III. RESULTS

A. OPERABILITY INDEX

In this study two criteria are considered for the near surface operations of the submarine in deep water, for both the limited diameter and the limited length cases. First is the number of periscope submergence events per hour (N_{p1}), which can be calculated using Equation (23) and selected as 300, which corresponds to five periscope submergence events per minute. This is an arbitrary number and different numbers could be picked for different operational considerations. The same number is used for all cases to represent all possible choices. The other criterion is the number of sail broaching events per hour (N_{p2}), which can be also calculated from Equation (23) and selected as one. Since a single event occurrence may result in submarine detection, this places far greater emphasis on sail broaching than periscope submergence.

Having the tools to compute the two performance indices defined above in a given seaway. Suppose that the submarine conducts periscope depth operation in a seaway characterized by a significant wave height (Pierson-Moskowitz Wave Spectrum), so that the sea spectrum is defined. For all round the clock boat headings relative to the predominant wave direction for which the operations are to be conducted, a polar plot diagram similar to the one in Figure 6 is prepared. Significant wave heights are represented along the radial direction of the polar plot. The shaded area in the plot shows wave height and wave direction combinations where the selected tactical assessment criterion is exceeded. Three plots are combined on a single plot for different shape factors, which are selected as two, three and four at the same speed/depth combination.

Letting the polar area of the disk in Figure 6 be A_0 and the subset of A_0 within which the boat can conduct the operation be A, a performance index characterizing the ability of the boat perform this operation in the specified submarine velocity and depth can be defined as $100(A/A_0)$. Generally a submarine's forward speed ranges from three to twelve knots in periscope depth operations. We used three, five, eight and eleven knots submarine forward speeds, U, in our calculations. Depths, h, beneath the surface were selected from 1.5 to 2.5 boat diameters measured from the keel up. The calculations are repeated for both the limited diameter and the limited length cases and for the shape factors n_a *and* n_f, which are selected as two, three and four. In computing the above index we could easily take into account the probability of occurrence of a particular sea state and wave heading angle in the area of interest by introducing appropriate weight factors. In this study we assumed that all possible sea-states and wave heading angles are equally probable. In the following sections we discuss the results for both criteria/operability indices and also for the combined criterion/operability index, where both criteria are taken into consideration at the same time. In each case, combined plots for different shape factors at certain speed/depth combination are shown.

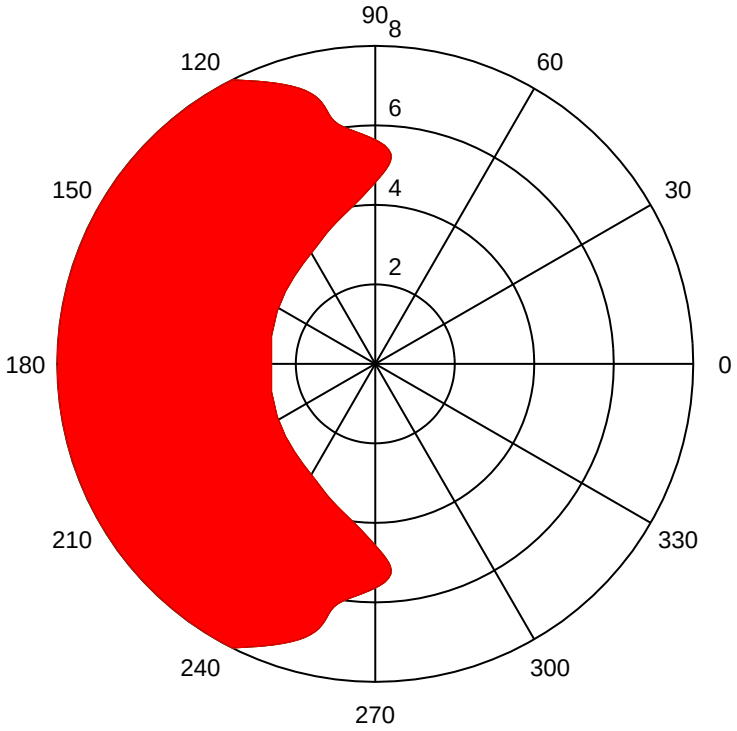

Figure 6. Typical performance assessment of a submarine

B. PERISCOPE SUBMERGENCE CRITERION RESULTS

The operability indices for the periscope submergence criterion for the limited diameter and limited length cases in different speeds, operating depths and shape factors are shown in Tables I and II, and in Figure 7. Typical polar plots are shown in Figures 8 through 30. Based on these results, the following conclusions can be drawn:

1. Regardless of the variation of the parameters in the criterion, head seas appear to result in a larger number of expected criterion violations than following seas. This is valid for both limited length and limited diameter cases.
2. Changes in the shape factors appear to have greater effects at smaller speeds and larger operating depths. At smaller depths, smaller shape factors yield slightly higher operability indices, while at larger depths and larger speeds, the reverse may occur.
3. An optimum shape factor for a certain operating depth, which minimizes the expected number of periscope submergence events can be found, and this appears to be a weak function of speed.
4. Similar values of the operability index may result in very different response characteristics. This is because the shape shape of the polar plots may be quite different, even though their areas are the same.

		LIMITED DIAMETER			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.7228	0.6614	0.6270	0.6154
	n=3	0.6244	0.6102	0.5974	0.5903
	n=4	0.6192	0.6080	0.5935	0.5840
h=2D	n=2	0.7145	0.7351	0.6239	0.6053
	n=3	0.6772	0.6332	0.6163	0.5898
	n=4	0.6003	0.5914	0.5823	0.5806
h=2.5D	n=2	0.7050	0.6309	0.5941	0.6109
	n=3	0.6382	0.6313	0.6947	0.6165
	n=4	0.6897	0.7379	0.6578	0.6035

Table I : Operability indices for periscope submergence criterion for the limited diameter case.

		LIMITED LENGTH			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.6313	0.6153	0.6027	0.6037
	n=3	0.6244	0.6102	0.5974	0.5903
	n=4	0.6264	0.6102	0.5955	0.5897
h=2D	n=2	0.7717	0.7268	0.6320	0.6219
	n=3	0.6772	0.6332	0.6163	0.5898
	n=4	0.6266	0.6102	0.5973	0.6009
h=2.5D	n=2	0.7703	0.6640	0.6097	0.5852
	n=3	0.6382	0.6313	0.6947	0.6165
	n=4	0.6863	0.7349	0.6513	0.6037

Table II : Operability indices for periscope submergence criterion for the limited length case.

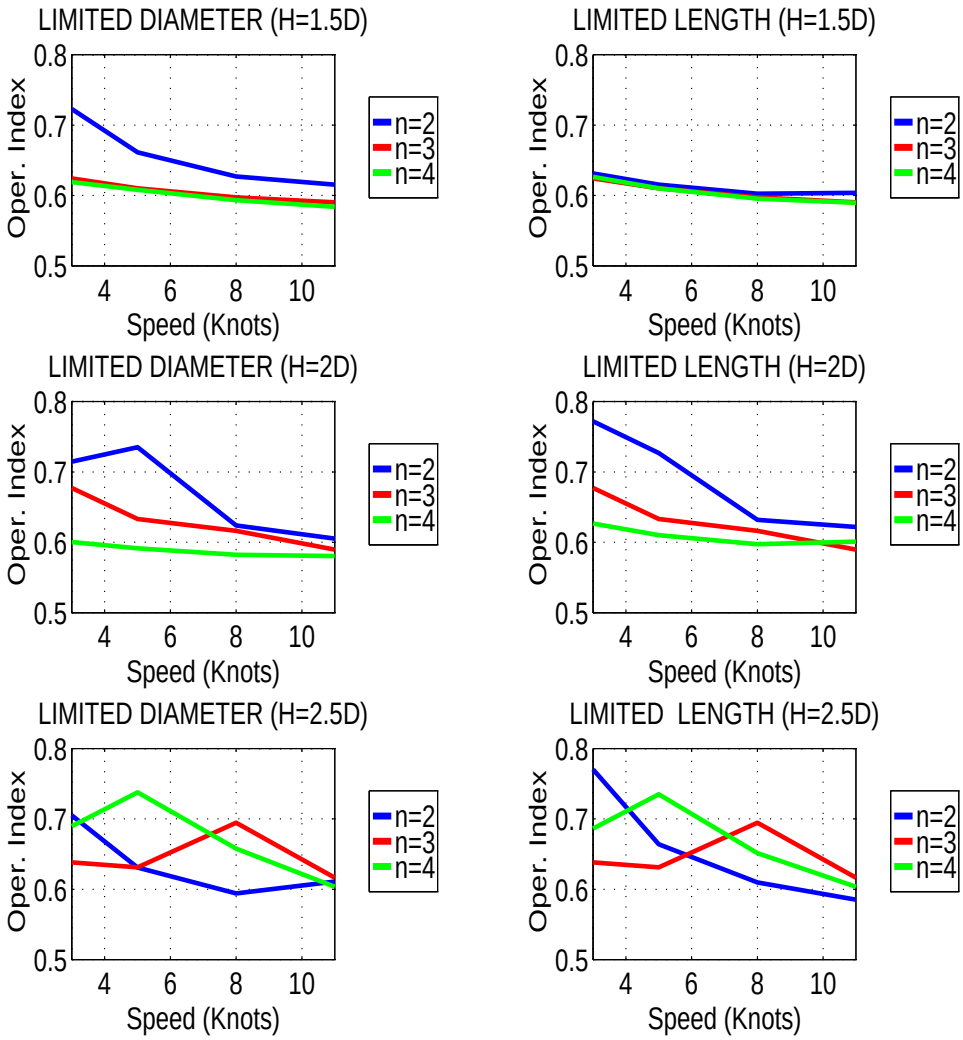

Figure 7. OI vs. submarine speed plots for periscope submergence criterion.

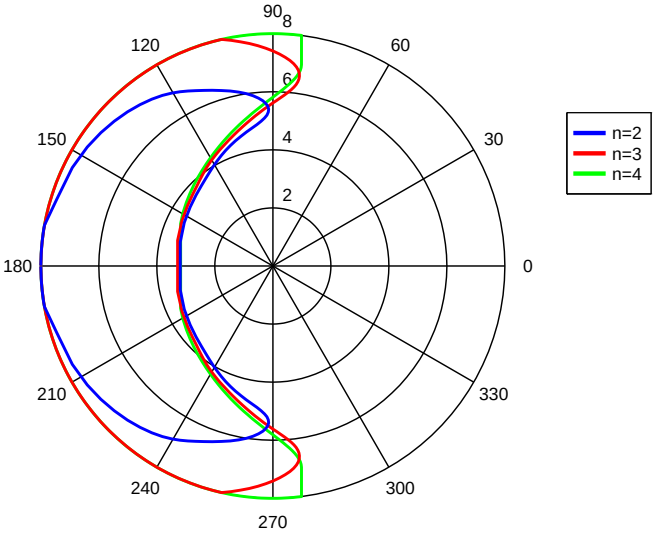

Figure 8. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for *U*=3 Knots, h=1.5*D*.

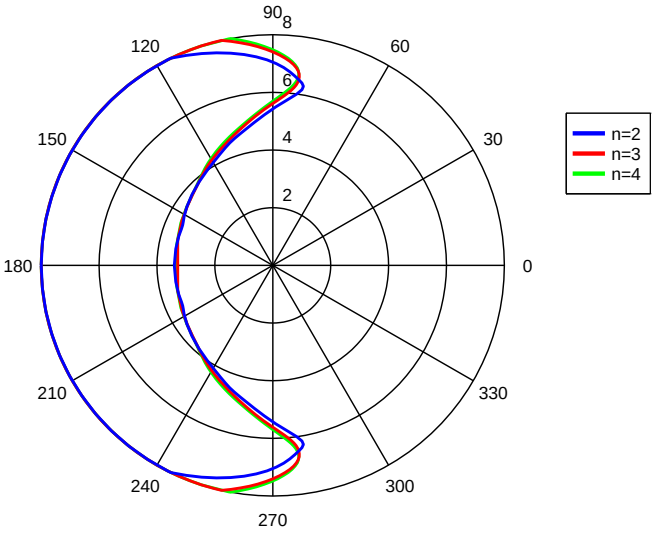

Figure 9. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=1.5*D*.

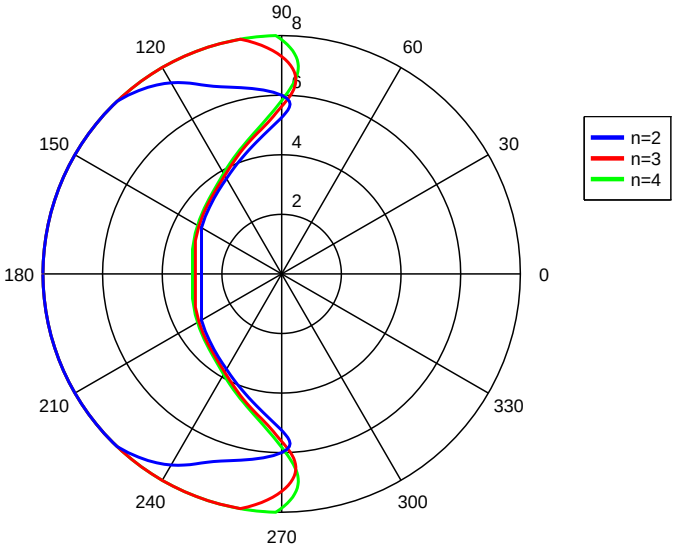

Figure 10. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=1.5*D*.

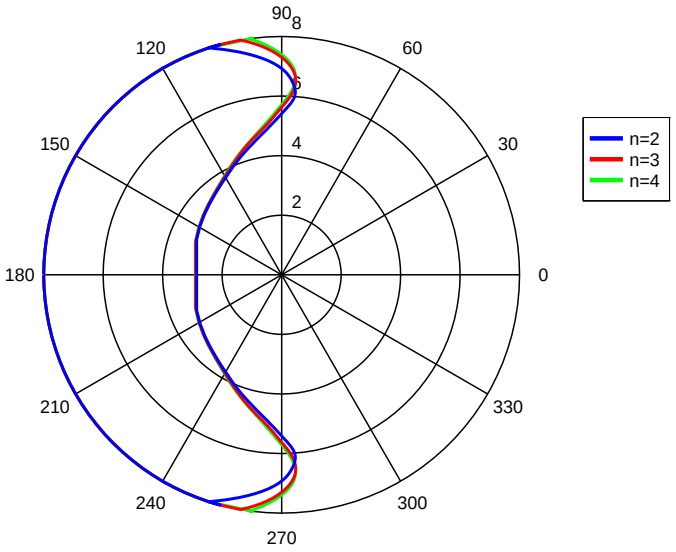

Figure 11. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=1.5*D*.

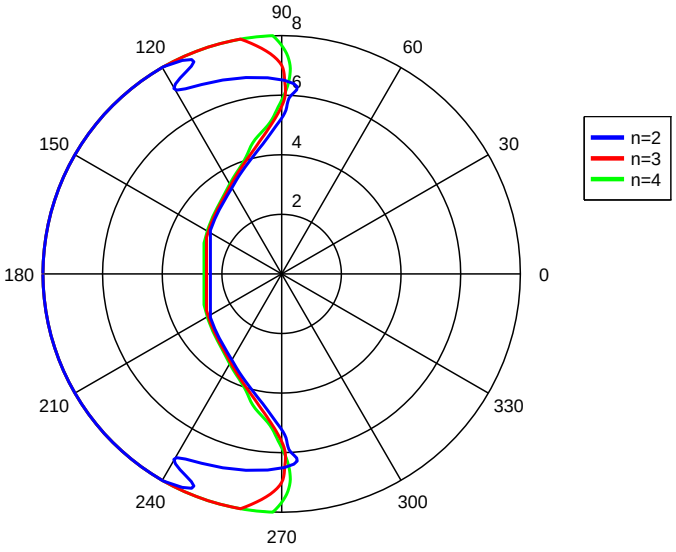

Figure 12. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=1.5*D*.

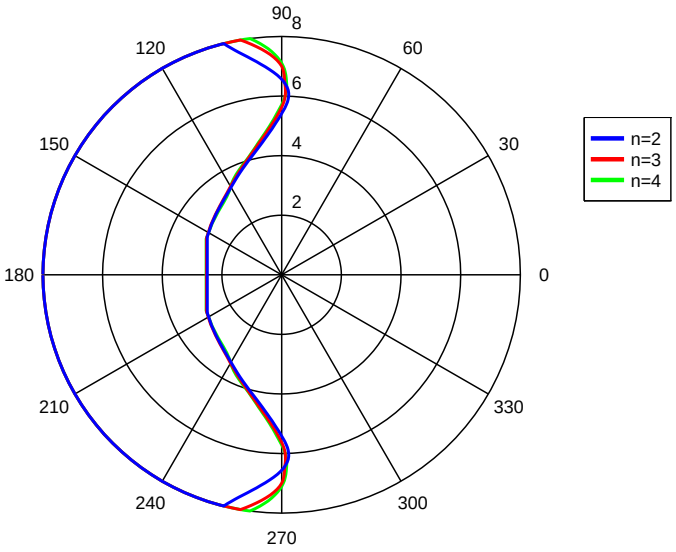

Figure 13. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=1.5*D*.

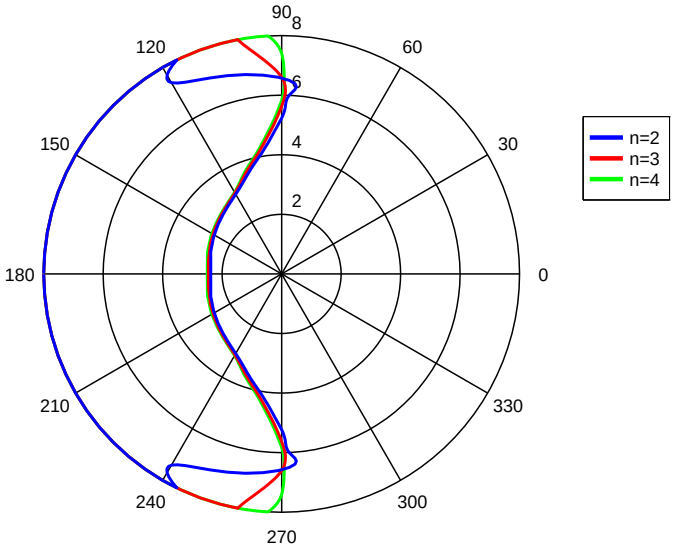

Figure 14. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=1.5*D*.

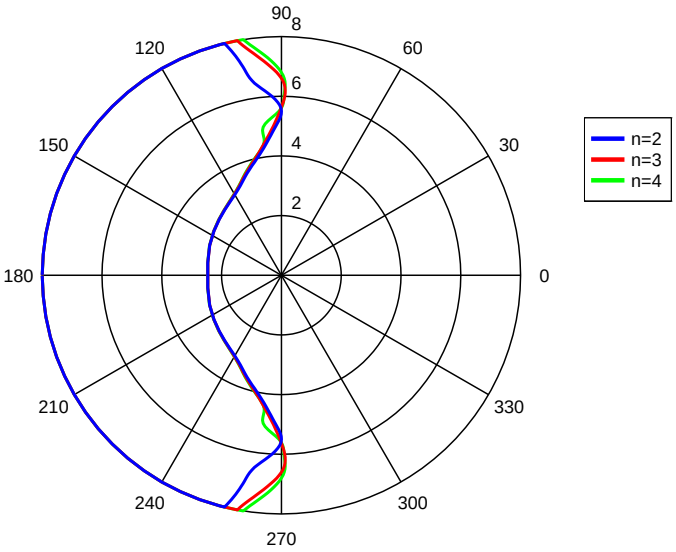

Figure 15. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, 1.5*D*.

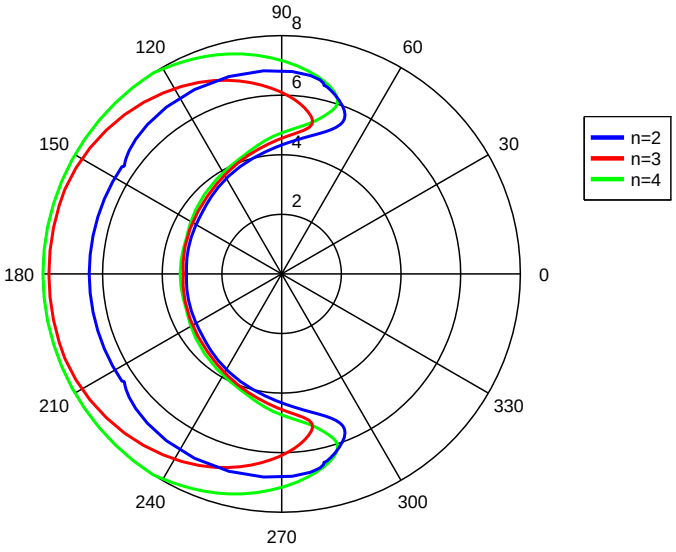

Figure 16. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2*D*.

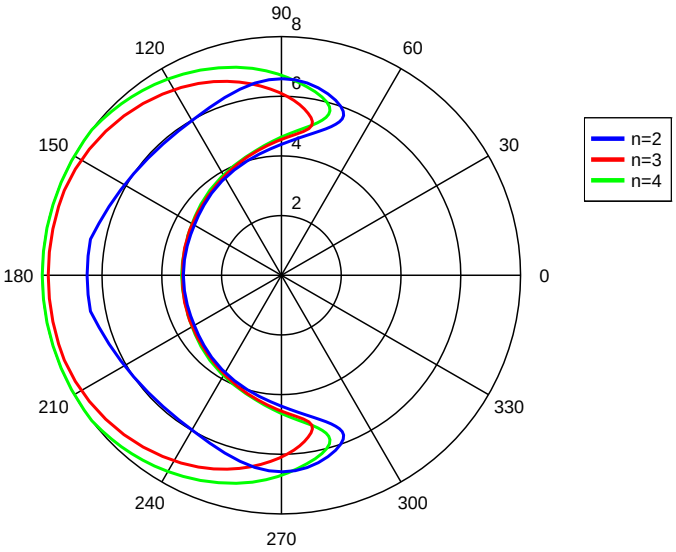

Figure 17. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2*D*.

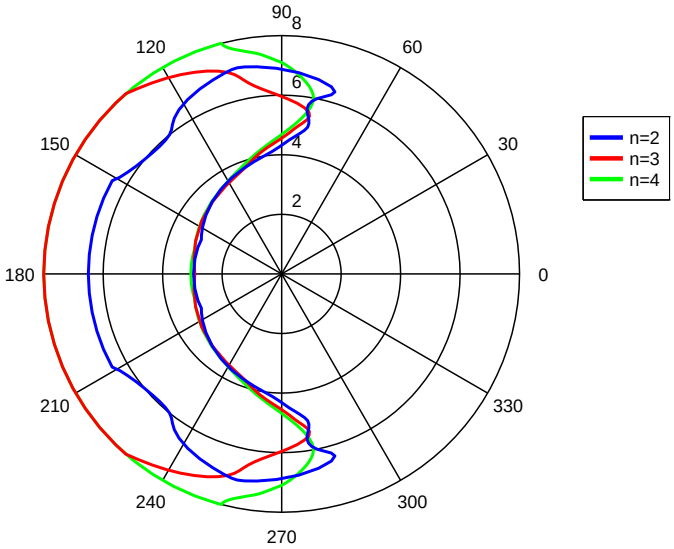

Figure 18. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2*D*.

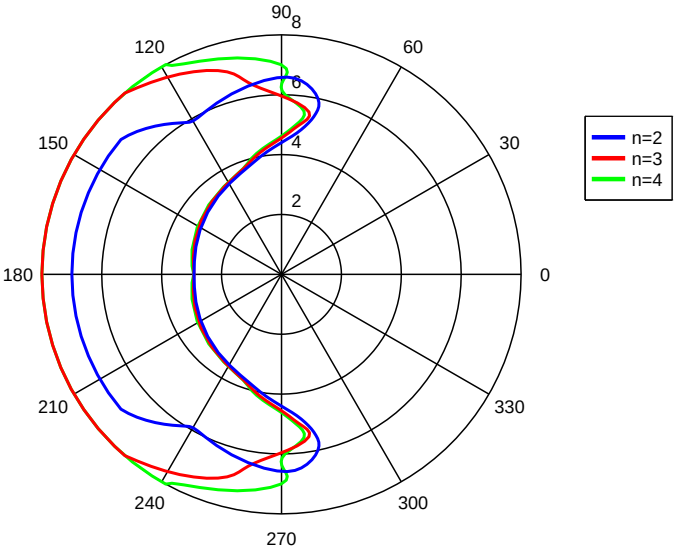

Figure 19. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2*D*.

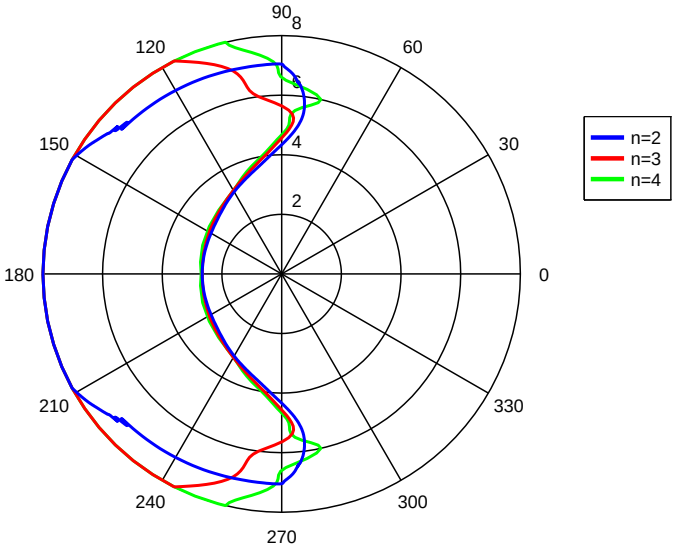

Figure 20. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2*D*.

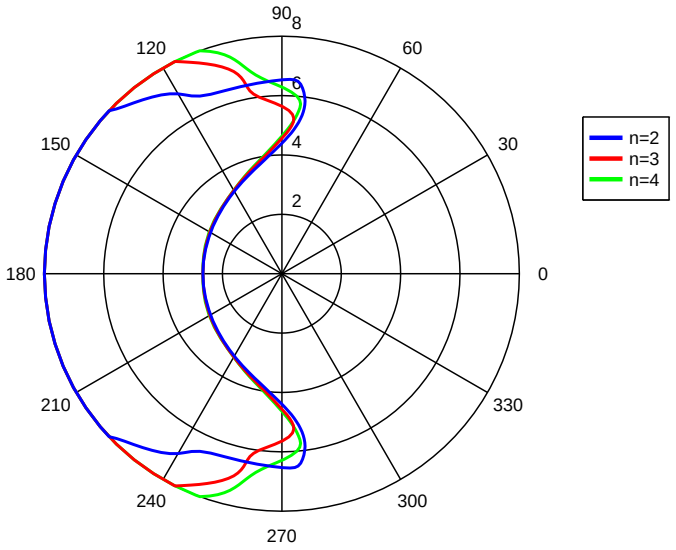

Figure 21. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2*D*.

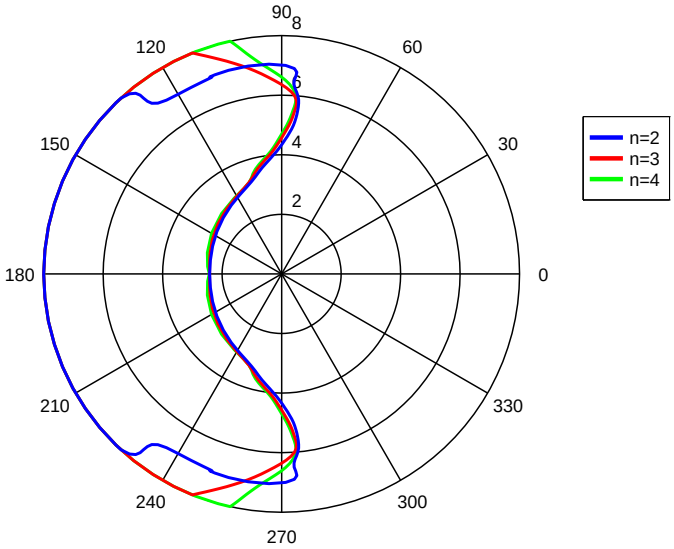

Figure 22. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2*D*.

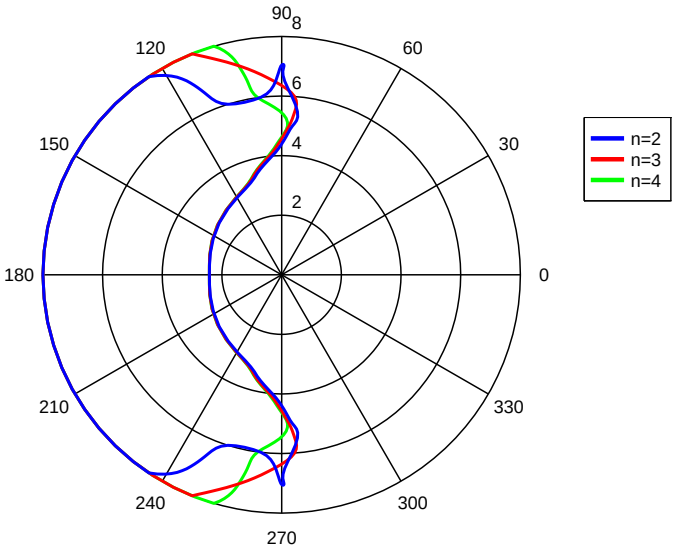

Figure 23. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2*D*.

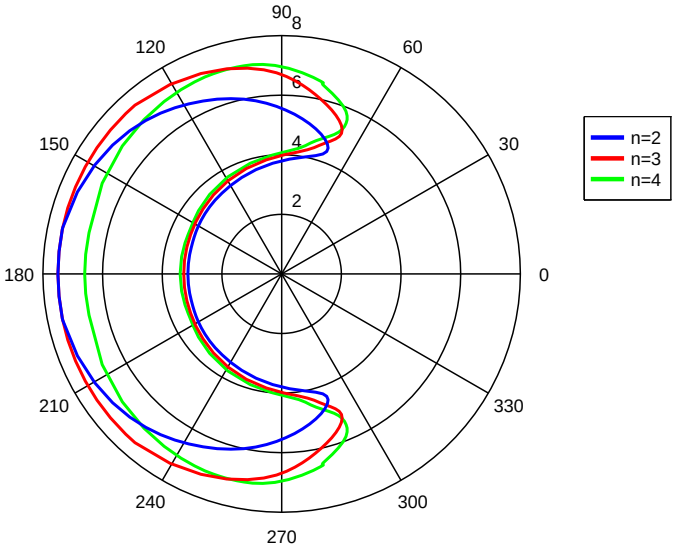

Figure 24. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2.5*D*.

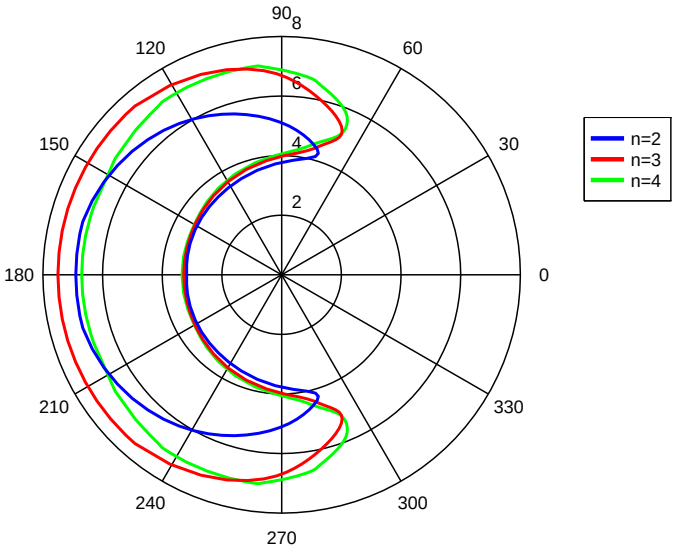

Figure 25. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2.5*D*.

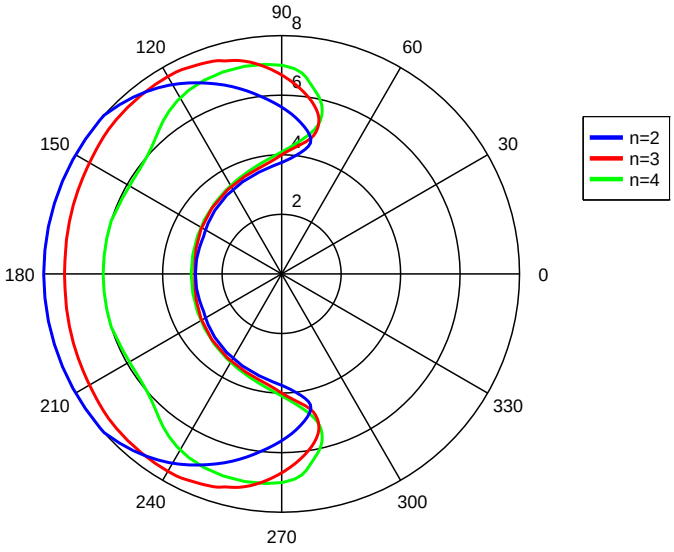

Figure 26. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2.5*D*.

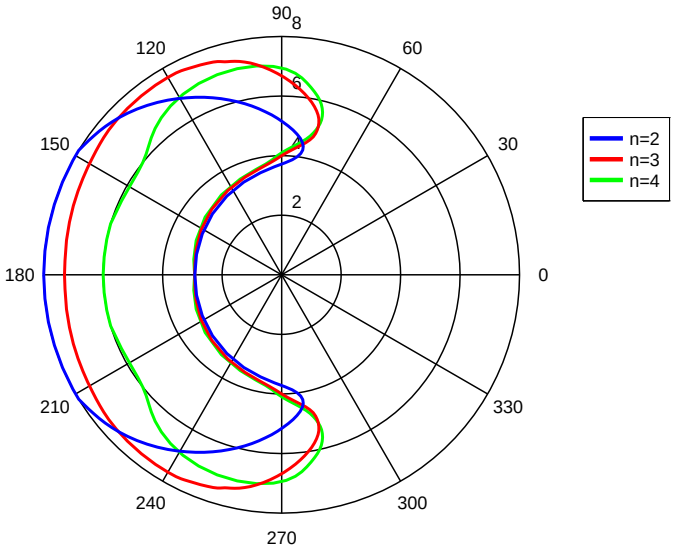

Figure 27. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2.5*D*.

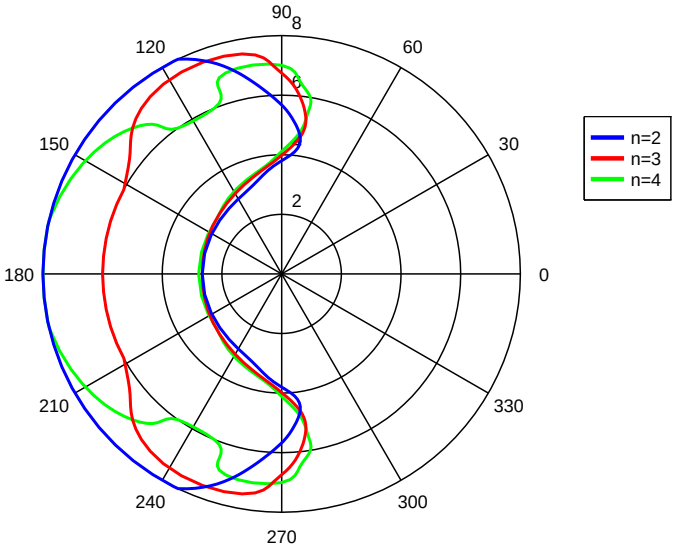

Figure 28. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2.5*D*.

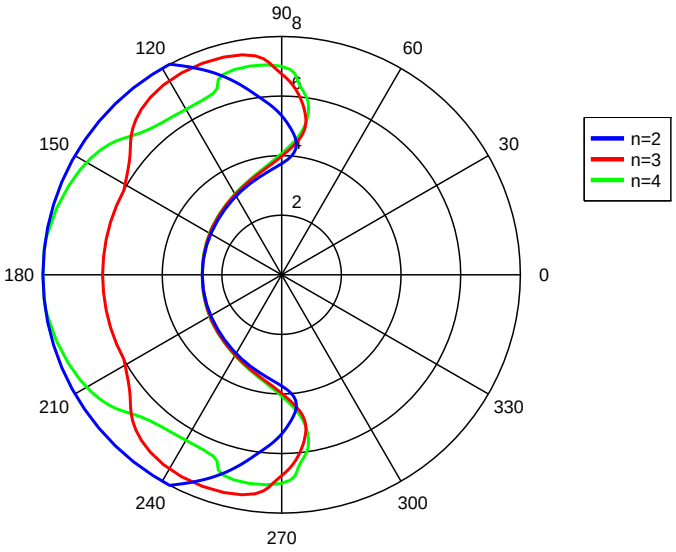

Figure 29. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2.5*D*.

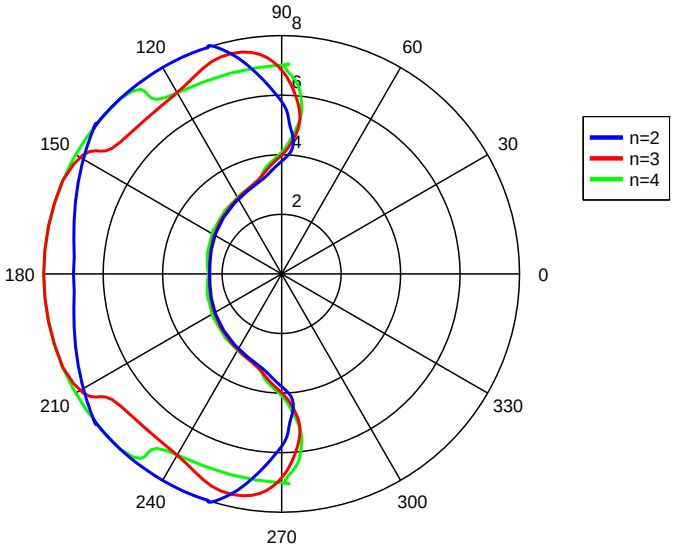

Figure 30. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2.5*D*.

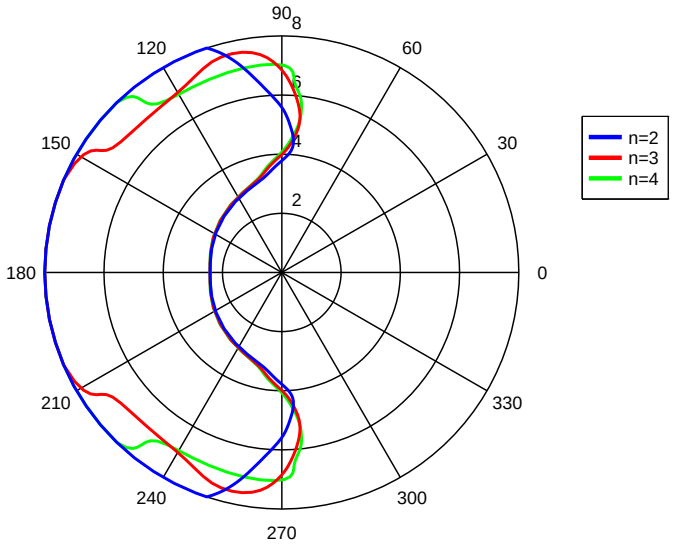

Figure 31. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2.5*D*.

C. SAIL BROACHING CRITERION RESULTS

The operability indices for the sail broaching criterion for the limited diameter and limited length cases in different speeds, operating depths and shape factors are shown in Tables III and IV, and in Figure 32. Typical polar plots are shown in Figures 33 through 56. Based on these results, the following conclusions can be drawn:

1. At smaller speeds, higher shape factors appear to result in smaller number of expected criterion violations. Smaller shape factors generally yield smaller indices.
2. The operability index tends to increase with increasing depth, and in general, it is a weak function of speed for all shape factors.
3. The operability index does not appear to depend on sea direction consistently. At certain directions, the operability index decreases significantly for various shape factor and speed/depth combinations.

		LIMITED DIAMETER			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.6101	0.6355	0.7321	0.5423
	n=3	0.7123	0.7138	0.7432	0.7013
	n=4	0.8405	0.8098	0.8029	0.7388
h=2D	n=2	0.9091	0.8768	0.8969	0.7627
	n=3	0.9135	0.9698	0.9635	0.9061
	n=4	0.9235	0.9356	0.9333	0.9816
h=2.5D	n=2	0.8466	0.7435	0.8083	0.7007
	n=3	1.0000	1.0000	0.7813	0.8746
	n=4	0.9777	0.8661	0.9421	0.8258

Table III : Operability indices for the sail broaching criterion for the limited diameter case.

		LIMITED LENGTH			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.6173	0.6726	0.6942	0.6070
	n=3	0.7123	0.7138	0.7432	0.7013
	n=4	0.7221	0.7314	0.7452	0.7717
h=2D	n=2	0.8744	0.9005	0.9006	0.8634
	n=3	0.9135	0.9698	0.9635	0.9061
	n=4	0.9068	0.9333	0.9608	0.9479
h=2.5D	n=2	0.6925	0.6920	0.7799	0.7395
	n=3	1.0000	1.0000	0.7813	0.8746
	n=4	0.9761	0.8963	0.9408	0.8310

Table IV : Operability indices for sail broaching criterion for the limited length case.

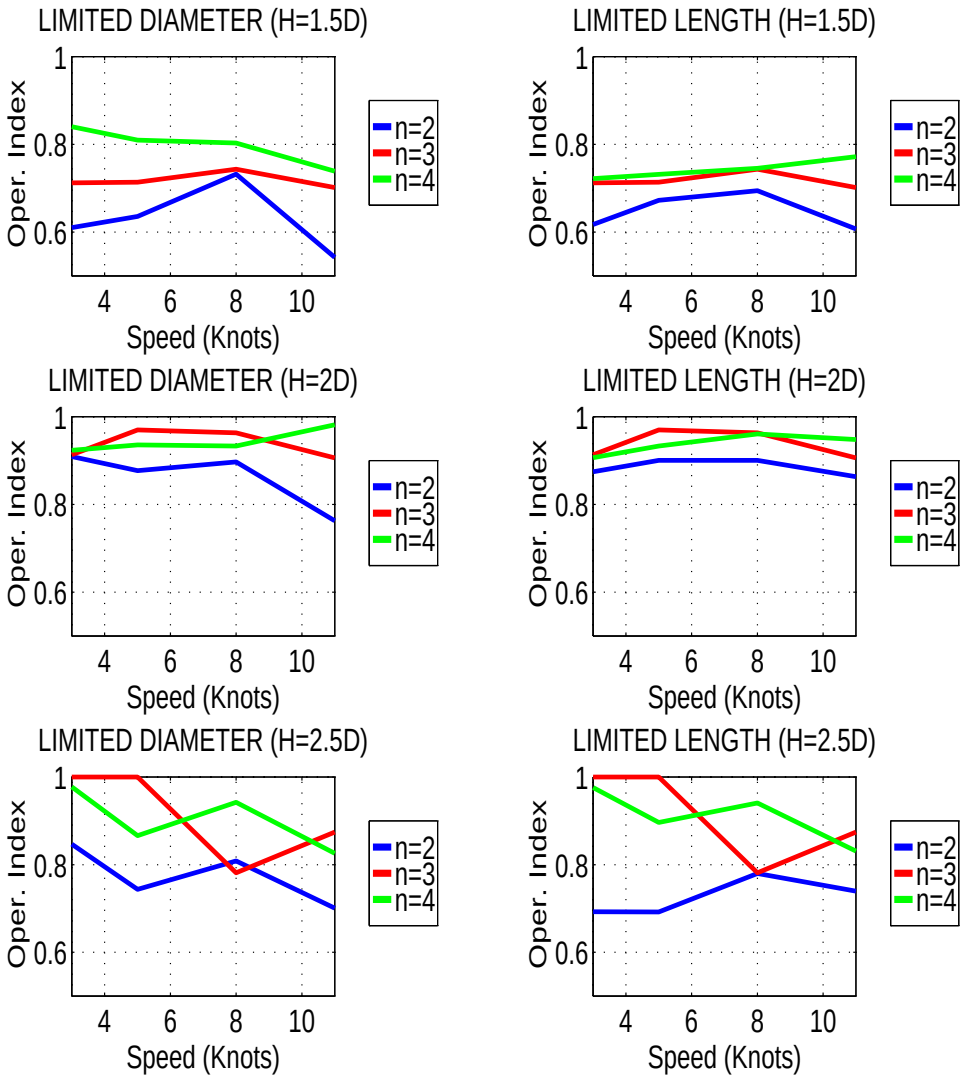

Figure 32. OI vs. submarine speed plots for sail broaching criterion.

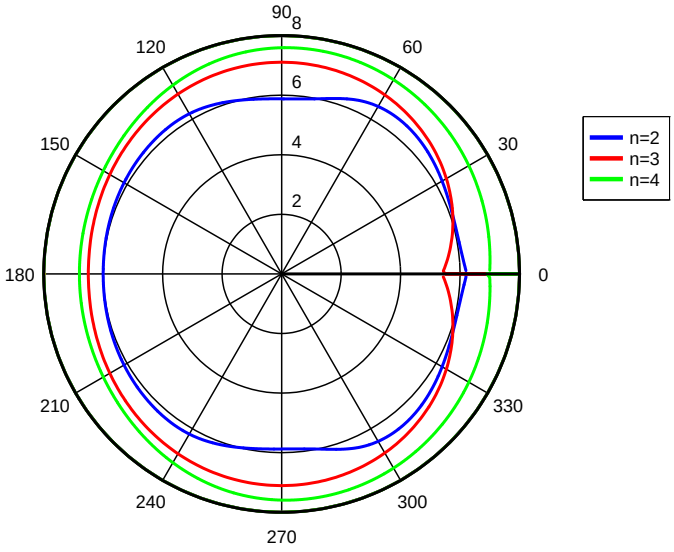

Figure 33. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=1.5*D*.

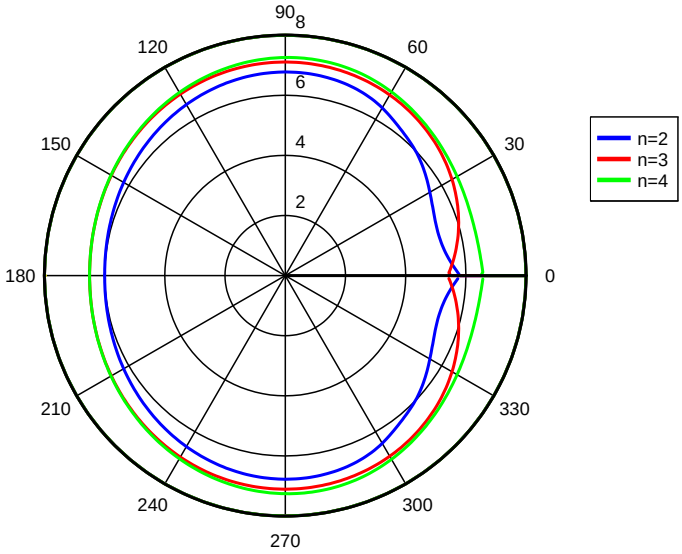

Figure 34. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=1.5*D*.

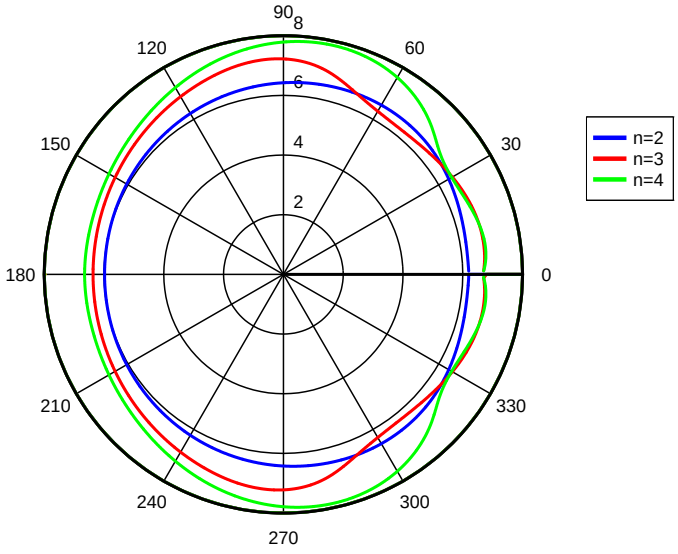

Figure 35. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=1.5*D*.

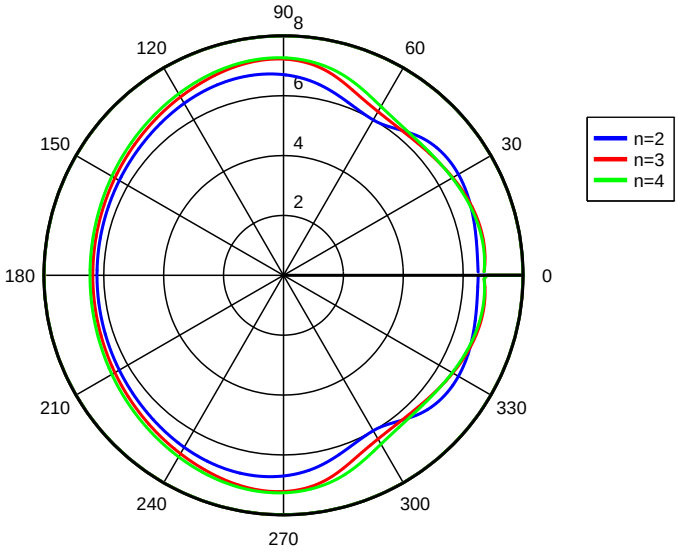

Figure 36. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=1.5*D*.

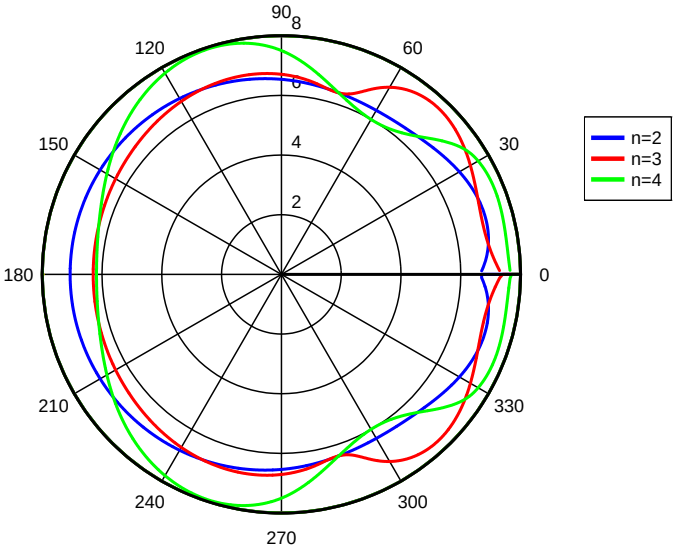

Figure 37. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=1.5*D*.

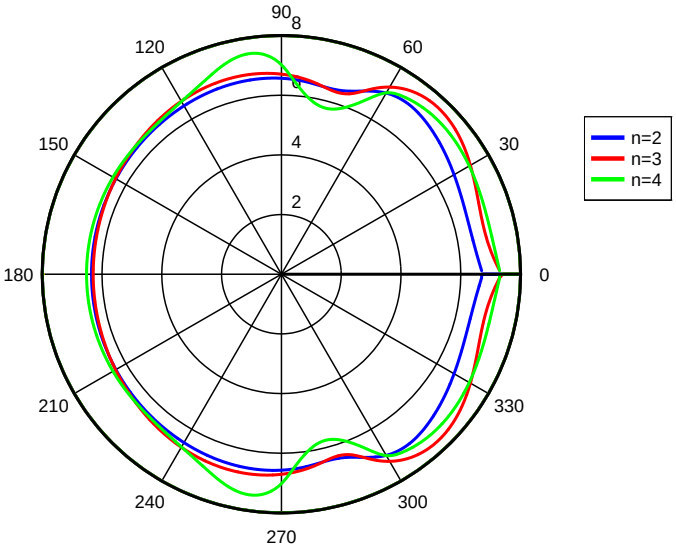

Figure 38. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=1.5*D*.

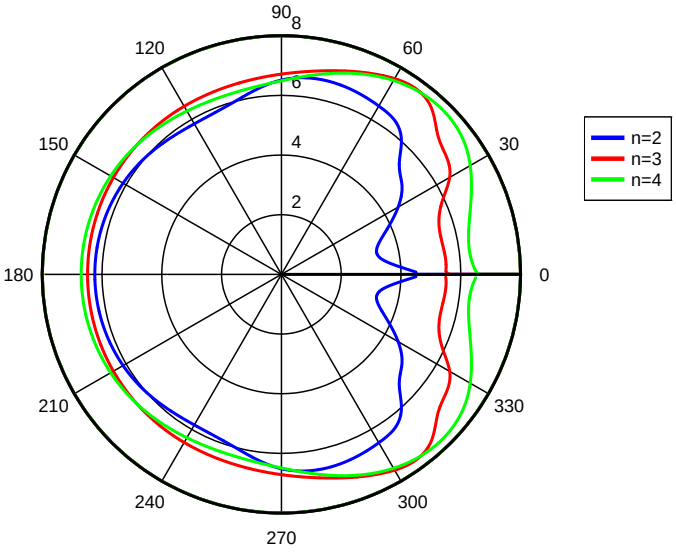

Figure 39. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=1.5*D*.

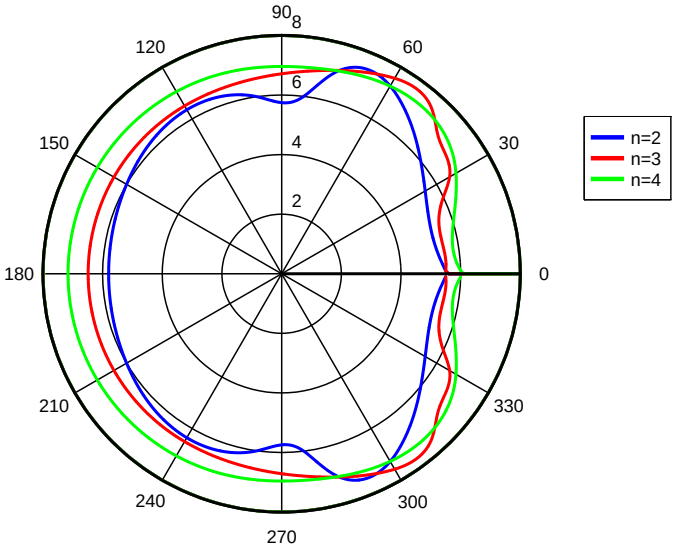

Figure 40. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=1.5*D*.

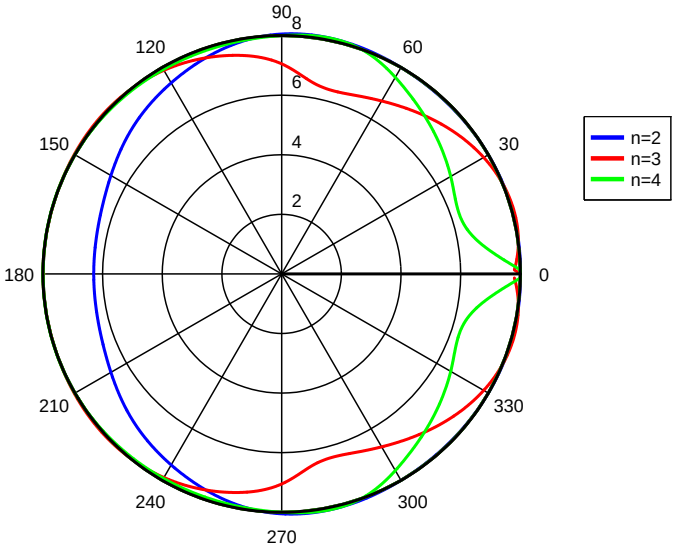

Figure 41. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2*D*.

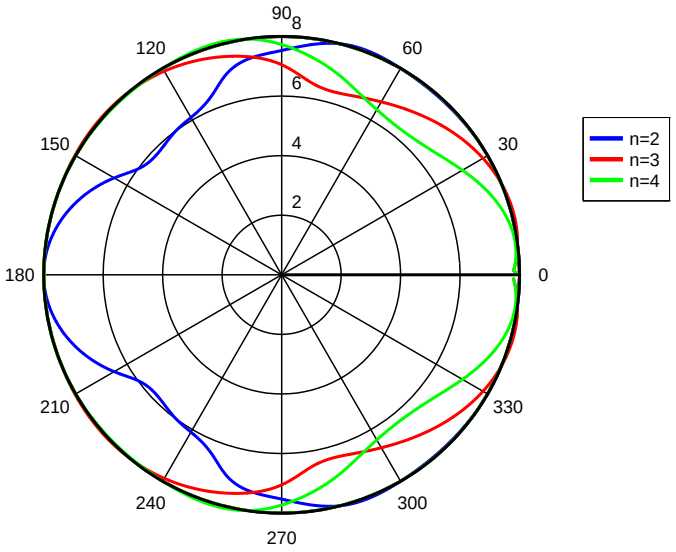

Figure 42. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2*D*.

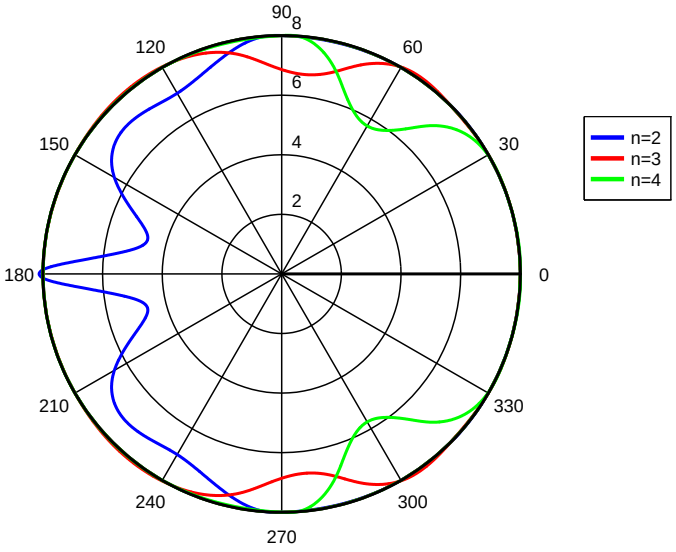

Figure 43. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2*D*.

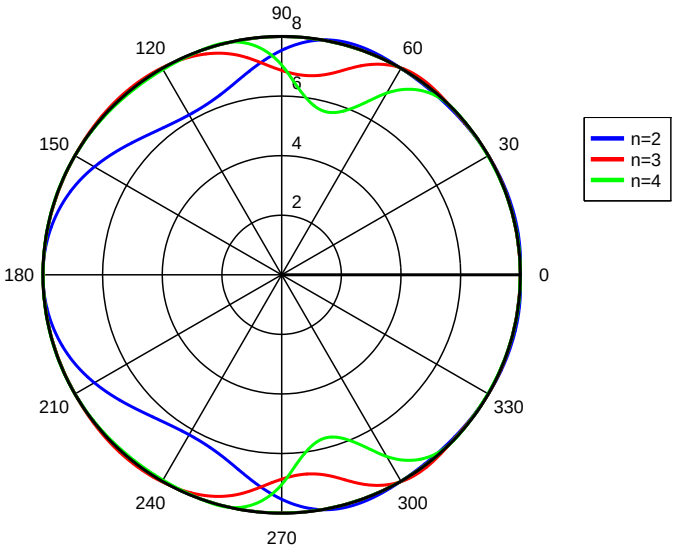

Figure 44. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2*D*.

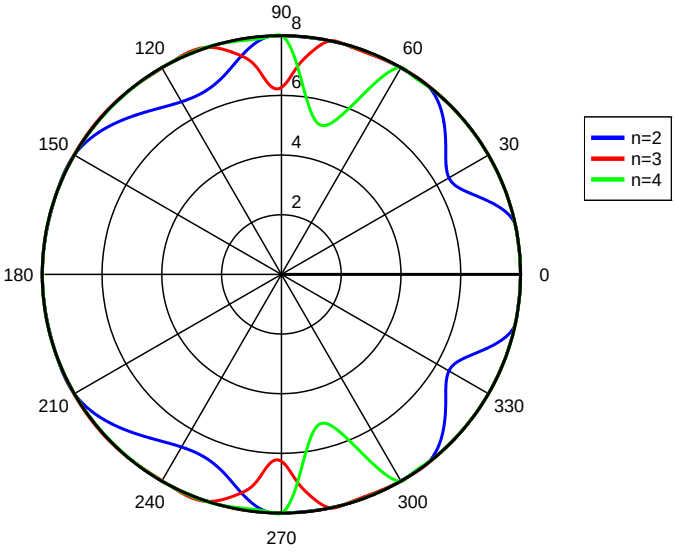

Figure 45. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2*D*.

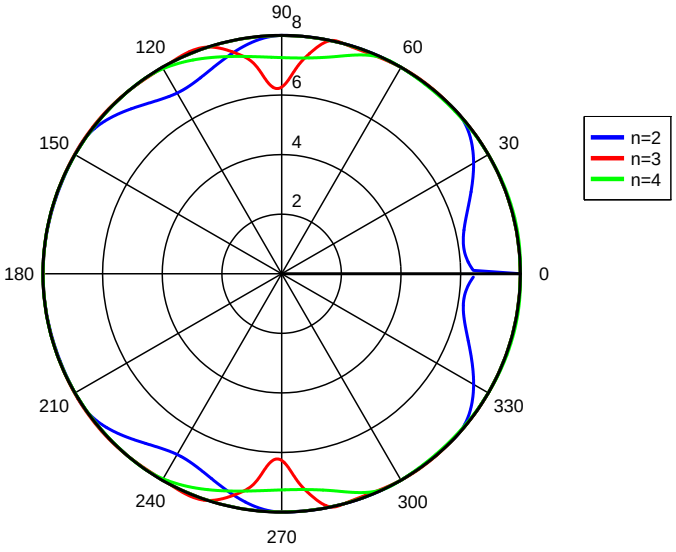

Figure 46. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2*D*.

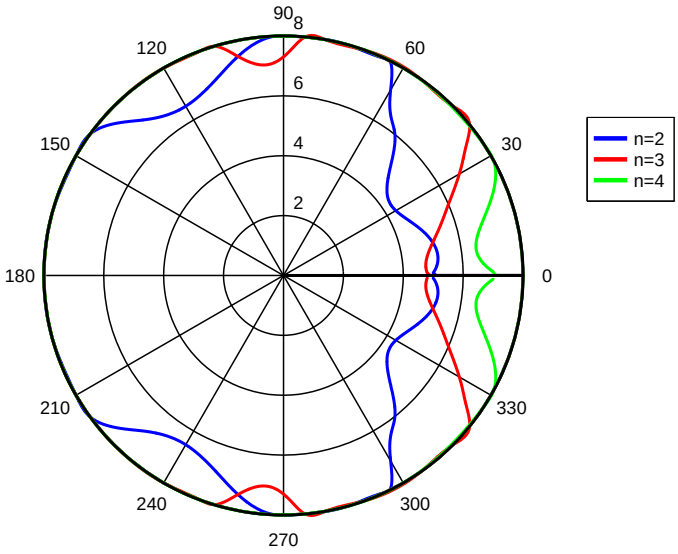

Figure 47. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2*D*.

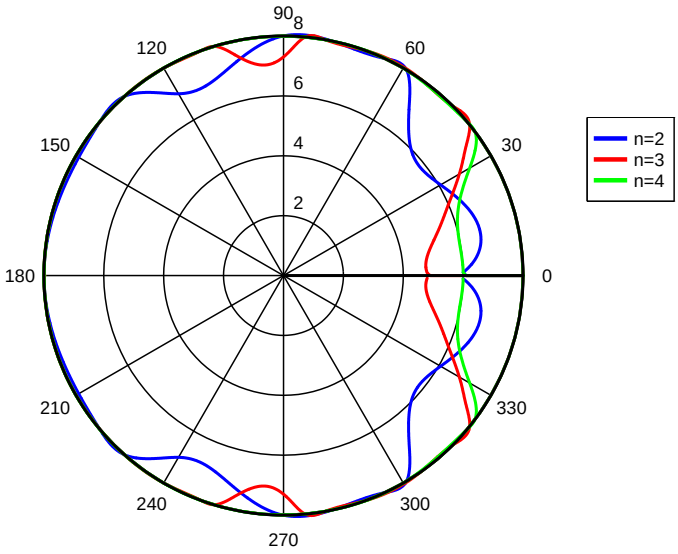

Figure 48. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2*D*.

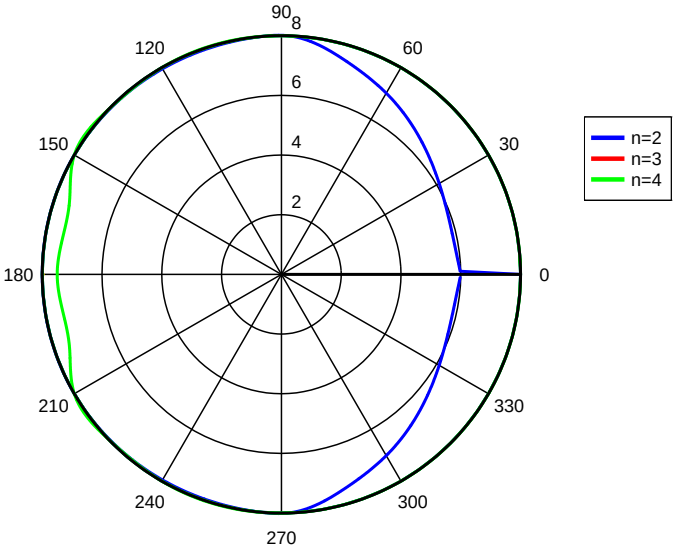

Figure 49. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2.5*D*.

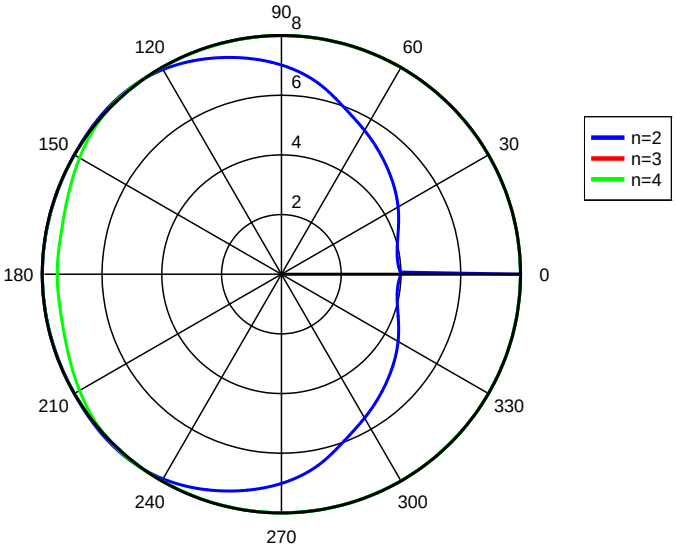

Figure 50. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2.5*D*.

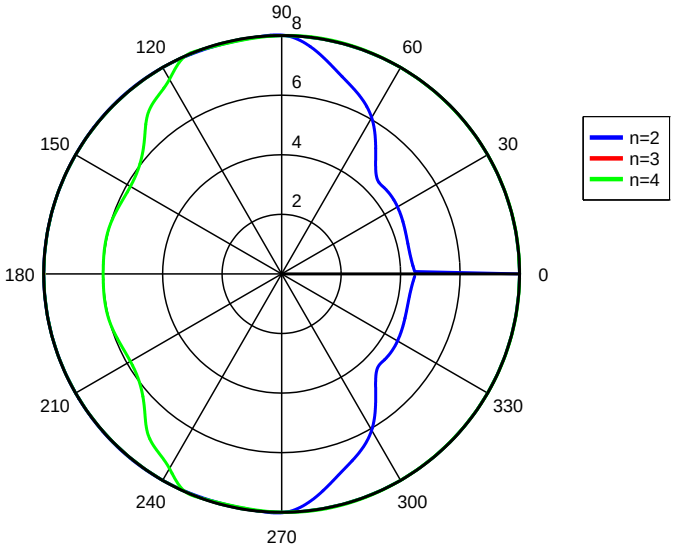

Figure 51. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2.5*D*.

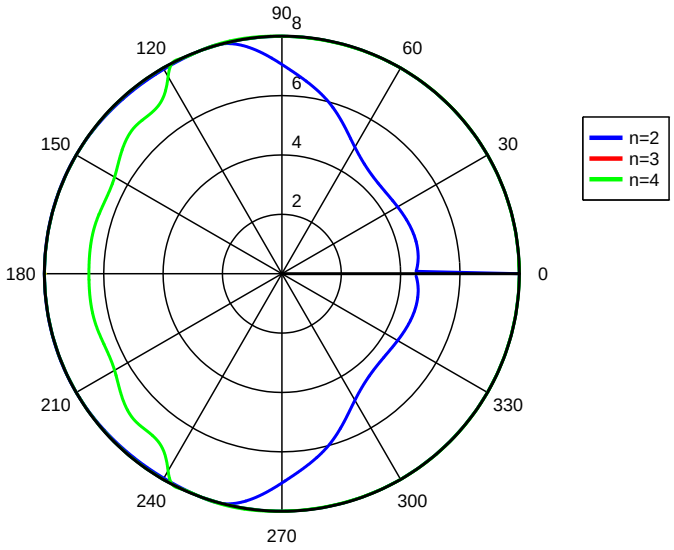

Figure 52. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2.5*D*.

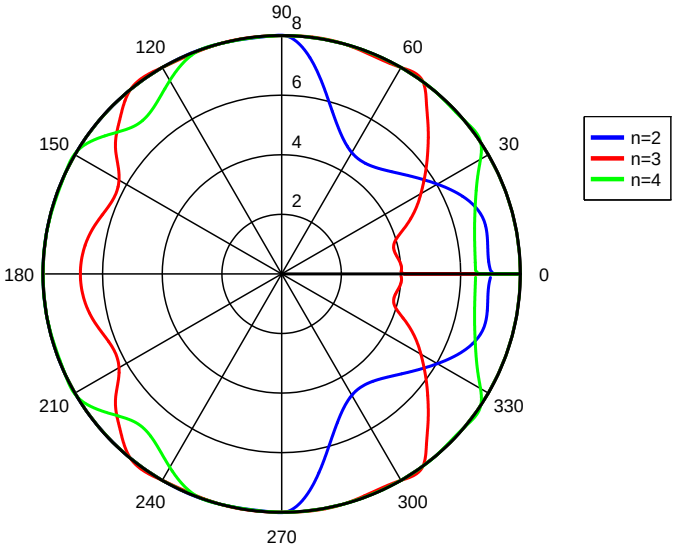

Figure 53. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2.5*D*.

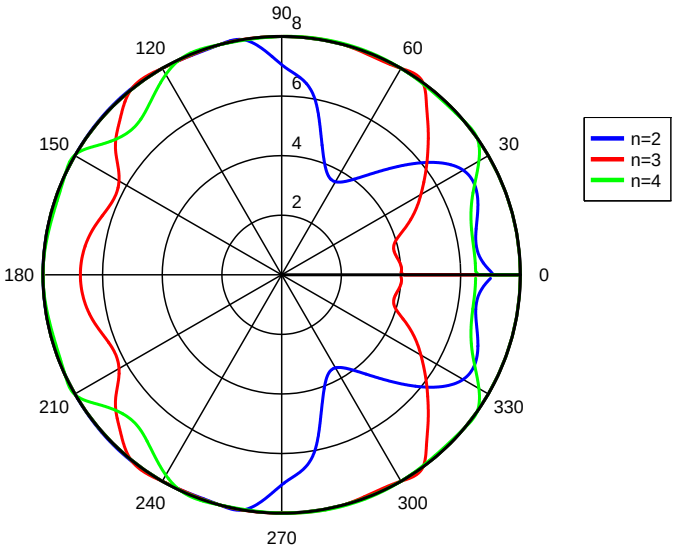

Figure 54. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2.5*D*.

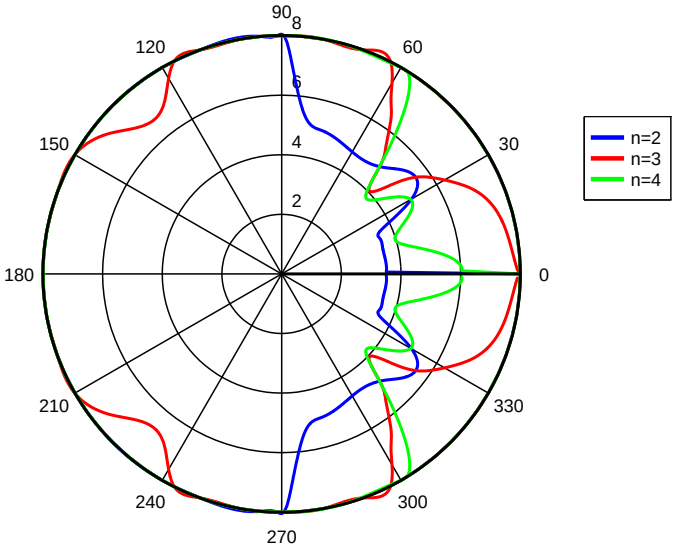

Figure 55. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2.5*D*.

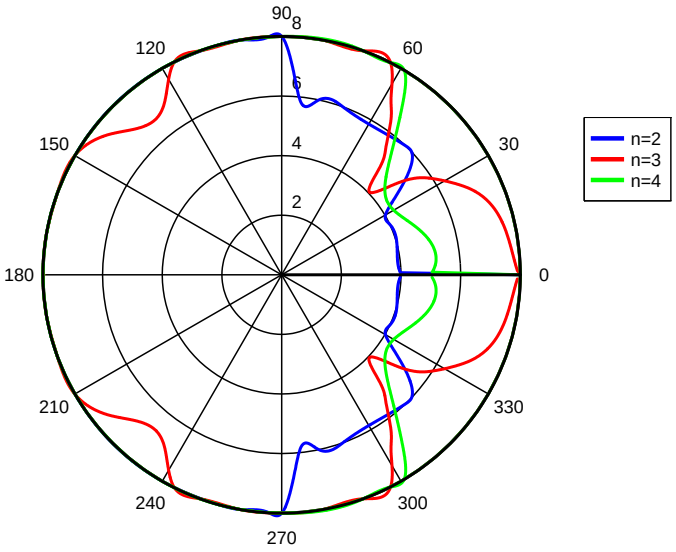

Figure 56. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2.5*D*.

D. COMBINED CRITERION RESULTS

The operability indices for the combined criterion for the limited diameter and limited length cases in different speeds, operating depths and shape factors are shown in Tables V and VI, and in Figure 57. Typical polar plots are shown in Figures 58 through 81. Based on these results, the following conclusions can be drawn:

1. At smaller operating depths, varying the shape factors appear to yield a slight change in the number of expected criterion violations. At higher depths, smaller shape factors result in smaller operability indices.
2. Velocity has a little effect on the operability indices at smaller operating depths. As the depth increases, the indices appear to decrease with increasing speed.

		LIMITED DIAMETER			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.4259	0.4259	0.4297	0.3085
	n=3	0.4694	0.4689	0.5067	0.4492
	n=4	0.5474	0.5107	0.4875	0.4976
h=2D	n=2	0.6236	0.6423	0.5307	0.3861
	n=3	0.5907	0.6030	0.5798	0.4959
	n=4	0.5238	0.5270	0.5179	0.5622
h=2.5D	n=2	0.5516	0.3744	0.4024	0.3116
	n=3	0.6382	0.6040	0.4760	0.4911
	n=4	0.6674	0.6342	0.5999	0.4293

Table V : Operability indices for combined criterion for the limited diameter case.

		LIMITED LENGTH			
		U=3	**U=5**	**U=8**	**U=11**
h=1.5D	n=2	0.4147	0.4295	0.4396	0.3974
	n=3	0.4694	0.4689	0.5067	0.4492
	n=4	0.4762	0.4772	0.4651	0.4638
h=2D	n=2	0.6461	0.6408	0.5286	0.4994
	n=3	0.5907	0.6030	0.5798	0.4959
	n=4	0.5334	0.5435	0.5676	0.5488
h=2.5D	n=2	0.4628	0.3560	0.3896	0.3247
	n=3	0.6382	0.6313	0.4760	0.4911
	n=4	0.6624	0.6312	0.5921	0.4347

Table VI : Operability indices for combined criterion for the limited length case.

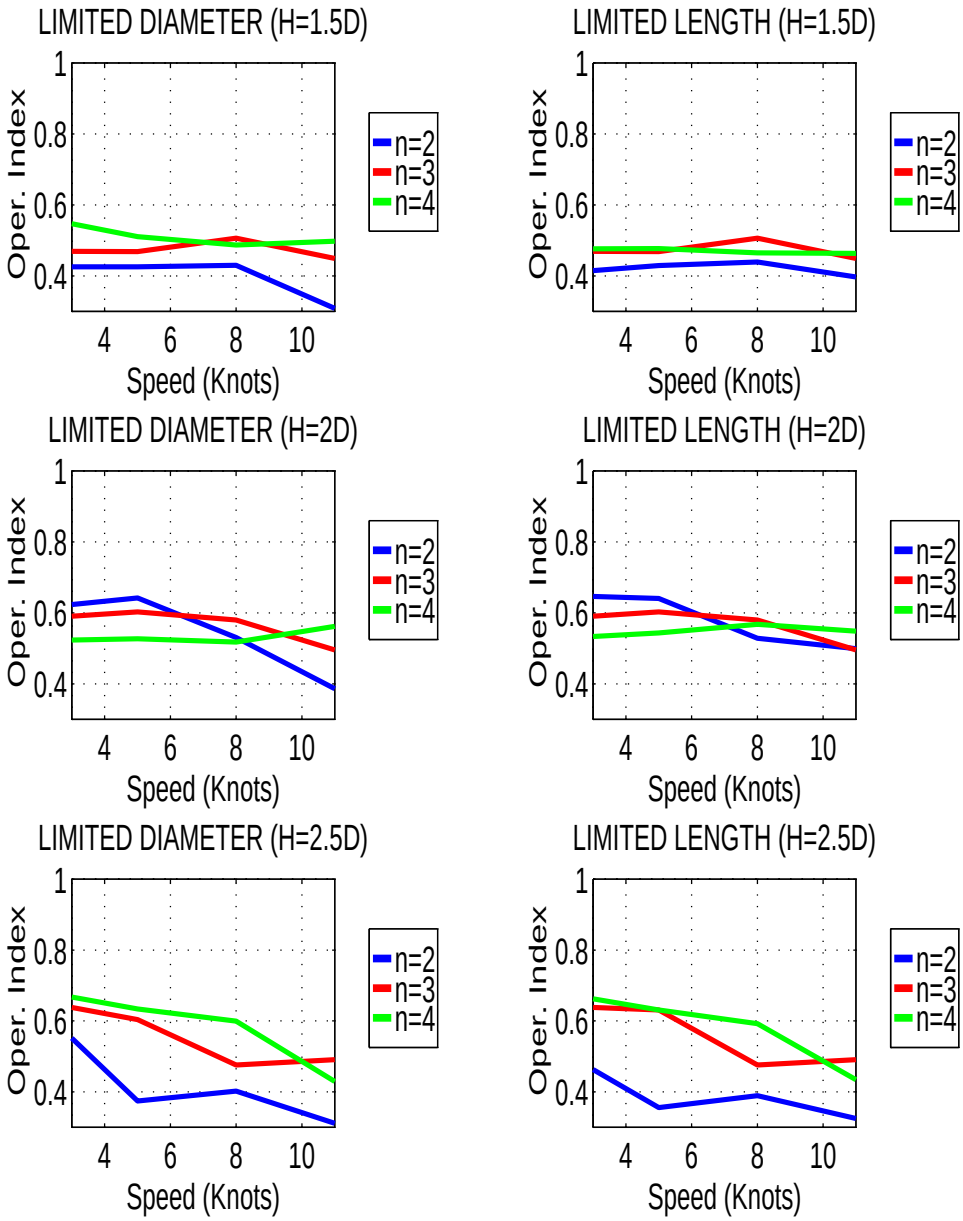

Figure 57. OI vs. submarine speed plots for combined criterion.

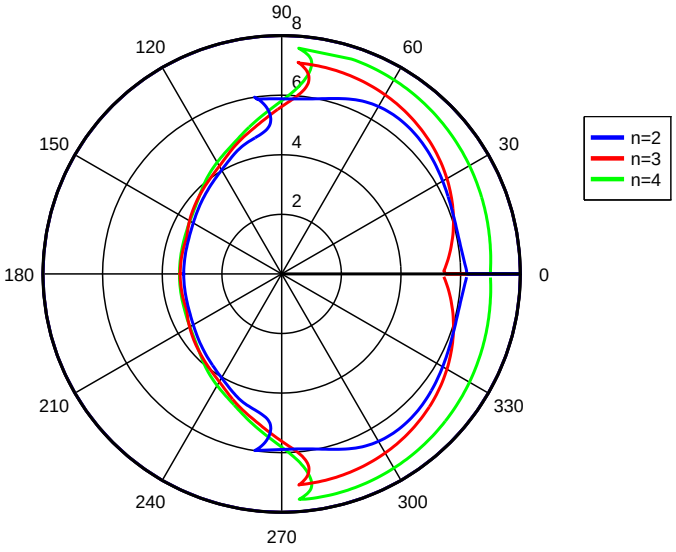

Figure 58. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=1.5*D*.

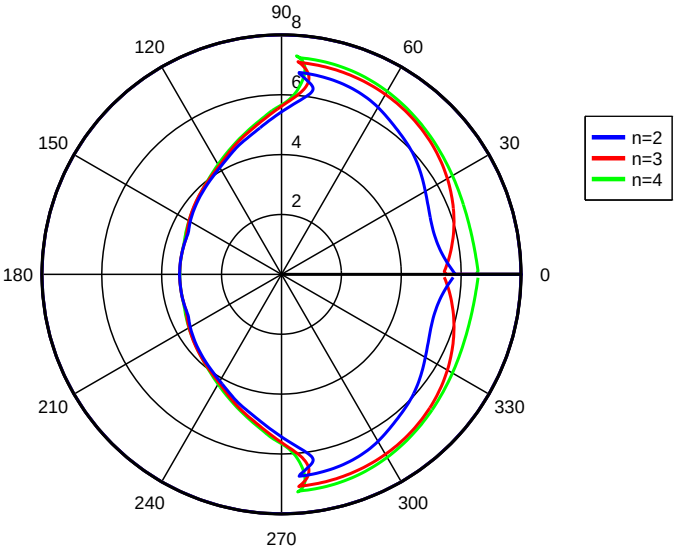

Figure 59. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=1.5*D*.

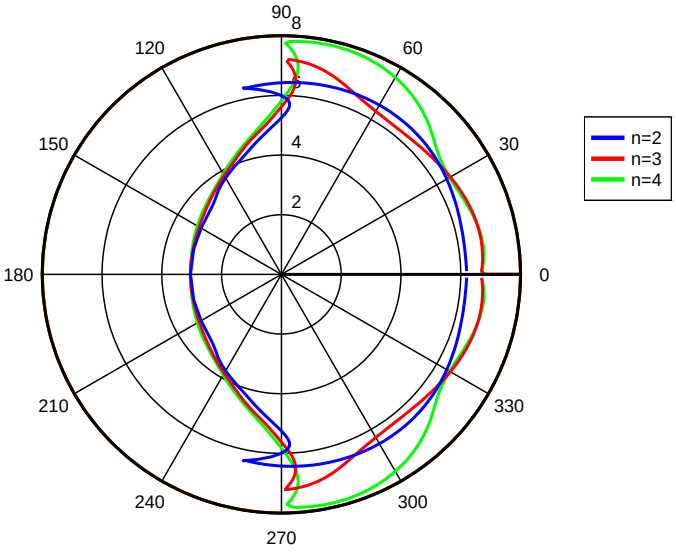

Figure 60. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=1.5*D*.

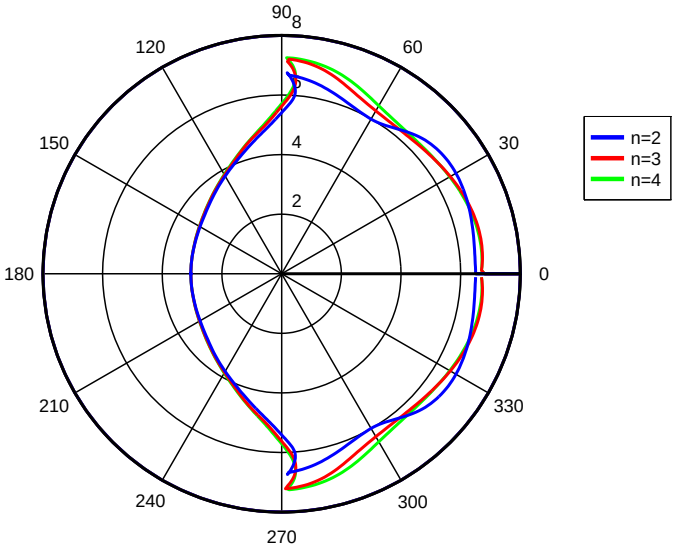

Figure 61. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=1.5*D*.

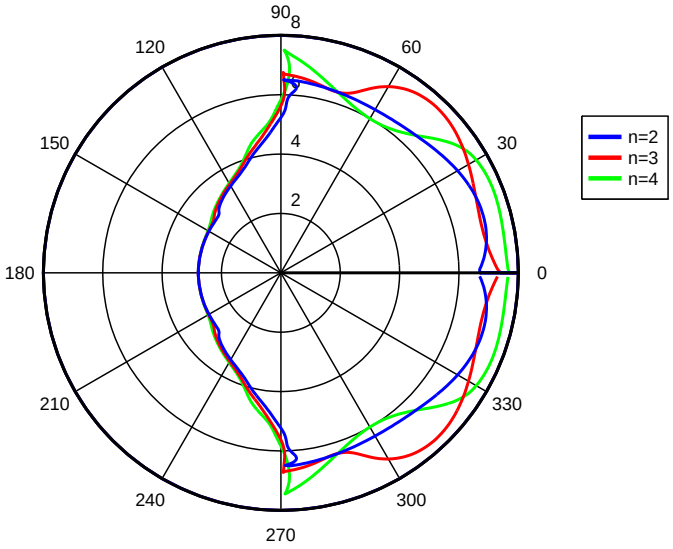

Figure 62. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=1.5*D*.

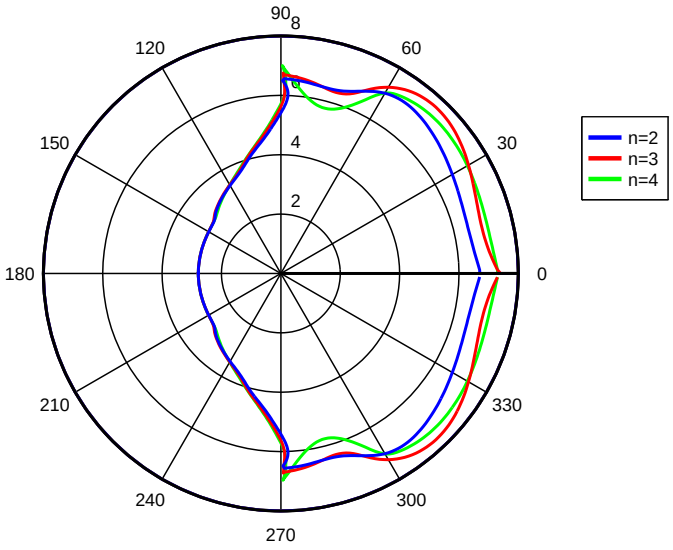

Figure 63. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=1.5*D*.

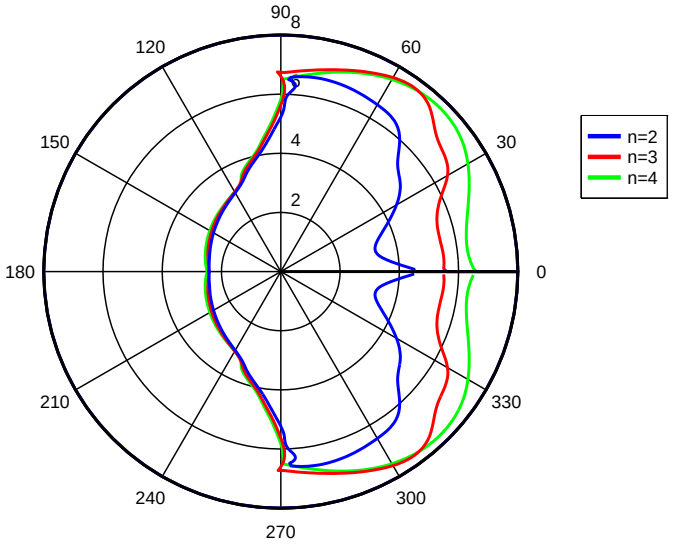

Figure 64. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=1.5*D*.

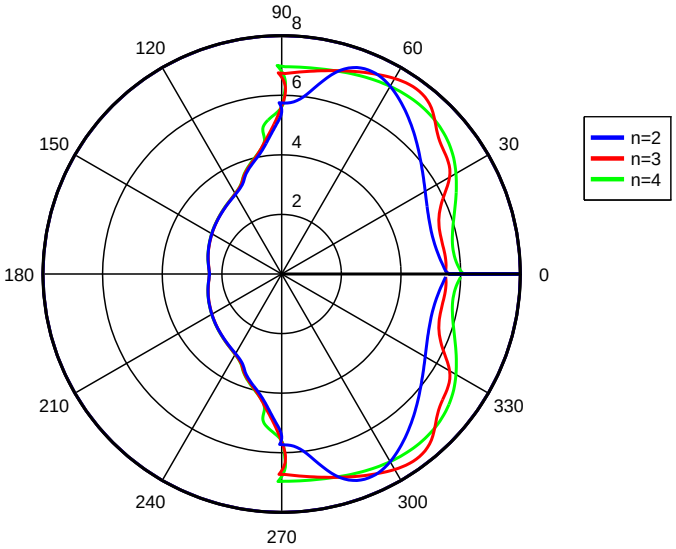

Figure 65. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=1.5*D*.

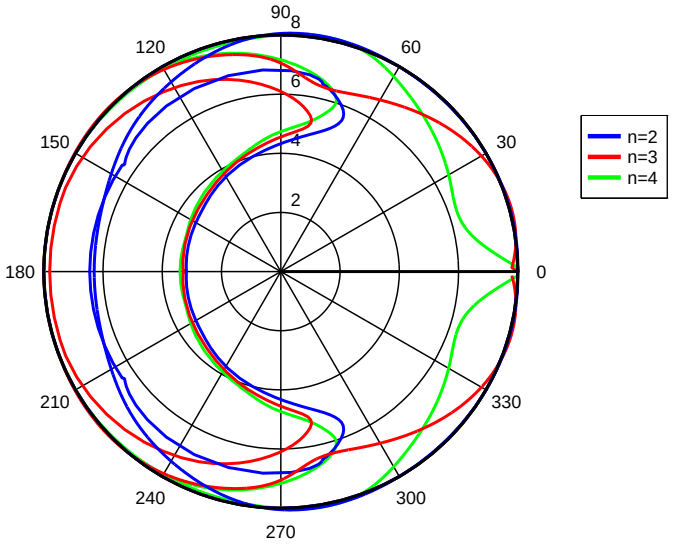

Figure 66. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2*D*.

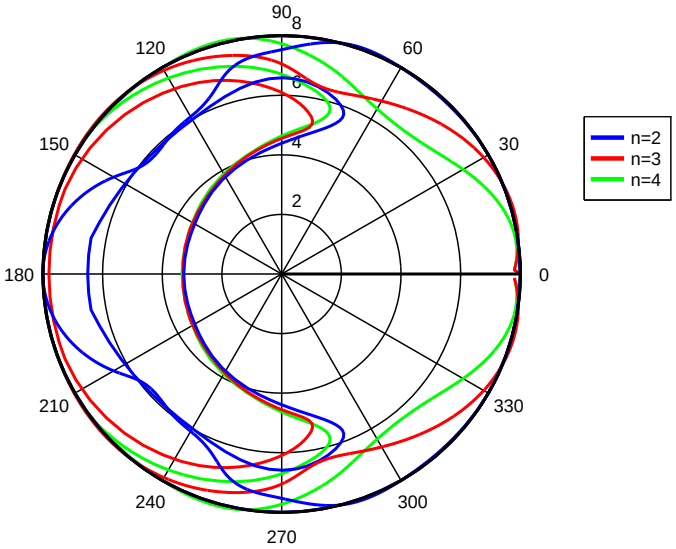

Figure 67. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2*D*.

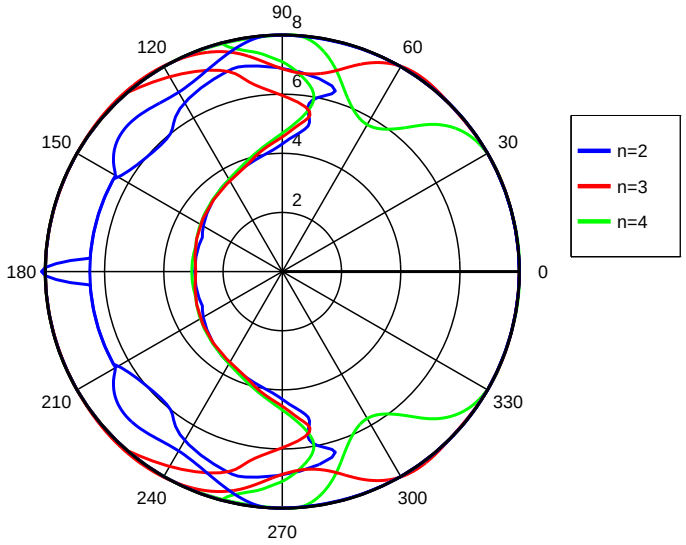

Figure 68. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2*D*.

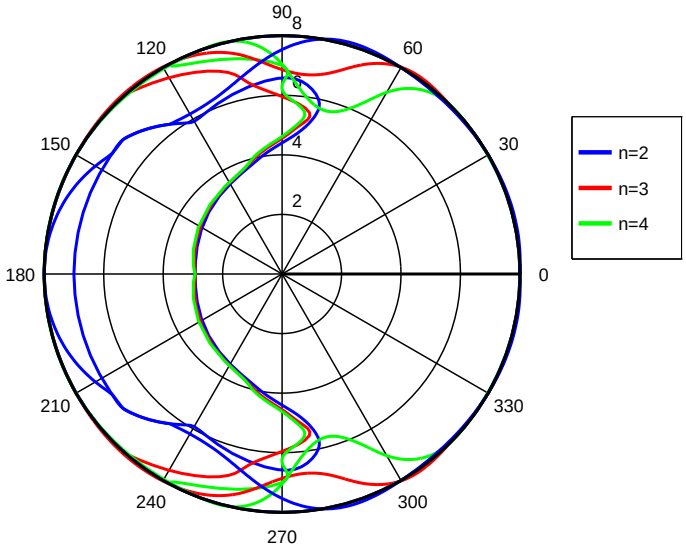

Figure 69. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2*D*.

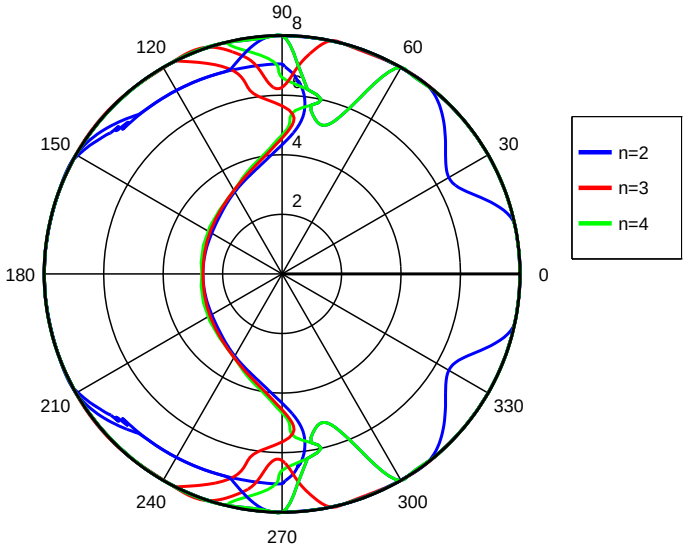

Figure 70. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2*D*.

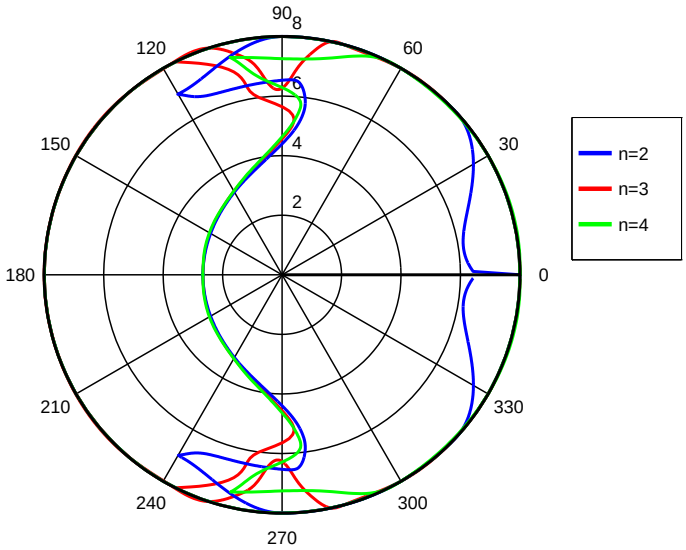

Figure 71. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2*D*.

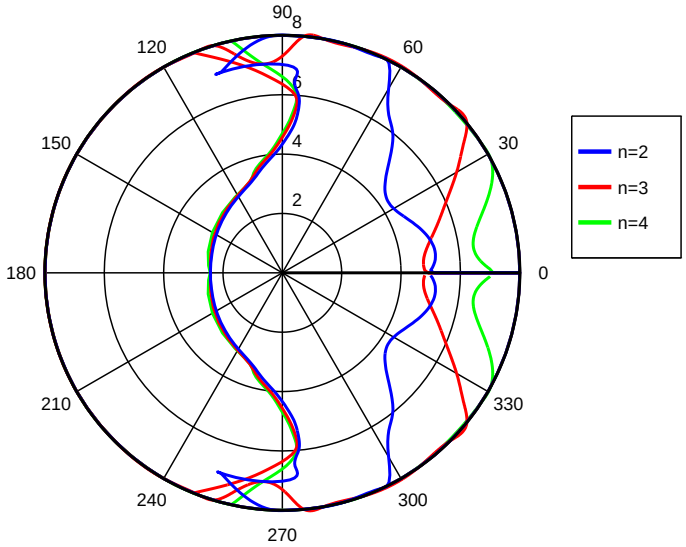

Figure 72. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2*D*.

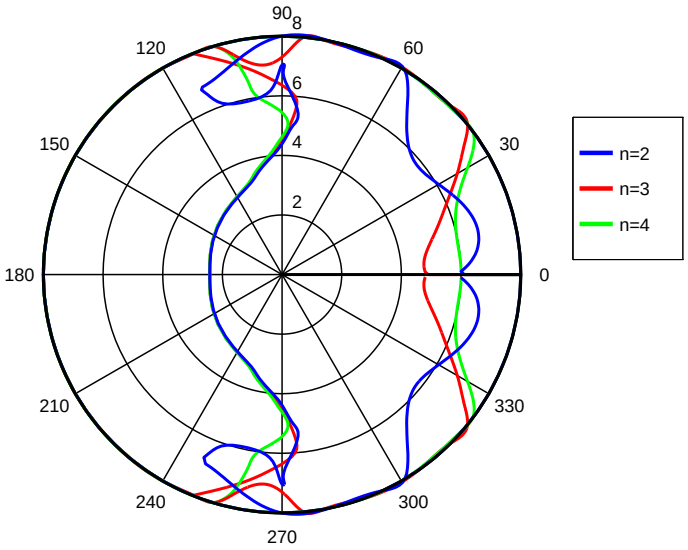

Figure 73. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2*D*.

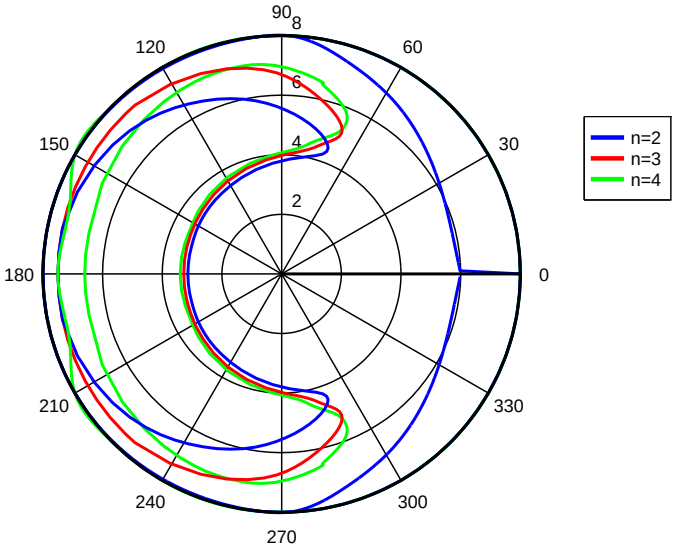

Figure 74. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=3 Knots, h=2.5*D*.

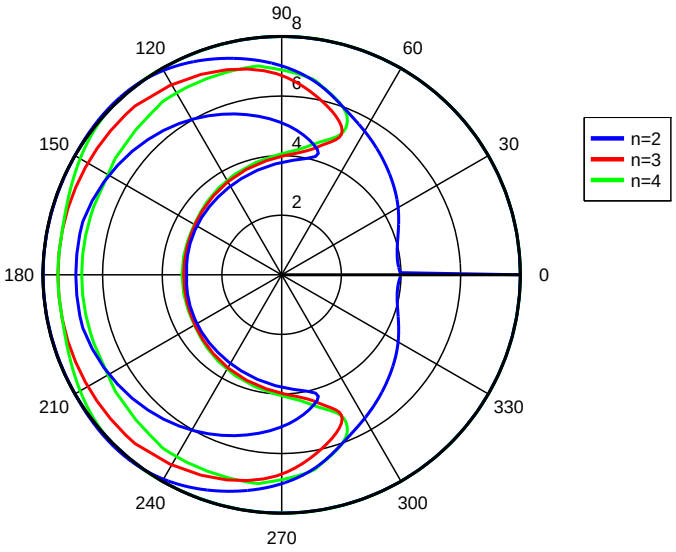

Figure 75. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=3 Knots, h=2.5*D*.

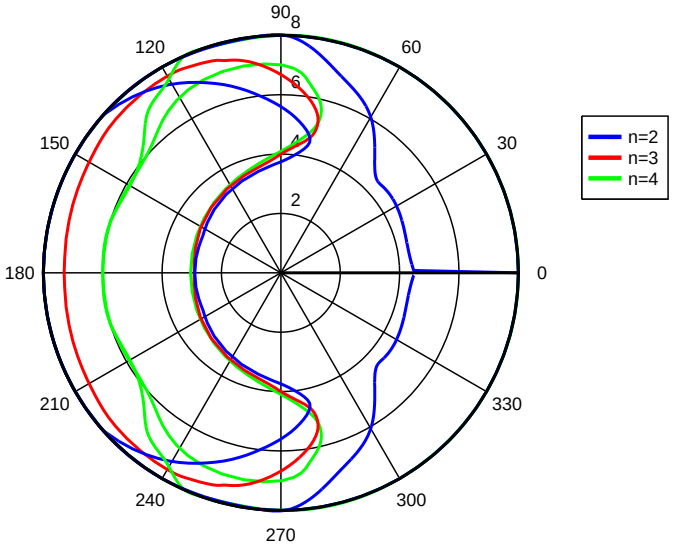

Figure 76. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=5 Knots, h=2.5*D*.

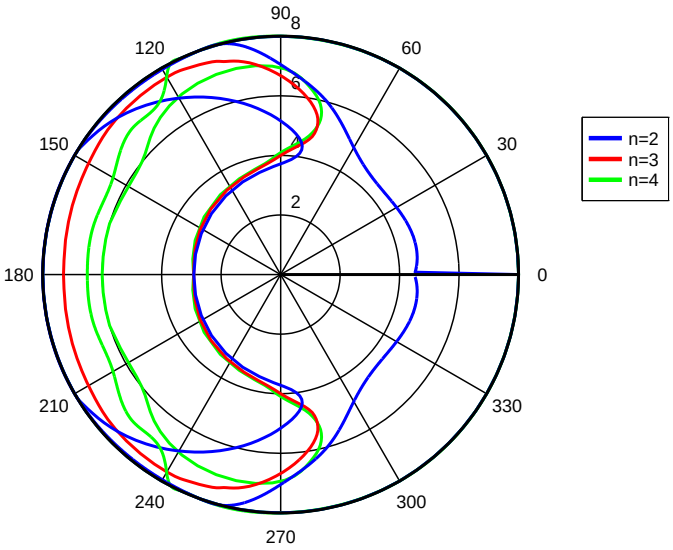

Figure 77. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=5 Knots, h=2.5*D*.

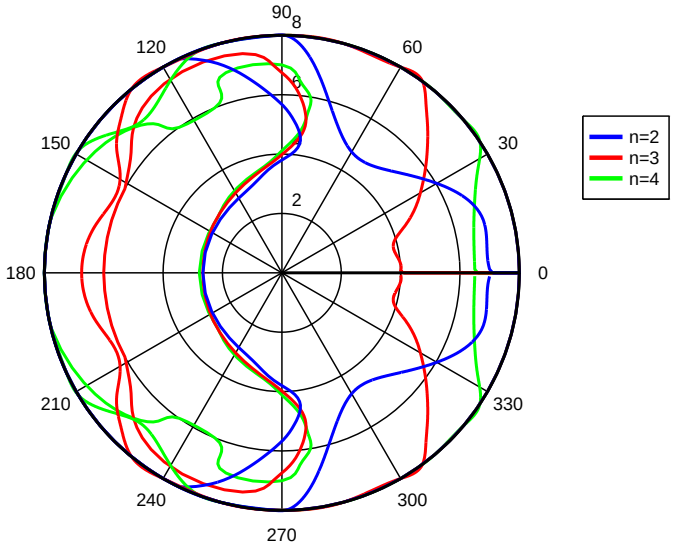

Figure 78. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=8 Knots, h=2.5*D*.

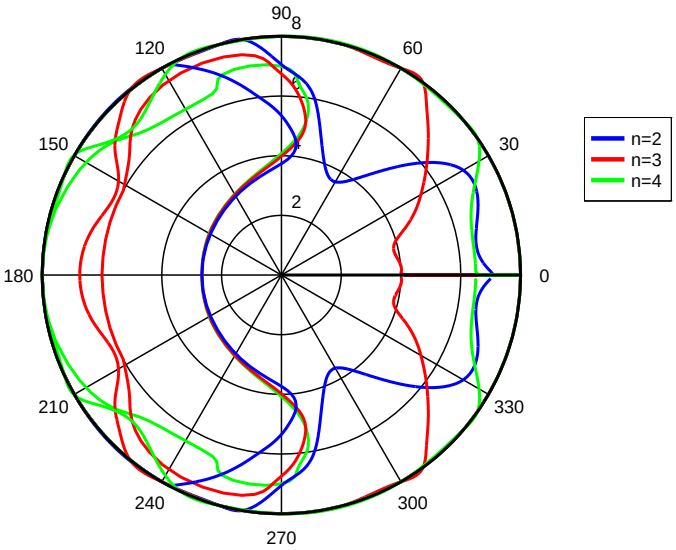

Figure 79. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=8 Knots, h=2.5*D*.

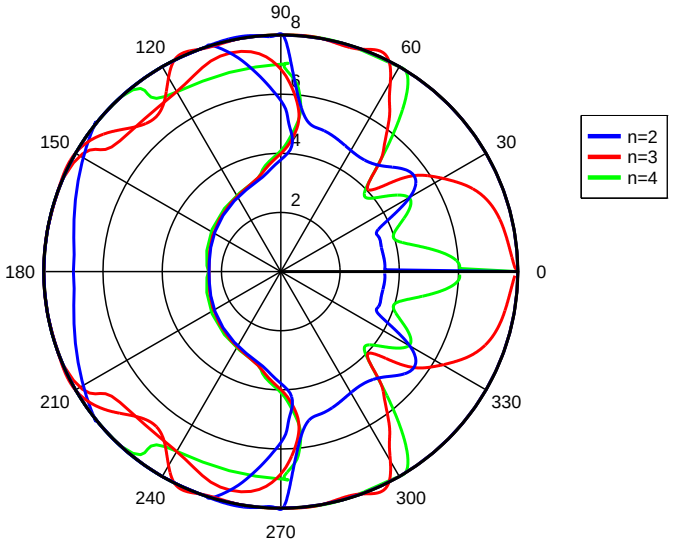

Figure 80. Sea state-polar plot, showing the effect of shape factors in limited diameter case, for U=11 Knots, h=2.5*D*.

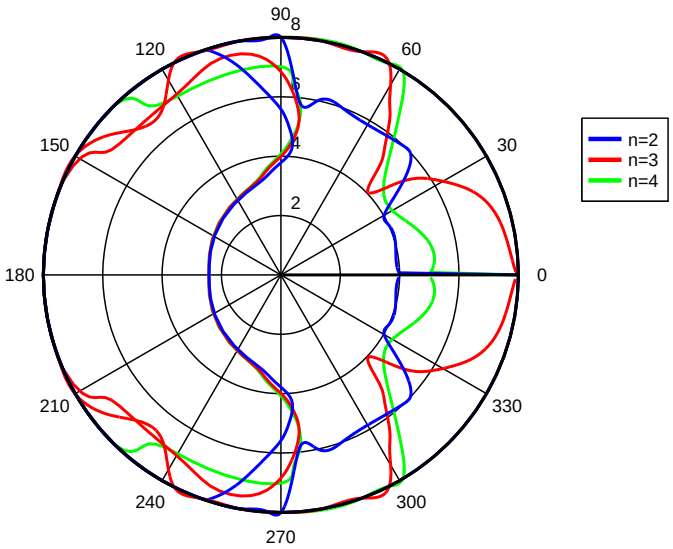

Figure 81. Sea state-polar plot, showing the effect of shape factors in limited length case, for U=11 Knots, h=2.5*D*.