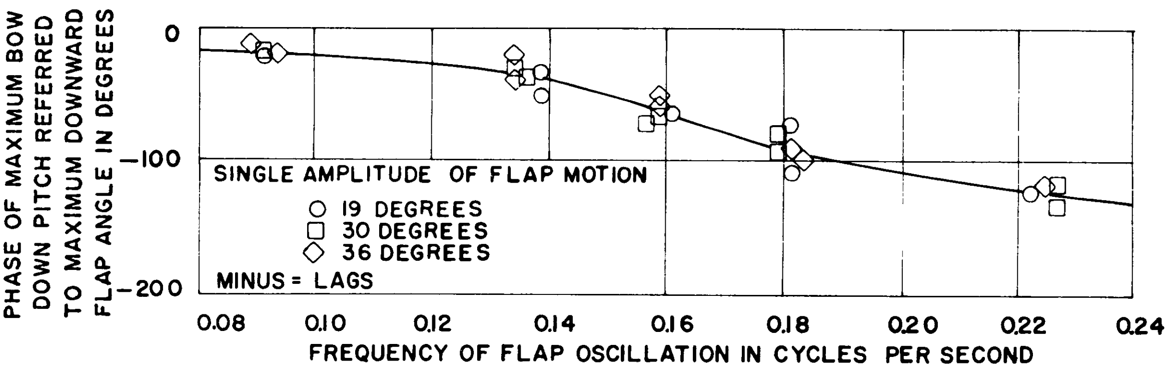

Figure 18d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

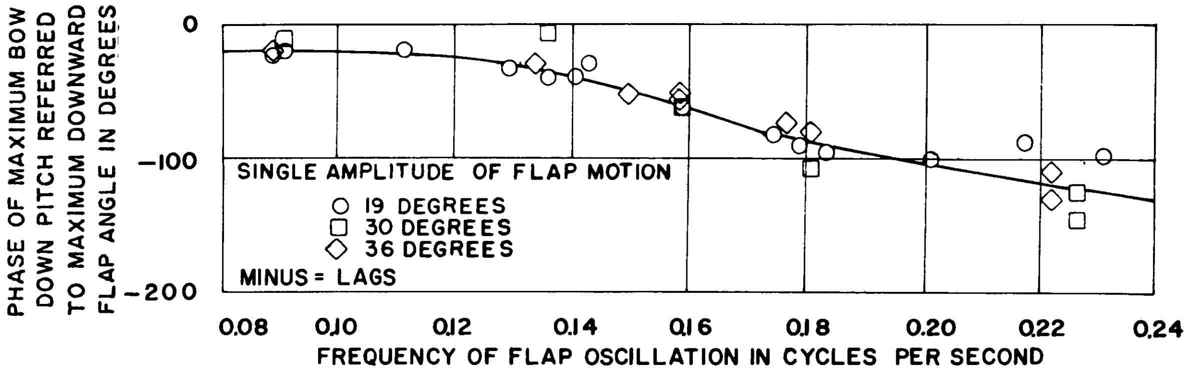

Figure 18e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

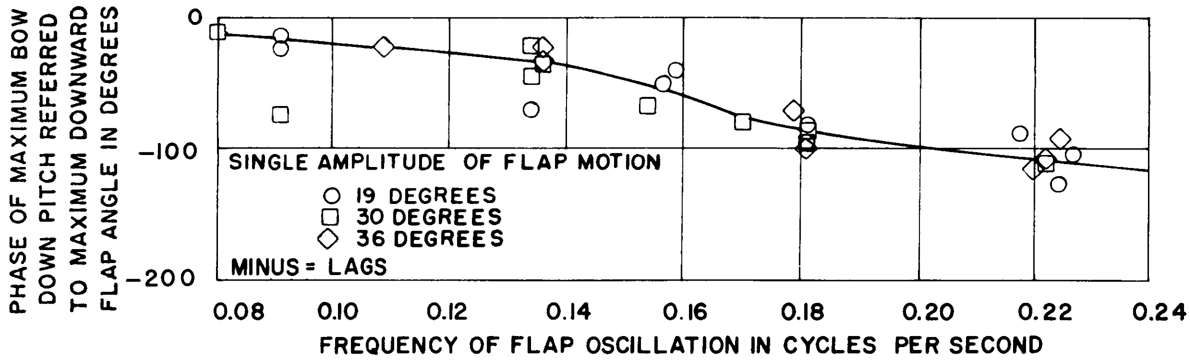

Figure 18f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

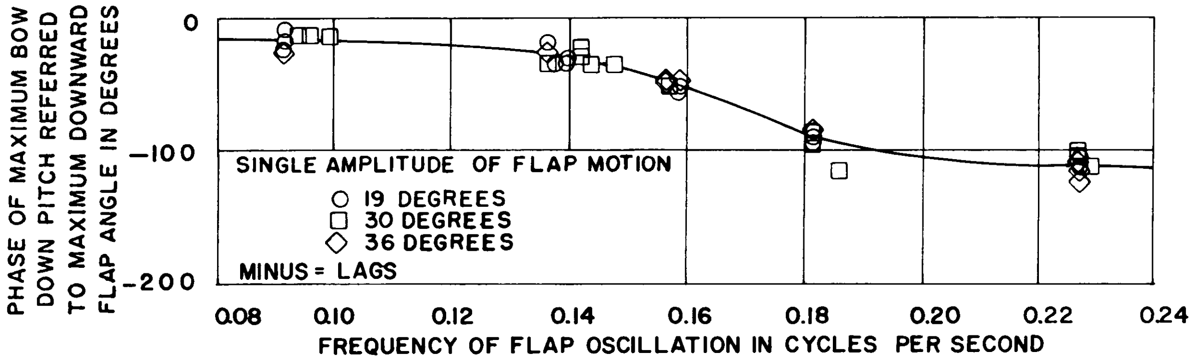

Figure 18g - Flap Configuration C Plus Flaps in Shroud,
Ship Speed 16.3 Knots

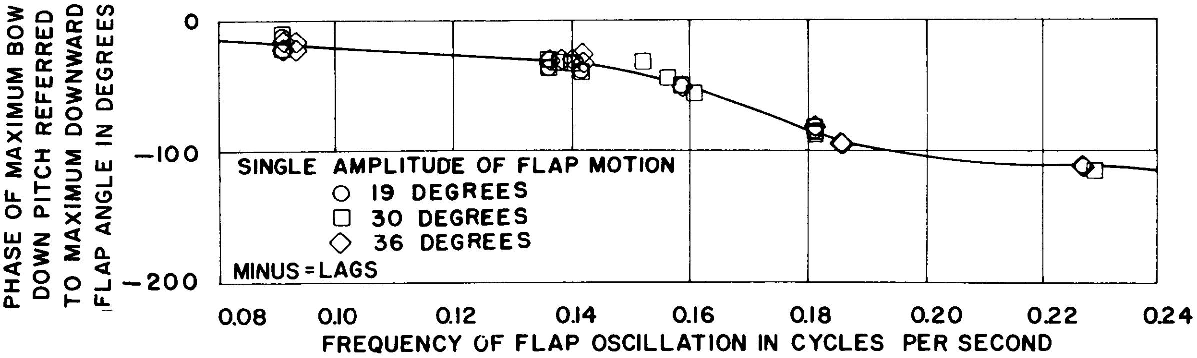

Figure 18h - Flap Configuration C Plus Flaps in Shroud,
Ship Speed 22.1 Knots

Figure 19 - Phase between Maximum Downward Bow Acceleration and Maximum Downward Flap Angle

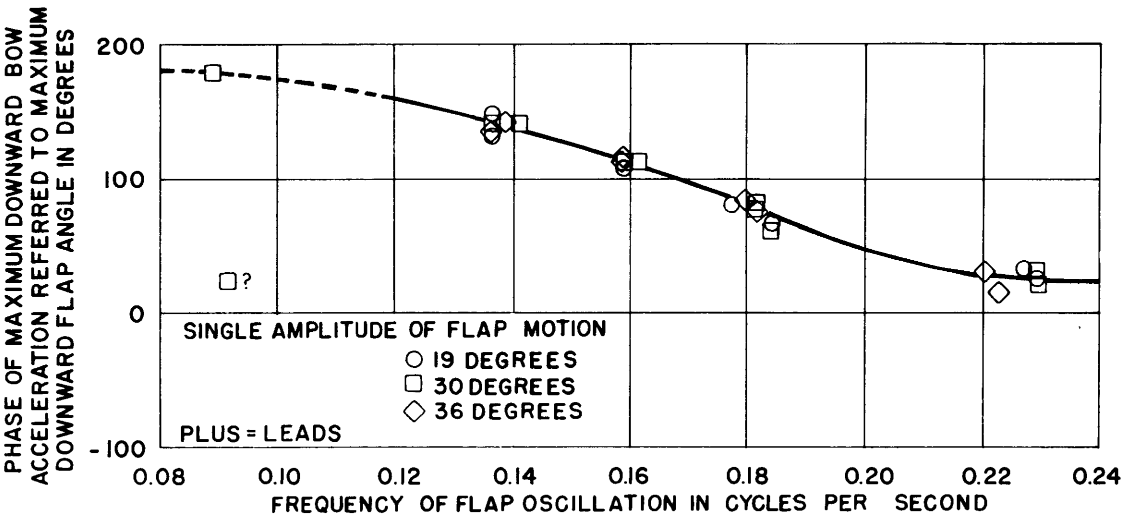

Figure 19a - Flaps in Shroud only, Ship Speed 16.3 Knots

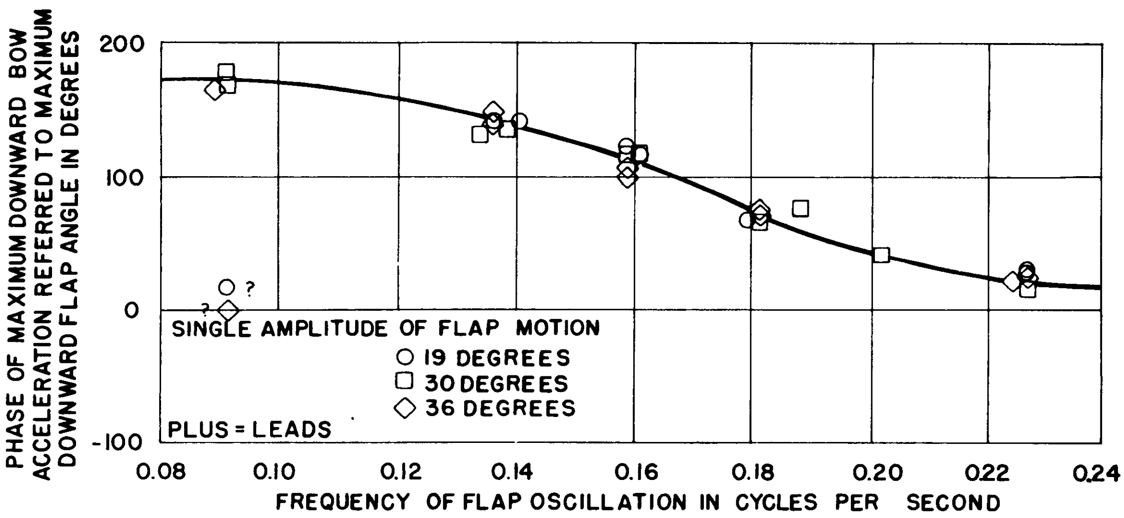

Figure 19b - Flaps in Shrouds only, Speed 22.1 Knots

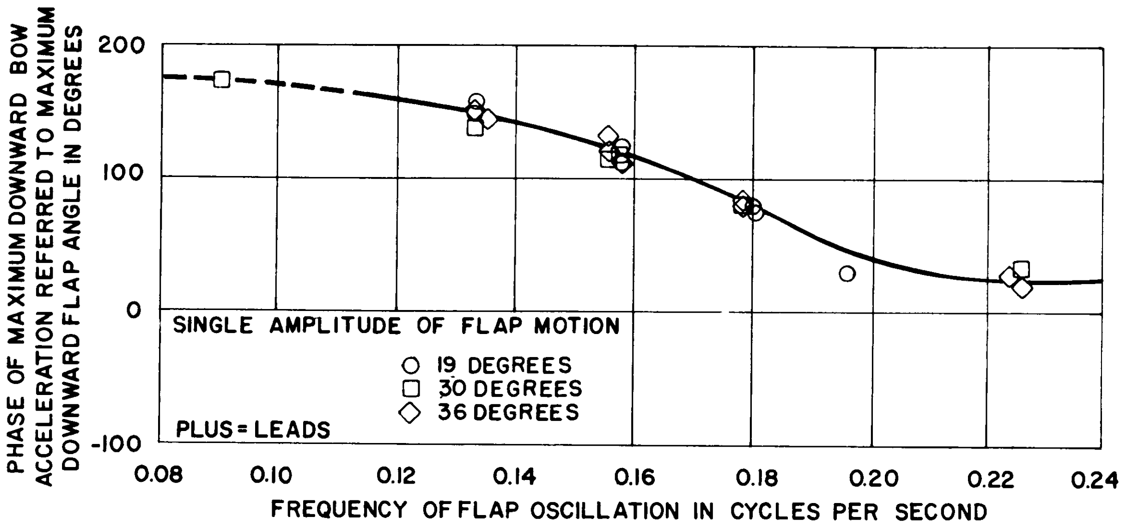

Figure 19c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

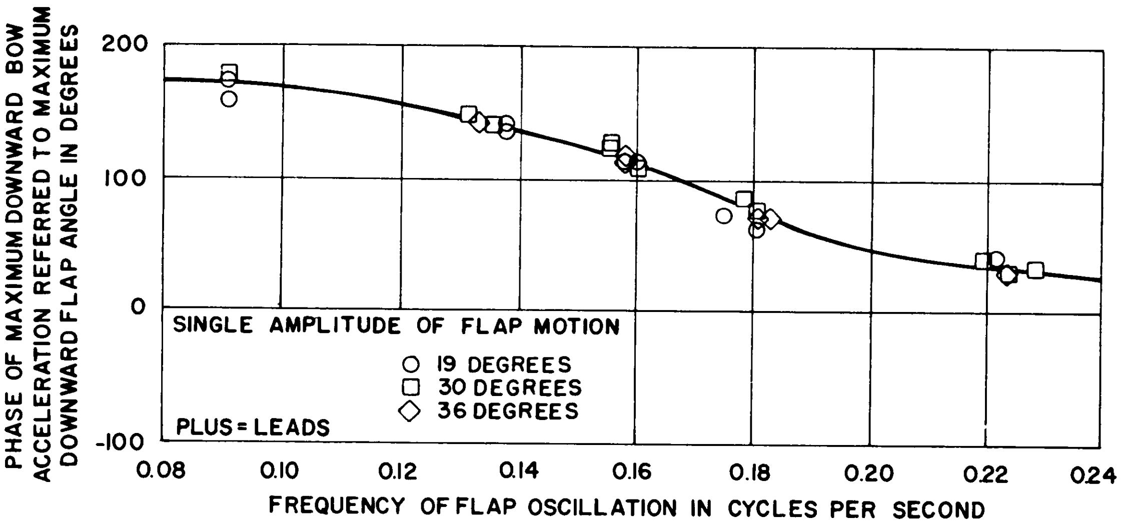

Figure 19d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

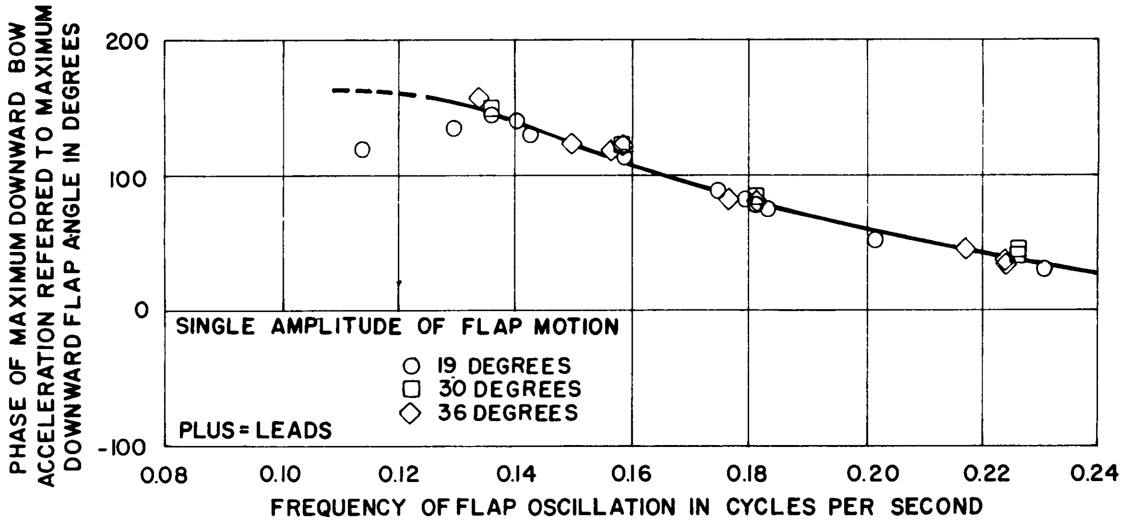

Figure 19e - Flap Configuration B Plus Flaps in Shrouds, Ship Speed 16.3 Knots

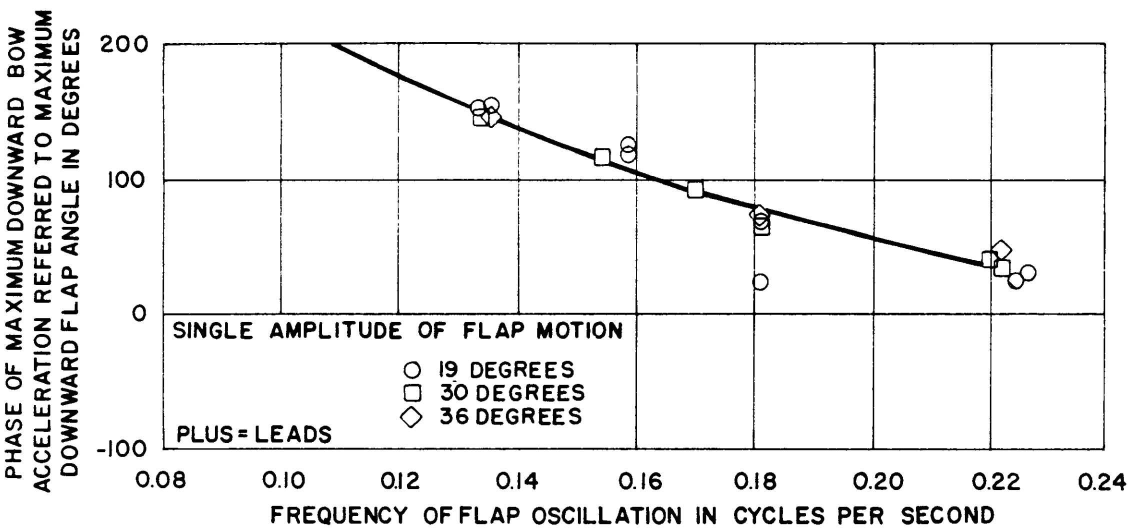

Figure 19f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

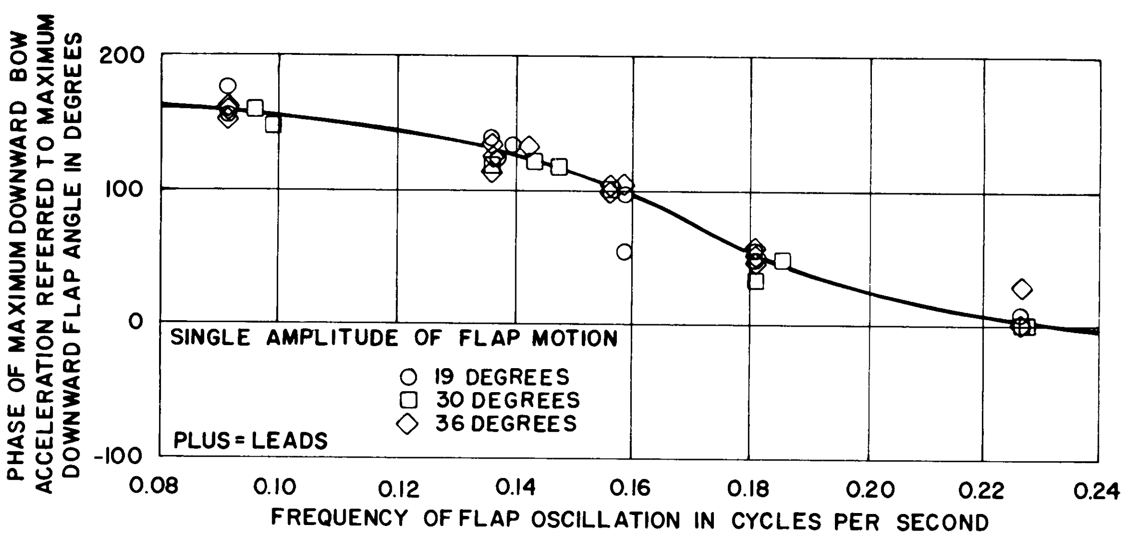

Figure 19g - Flap Configuration C Plus Flaps in Shrouds, Ship Speed 16.3 Knots

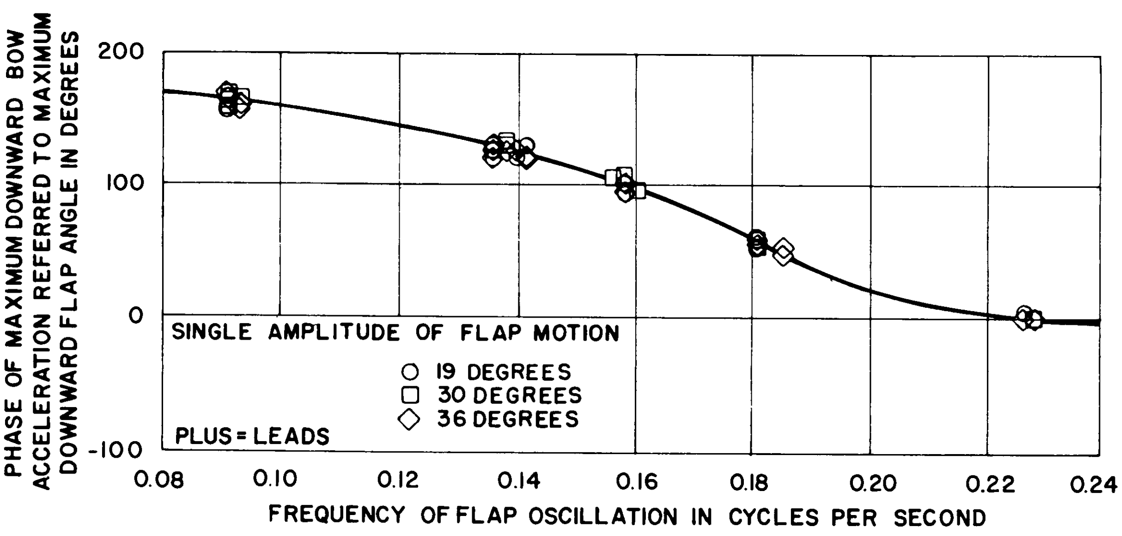

Figure 19h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

Figure 20 - Phase between Maximum Bow Immersion and Maximum Downward Flap Angle

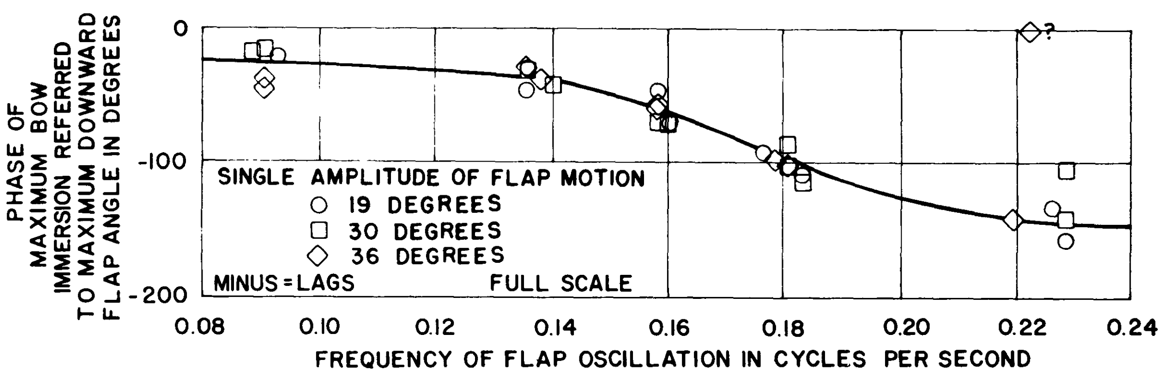

Figure 20a - Flaps in Shrouds only, Speed 16.3 Knots

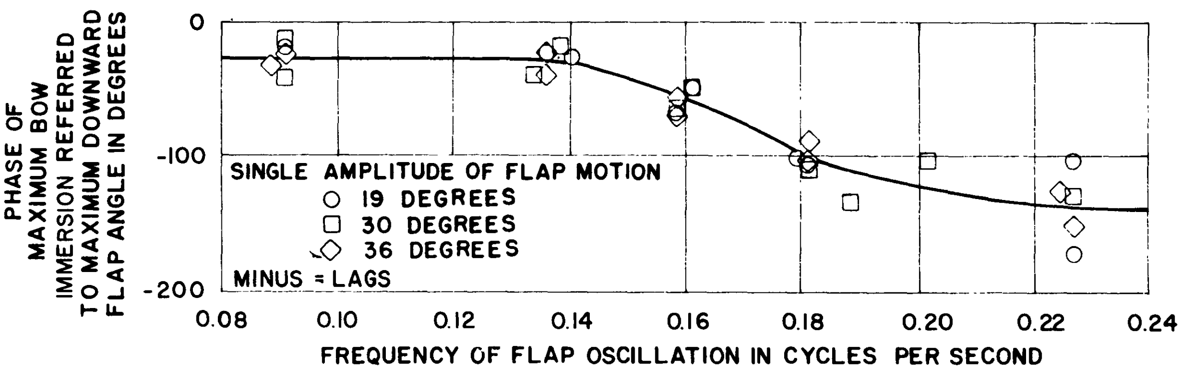

Figure 20b - Flaps in Shroud only, Ship Speed 22.1 Knots

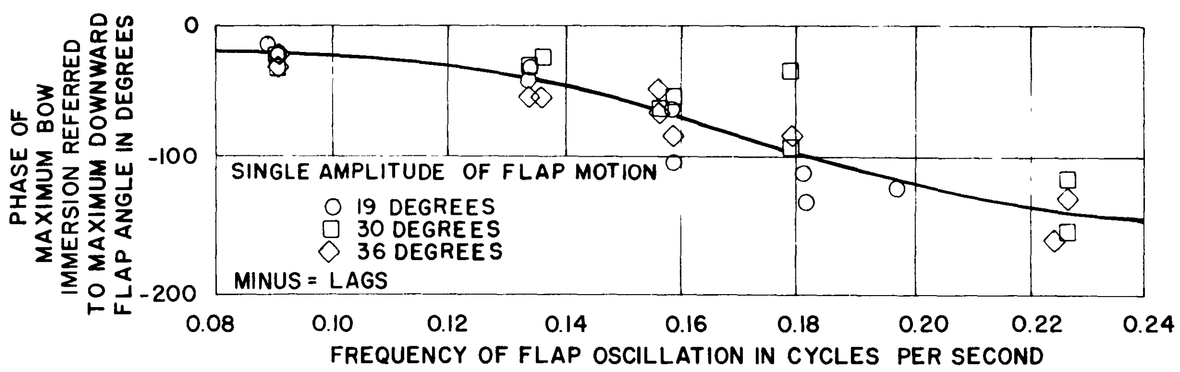

Figure 20c - Flap Configuration A Plus Flaps in Shroud, Ship Speed 16.3 Knots

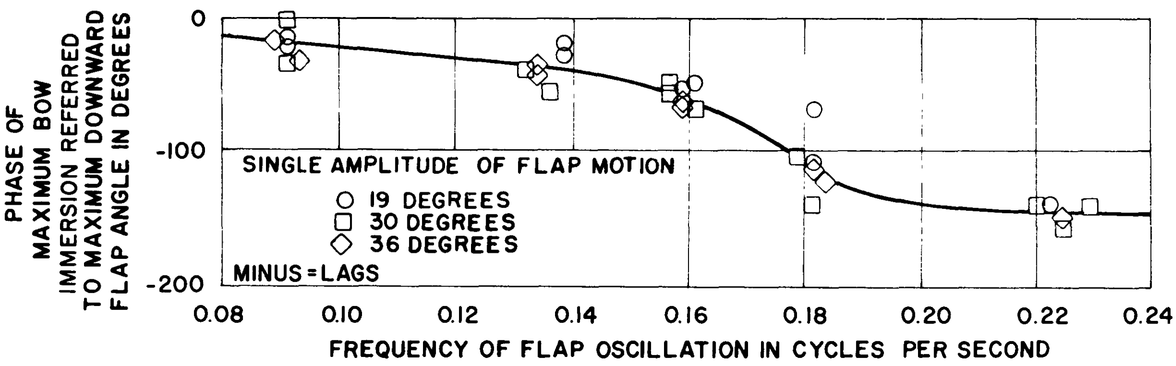

Figure 20d - Flap Configuration A Plus Flaps in Shroud, Ship Speed 22.1 Knots

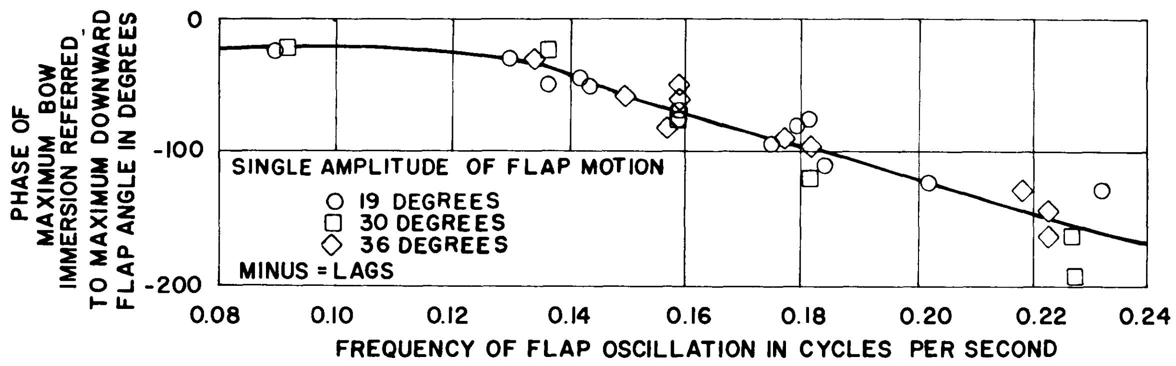

Figure 20e - Flap Configuration B Plus Flaps in Shroud, Ship Speed 16.3 Knots

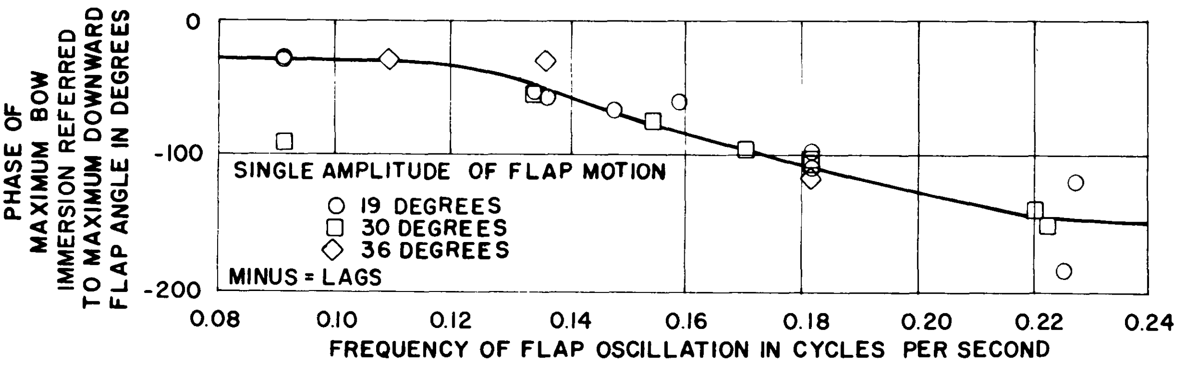

Figure 20f - Flap Configuration B Plus Flaps in Shroud, Ship Speed 22.1 Knots

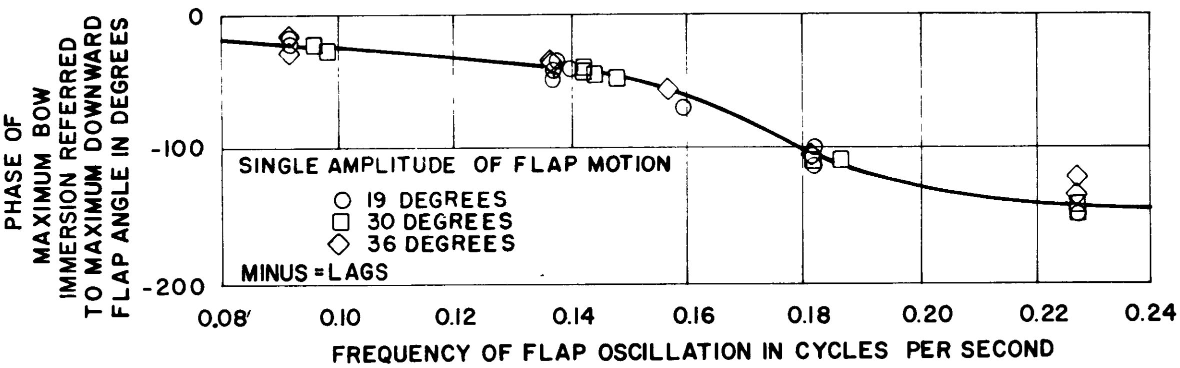

Figure 20g - Flap Configuration C Plus Flaps in Shroud, Ship Speed 16.3 Knots

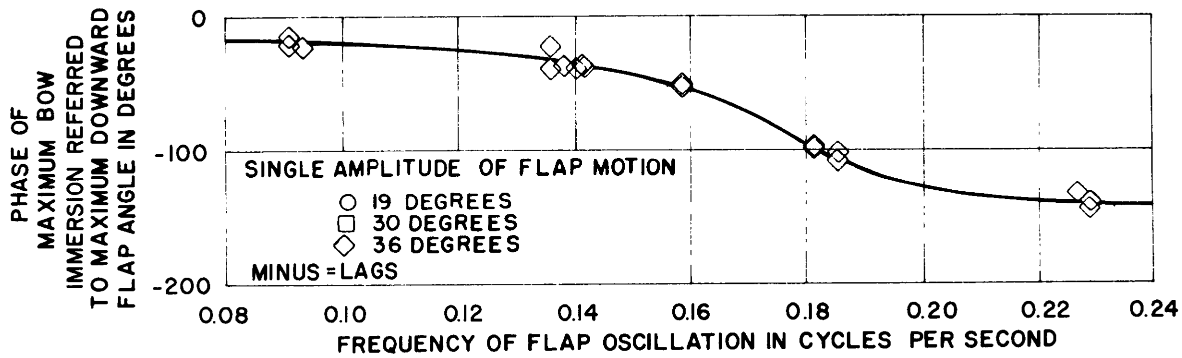

Figure 20h - Flap Configuration C Plus Flaps in Shroud, Ship Speed 22.1 Knots

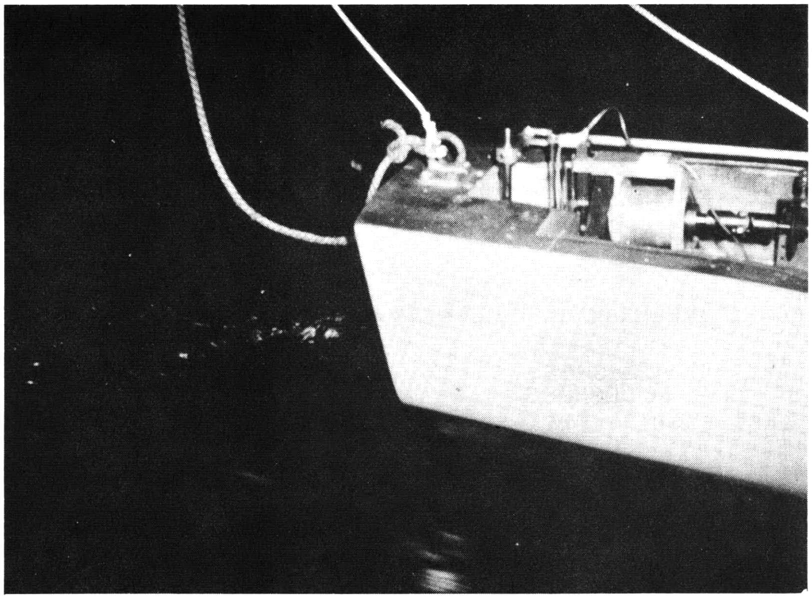

Figure 21a - Flaps Down

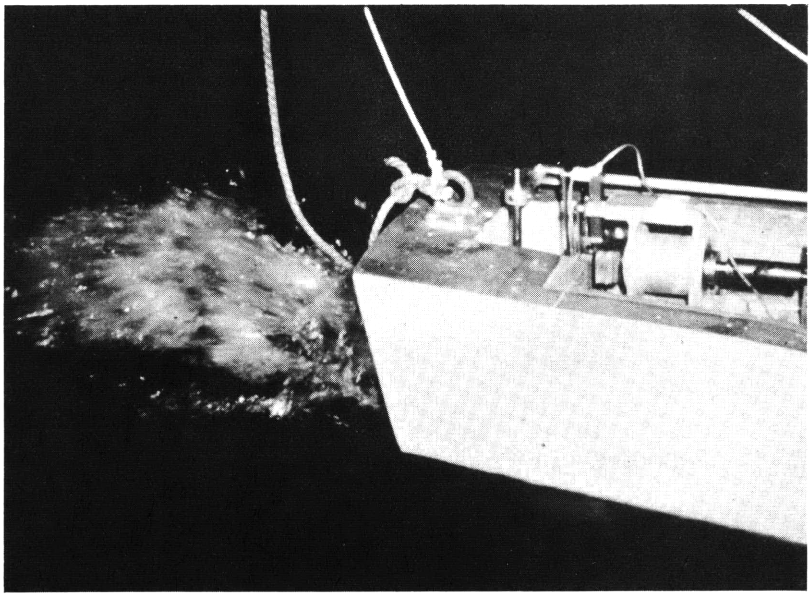

Figure 21b - Flaps Up

Figure 21 - Wake Disturbance Due to Flap Oscillation

TABLE 1

Particulars of Model and Ship

Item	Model	Ship
Length, overall	21.24 ft	414 ft 6 in.
Length, between perpendiculars	19.98 ft	390 ft 0 in.
Beam	2.24 ft	43 ft 8 in.
Draft, for tests	0.77 ft	15 ft 0 in.
Displacement (conventional propeller installed)	1,092.0 lbs FW	3,717.3 LT SW
Displacement (pumpjet installed)	1,082.0 lbs FW	3,683.2 LT SW
Block coefficient	0.483	0.483
Longitudinal radius of gyration	0.28 LBP	0.28 LBP
Scale ratio	1:19.515	
Natural pitching period	1.43 sec	6.32 sec

TABLE 2

Frequencies and Amplitudes of Flap Motion, Phase 2 Tests

Frequency of Flap Oscillation, cps	Amplitude of Flap Oscillation, deg
0.09	19
0.13	30
0.16	36
0.18	
0.23	

TABLE 3

Wave Dimensions for Tests with Conventional Propeller

$\frac{\text{Wave Length}}{\text{Ship Length}}$	Full-Scale Wave Length, ft	$\frac{\text{Wave Length}}{\text{Wave Height}}$
0.5	195.2	40
0.75	292.7	40
1.0	390.3	40
1.125	439.1	40
1.25	487.9	50
1.375	536.7	50
1.5	585.5	50
1.75	683.0	50
2.0	780.6	60
2.25	878.2	60
2.5	975.8	60

TABLE 4
Type and Location of Transducers

Variable	Transducer	Location
Pitch	Computer Instruments Corp. rotary potentiometer	Longitudinal cg of model
Heave	Computer Instruments Corp. rotary potentiometer	Longitudinal cg of model
Wave Height	St. Anthony Falls sonic surface-wave transducer	16 ft forward of model cg
Bow acceleration	± 10g Statham accelerometer	Station 2 on model
Flap-actuating force	SR 4 strain gages (foil type)	Flap push rod
Vertical force generated by flaps and shroud	TMB force (block) gage	Between pumpjet and model hull
Flap angle	Computer Instruments Corp. rotary potentiometer	Phase 2: In linkage system actuated by Scotch yoke Phase 4: In line with and actuated by torque motor shaft
Model speed	Tachometer generator	On carriage
Bow immersion	Capacitance-type probe	Abreast of model FP

TABLE 5
Root-Mean-Square Pitch in Sea State A, Tests with Conventional Propeller

Speed, Knots	Root-Mean-Square Pitch, deg	Root-Mean-Square Wave Height, ft	$\frac{\text{RMS Pitch}}{\text{RMS Wave Height}}$ deg/ft
0	1.0	2.8	0.36
16.3	1.3	2.8	0.46
22.1	1.2	2.6	0.46

TABLE 6
Average of the Highest One-Tenth Pitch in Sea State A, Tests with Conventional Propeller

Speed, Knots	$\bar{\Psi}_{1/10}$ deg	$\bar{h}_{1/10}$, ft	$\frac{\bar{\Psi}_{1/10}}{\bar{h}_{1/10}}$, deg/ft
0	5.3	13.8	0.38
16.3	6.6	12.8	0.52
22.1	6.1	12.7	0.48

Note: All values are double amplitude.

TABLE 7
Root-Mean-Square Pitch in Sea States B and C (Results from Phase 3 and 4 Tests)

Sea State*	Speed, Knots	Flap Oscillating	Root-Mean-Square Pitch deg	Root-Mean-Square Wave Height, ft	$\frac{\text{RMS Pitch}}{\text{RMS Wave Height}}$ deg/ft	Percent Reduction†
B	16.3	No	1.3	2.4	0.54	
B	16.3	Yes	1.2	2.8	0.44	18.5
B	22.1	No	1.2	2.4	0.49	
B	22.1	Yes	1.0	2.6	0.38	22.4
C	16.3	No	1.6	3.7	0.43	
C	16.3	Yes	1.4	3.6	0.39	9.3
C	22.1	No	1.5	3.7	0.40	
C	22.1	Yes	1.2	3.6	0.33	17.5

*Refer to Figure 7

†See Remarks on page 12

TABLE 8

Average of the Highest One-Tenth Pitch in Sea States B and C
(Results from Phase 3 and 4 Tests)

Sea State*	Speed, Knots	Flap Oscillating	$\bar{\Psi}_{1/10}$, deg	$\bar{h}_{1/10}$ ft	$\frac{\bar{\Psi}_{1/10}}{\bar{h}_{1/10}}$ deg/ft	Percent Reduction†
B	16.3	No	7.0	11.7	0.60	
B	16.3	Yes	6.3	13.0	0.49	18.3
B	22.1	No	6.0	11.6	0.52	
B	22.1	Yes	4.7	12.2	0.39	25.0
C	16.3	No	7.4	16.7	0.44	
C	16.3	Yes	6.8	16.3	0.41	6.8
C	22.1	No	7.0	16.9	0.41	
C	22.1	Yes	5.5	15.9	0.34	17.1

Note: All values double amplitude

* Refer to Figure 7

† See Remarks on page 12

TABLE 9

Root-Mean-Square Flap-Actuating Force
(Results from Phase 4 Tests)

Sea State*	Speed, Knots	Root-Mean-Square Force, tons
B	16.3	42.5
B	22.1	59.1
C	16.3	48.4
C	22.1	74.3

*Refer to Figure 7

TABLE 10

Average of the Highest One-Tenth Flap-Actuating Force
(Results from Phase 4 Tests)

Sea State*	Speed, Knots	$\bar{F}_{1/10}$, tons
B	16.3	210.4
B	22.1	293.3
C	16.3	237.6
C	22.1	316.2

Note: All values double amplitude

* Refer to Figure 7

TABLE 11

Root-Mean-Square Lift Force* (Results from Phase 4 Tests)

Sea State**	Speed, Knots	Root-Mean-Square Force, tons
B	16.3	60.7
B	22.1	83.6
C	16.3	73.0
C	22.1	113.1

*Acting at approximately Station 19.

**Refer to Figure 7.

TABLE 12

Average of the Highest One-Tenth Lift Force*

(Results from Phase 4 Tests)

Sea State**	Speed, Knots	$\bar{F}_{1/10}$, tons
B	16.3	248.5
B	22.1	308.6
C	16.3	260.8
C	22.1	336.4

Note: All values double amplitude.

* Acting at approximately Station 19.

** Refer to Figure 7.

TABLE 13

Root-Mean-Square Heave (Results from Phase 3 and 4 Tests)

Sea State*	Speed, Knots	Flap Oscillating	Root-Mean-Square Heave ft	Root-Mean-Square Wave Height. ft	RMS Heave / RMS Wave Height	Percent Change†
B	16.3	No	2.4	2.4	1.00	
B	16.3	Yes	2.8	2.8	1.00	0
B	22.1	No	2.9	2.4	1.20	
B	22.1	Yes	2.9	2.6	1.13	5.8
C	16.3	No	3.3	3.7	0.88	
C	16.3	Yes	3.1	3.6	0.86	2.3
C	22.1	No	4.4	3.7	1.17	
C	22.1	Yes	3.7	3.6	1.05	10.3

*Refer to Figure 7

†See Remarks on page 12

TABLE 14

Average of the Highest One-Tenth Heave (Results from Phase 3 and 4 Tests)

Sea State*	Speed Knots	Flap Oscillating	$\bar{z}_{1/10}$ ft	$\bar{h}_{1/10}$ ft	$\frac{\bar{z}_{1/10}}{\bar{h}_{1/10}}$	Percent Change†
B	16.3	No	11.4	12.1	0.94	
B	16.3	Yes	12.1	13.0	0.94	0.0
B	22.1	No	12.7	11.7	1.08	
B	22.1	Yes	13.0	12.2	1.07	0.9
C	16.3	No	14.5	16.7	0.87	
C	16.3	Yes	14.2	16.3	0.87	0.0
C	22.1	No	15.7	16.9	0.92	
C	22.1	Yes	15.8	15.9	0.99	7.1

Note: All values double amplitude
* Refer to Figure 7
† See Remarks on page 12

TABLE 15

Root-Mean-Square Bow Acceleration (Results from Phase 3 and 4 Tests)

Sea State*	Speed, Knots	Flap Oscillating	Root-Mean-Square Bow Acceleration, g	Root-Mean-Square Wave Height, ft	$\frac{\ddot{\zeta}_{RMS}}{\text{RMS Wave Height}}$ g/ft	Percent Reduction†
B	16.3	No	0.18	2.3	0.079	
B	16.3	Yes	0.17	2.8	0.062	21.5
B	22.1	No	0.20	2.4	0.082	
B	22.1	Yes	0.16	2.9	0.055	32.9
C	16.3	No	0.20	3.7	0.054	
C	16.3	Yes	0.17	3.6	0.048	11.1
C	22.1	No	0.23	3.7	0.062	
C	22.1	Yes	0.20	3.6	0.056	9.7

*Refer to Figure 7
†See Remarks on page 12

TABLE 16

Average of the Highest One-Tenth Bow Acceleration (Results from Phase 3 and 4 Tests)

Sea State*	Speed, Knots	Flap Oscillating	$\ddot{\zeta}_{1/10}$ g	$\bar{h}_{1/10}$ ft	$\frac{\ddot{\zeta}_{1/10}}{\bar{h}_{1/10}}$ g/ft	Percent Reduction†
B	16.3	No	0.83	11.7	0.073	
B	16.3	Yes	0.80	13.0	0.061	16.4
B	22.1	No	0.87	11.5	0.075	
B	22.1	Yes	0.85	12.4	0.069	8.0
C	16.3	No	0.94	16.8	0.058	
C	16.3	Yes	0.85	16.4	0.052	10.3
C	22.1	No	1.00	16.9	0.059	
C	22.1	Yes	0.95	15.9	0.059	0

Note: All values double amplitude
* Refer to Figure 7
† See Remarks on page 12

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Pitch Reduction of Ships						
Active stern-mounted flaps in wake of ducted propeller						
Lift produced by oscillating flaps						
Model tests in irregular waves						
Automatic control of flaps						
Flap actuating forces						
AGDE-1 Destroyer Escort						

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1. Destroyer escorts--Pitch--Reduction
2. Destroyer escorts--Motion--Model tests
3. Destroyer escorts--Flaps--Effectiveness
4. Shrouded propellers--Flaps--Effectiveness
5. AGDE-1 (U.S destroyer escort)
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II. S-F013 02 04; Task 1712

David Taylor Model Basin. Report 2183.
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