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HYDRODYNAMIC ANALYSIS OF DOLPHIN FIN PROFILES

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DOLPHIN fins have well-streamlined cross-sections that may be useful as hydrofoils or airfoils designed to operate in the Reynolds number range around 10^6. Possible applications might be torpedo fins and propeller or pumpjet blades, boat propellers, rudders, keels, struts and hydrofoils, helicopter rotor blades, windmill vanes, and sailplane wings and control surfaces.

Photographs of cross-sections of one dolphin tail fluke and two dorsal fins were obtained from animals that had died of natural causes. The cross-sections were obtained about midway between the bases and the tips of the three fins. Fin offsets were measured from the photographs and plotted on a 2-m scale. The best curves possible were drawn through the measured points; the maximum deviation being 0·2 per cent or about 0·02 cm. About eighty points were read from the 'best' curves and run on an IBM 7094 computer at the Naval Ordance Test Station to obtain pressure distribution using the Douglas two-dimensional airfoil programme which assumes potential flow. Pressure distribution is generally the most significant factor in analysing the performance of hydrofoil or airfoil cross-sections.

The profiles and pressure distributions of the three fins are shown in Fig. 1. Fin A is a tail fluke section of a common dolphin (*Delphinus bairdi*), fin B is a dorsal section of a Pacific striped dolphin (*Lagenorhyncus obliquidens*), and fin C is a dorsal section of a Dall porpoise (*Phocoenoides dalli*). The lower portion of Fig. 1 illustrates the upper half of the cross-section of each fin; the semi-thickness to chord ratio, y/c, is plotted against chord length from the leading edge. The upper portion of Fig. 1 shows the pressure distribution where:

$$C_P = \frac{P - P_0}{\rho \; V_0^2/2}$$

and P_0 is the depth pressure, P the local static pressure on the fin, ρ, mass density of the flowing fluid, and V_0, the fluid speed relative to the fin.

The fin chord lengths are between 12 and 18 cm long. The fin offsets are listed in Table 1. The effect of angle of attack on the pressure distribution of fin A is shown in Fig. 2. Maximum thickness and its location, leading edge radius, trailing edge thickness, and minimum pressure coefficient, C_p, and its location are listed in Table 2.

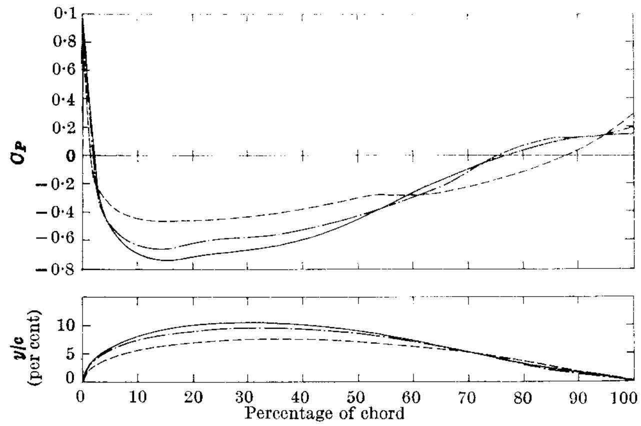

Fig. 1. Profiles and pressure distributions of three dolphin fins. A, ———, Tail fluke of common dolphin; B, – · – · –, dorsal fin of Pacific striped dolphin; C, - - - - - -, dorsal fin of Dall porpoise

The three fins are similar in that their maximum thicknesses are all located between 32 per cent and 36 per cent chord length of the leading edge; all are fairly thick (15·2 per cent to 21·1 per cent chord length) and have a relatively large leading edge radius (2·4 per cent to 4·2 per cent chord length); their minimum pressures are located between 14 per cent and 16 per cent chord length of the leading edge; all have a fairly long region of gentle adverse pressure gradient (increasing C_p) followed by a steep adverse pressure gradient; all trailing edges are relatively thin, and tail fluke A and dorsal fin B have cusped trailing edges. Fins A and B are surprisingly similar since they are cross-sections of different kinds of fins from different species. Fin C is a thinner section and came from Dall porpoise, reported to be the fastest of the three species[1].

All fins were generally symmetrical although some warpage appears in the photographs near their trailing edges. Fin offsets for the computer study are based on the semi-thickness and, therefore, symmetrical sections. The pressure distribution is strongly affected by small changes in fin profile; consequently, some of the minor waviness in the pressure distributions of Figs. 1 and 2 may not be real.

Analysis of the fin pressure-distributions indicates that the fin sections are ideally designed for operation at Reynolds numbers, R_e, in the vicinity of 10^6 where these fins operate. The low-drag airfoil sections designed for airplane wings operating at R_e around 10^7 and above are relatively poor in the range of $R_e = 10^6$, since the laminar boundary layer extends too far into the adverse pressure gradient region and separates, causing excessive drag[2].

The fin pressure-distributions are not similar to the more

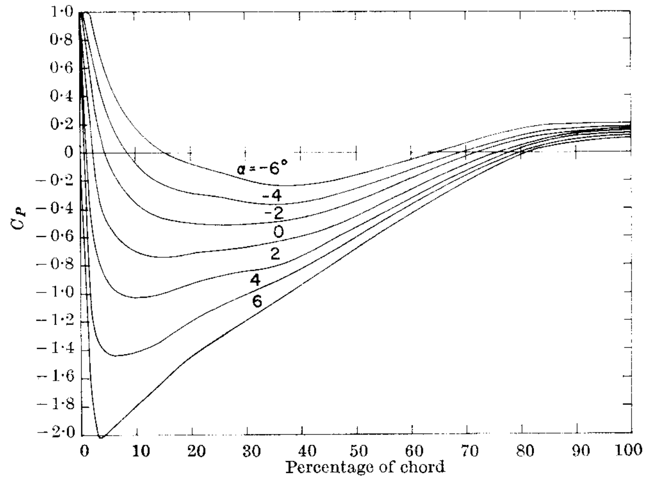

Fig. 2. Effect of angle of attack on the pressure distribution of Fin *A*

commonly known airfoils[2,3]. The fin profiles are a compromise between the less-known special airfoils *FX*05-191 by Wortmann[4] and *EA*6(-1-)-018 by Eppler[5] designed for the R_e region of 0·5–3·0 × 10^6. The differences between the designs of Wortmann and Eppler are sufficiently great to indicate that a compromise design is significant and may have unexpected beneficial characteristics. The favourable pressure gradient near the nose and the gentle adverse pressure gradient to trigger turbulence, combined with the cusp-shaped pressure gradient of fins *A* and *B* to provide a near-uniform boundary layer form parameter, appear to optimize the length of laminar flow and eliminate both laminar and turbulent boundary layer separation. The difference in adverse pressure gradient shape of fin *C* from those of fins *A* and *B* may be due to its reduced thickness ratio. Thinner sections of a given airfoil family have reduced adverse pressure gradient; consequently,

Table 1. Dolphin Fin Offsets

Distance from nose (% chord)	Fin semi-thickness (% chord)		
	Fin *A*	Fin *B*	Fin *C*
0	0·00	0·00	0·00
2	3·97	3·80	2·84
5	6·07	5·71	4·24
10	8·05	7·44	5·61
15	9·28	8·51	6·48
20	9·96	9·12	7·04
30	10·53	9·65	7·62
40	10·17	9·46	7·56
50	8·98	8·60	7·42
60	7·20	7·19	6·43
70	5·22	5·28	5·35
80	3·16	3·22	3·85
90	1·57	1·74	2·08
100	0·23	0·45	0·14

Table 2. DOLPHIN FIN CHARACTERISTICS

Fin designation	Maximum thickness (% chord)	Distance from nose to max. thickness (% chord)	Leading edge radius (% chord)	Trailing edge thickness (% chord)	Minimum C_P	Distance from nose to min. C_P (% chord)
A	21·1	32	4·2	0·46	−0·74	15
B	19·3	33	3·8	0·90	−0·66	14
C	15·2	36	2·4	0·28	−0·46	16

the adverse pressure region can be shifted backwards and modified without causing turbulent boundary layer separation.

The thicknesses of the trailing edge of the fins lie between 0·28 per cent and 0·90 per cent chord length. Airfoils experience essentially no drag increase for thickness ratios up to about 0·5 per cent chord length at R_e around 10^6 and only a small drag increase at 0·8–1·0 per cent thickness ratios[6]. The photograph of fin *B* showed evidence of slight deterioration, so its trailing edge may not be as thick as reported.

The thick-fin sections are probably needed primarily for strength. Thick sections also permit greater angle-of-attack, α, variations without producing excessive minimum pressure peaks at the leading edge that can result in flow separation and cavitation. Fig. 2 indicates that two-dimensional fin angles of attack up to 4° (7° for a fin aspect ratio of 4·0) should be permissible without producing separation and high drag. This angle is in the reasonable range of maximum α for propulsion by fluke undulation and for dorsal fin angle of attack resulting from manoeuvring. During acceleration at low speed, the fluke angle of attack could be considerably greater since added drag is not so important and the fluke would not stall until α reached about 20°.

From the point of view of cavitation, fins *A*, *B*, and *C* at $\alpha = 0°$ should reach speeds of 16·3 m/sec (31·6 knots), 17·3 m/sec (33·6 knots), and 20·7 m/sec (40·2 knots), respectively, before cavitating near the water surface. However, a realistic angle of attack is about 3° or 4°. Fin *A* would cavitate at 13·9 m/sec (27·0 knots) at $\alpha = 2°$, 11·7 m/sec (22·7 knots) at $\alpha = 4°$, and 9·9 m/sec (19·2 knots) at $\alpha = 6°$. It is likely that cavitation would be avoided by dolphins since cavitation is known to produce considerable surface damage to metals and might be painful to dolphins. If the fin profiles had been thinner or if the maximum thickness had been more rearward, the nose radius would have been smaller, making cavitation begin at much lower speeds at $\alpha = 4°$ but at higher speeds at $\alpha = 0°$.

Maximum speeds of tame dolphins trained for speed runs are 7·7 m/sec (15 knots) for the Pacific striped dolphin[7], 8·3 m/sec (16·1 knots) for the Pacific bottlenose dolphin[8], and 11·0 m/sec (21·4 knots) for the Pacific spotted dolphin[9].

Maximum top speed reported in the technical literature for the common dolphin is 10·3 m/sec (20 knots)[10].

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