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Design and Performance of the RAM Wing Planing Craft KUDU II

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-- NOTES --

DESIGN AND PERFORMANCE
OF THE
RAM WING PLANING CRAFT - KUDU II

T. M. Ward, H. F. Goelzer, and P. M. Cook

Abstract

KUDU II is a 36 ft. LOA, 14 ft. beam ram wing planing craft. The craft consists of two planing sponsons separated by a wing section. Each sponson contains an engine driving a surface piercing propeller and stations for two men. The engines develop a total of 1300 BHP and are capable of propelling the 11,900 lb. craft at 85 kts. (98 mph). KUDU routinely operates at speeds in excess of 69 kts. (80 mph) in the open ocean.

I. INTRODUCTION

The application of wing surfaces to marine craft has lead to a number of vehicle configurations which exhibit significant performance improvements. One such configuration is the ram wing planing craft where a wing section operating in the ground effect is mounted between two planing sponsons.

In 1973 the KUDU Aeroseacraft Corp. embarked on a program to design, build, test, and operate a ram wing planing craft suitable for high speed operation in the open ocean. This craft, the KUDU II, was launched in July, 1974. Fig. 1 shows the craft under way at 80 kts. (92 mph). The craft was instrumented and smooth water performance data have been recorded. Operating experience was gained through competition in offshore powerboat racing.

KUDU II won the 156 mile San Francisco offshore powerboat race in September 1974 when it maintained an average speed of 68.8 kts. (79.2 mph). The craft attained speeds of 81 kts. (93 mph) over several reaches of the course and is capable of carrying four men at 85 kts. (98 mph). Design, performance, and operating features of this craft are provided below.

II. Configuration

Basically, the craft consists of two small planing hulls or "sponsons" separated by an airfoil section, see Fig. 2. The overall length of the hull, excluding stern-drives, is 34 ft. and the maximum beam is 14 ft. KUDU draws 2.8 ft. when at rest. A weight and center of gravity (c.g.) statement is provided as Table 1.

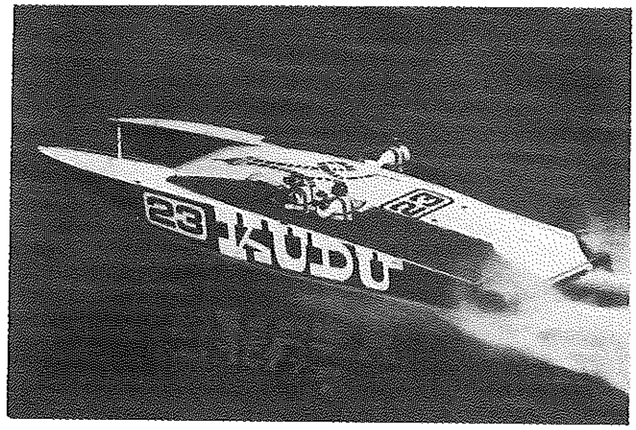


Fig. 1. The ram wing planing craft KUDU II.

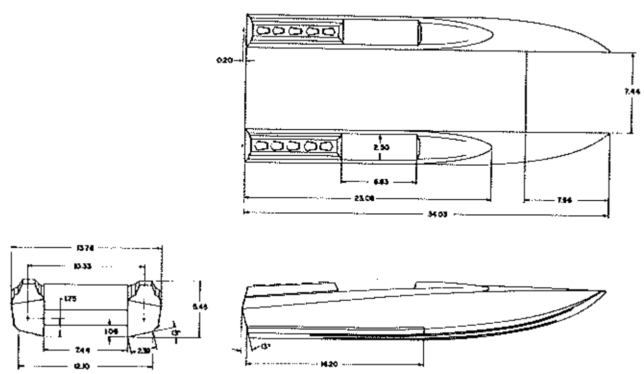


Fig. 2. General configuration.

Sponsons. The individual sponsons are assymmetric having a 90 deg deadrise on the inside and a 13 deg deadrise outboard in the area of the transom. Flat vertical sidewalls were used on the inside to reduce spray generation and skin friction drag. The 13 deg outboard deadrise represents a compromise between planing resistance and impact loads on water entry.

Wing. The wing section is illustrated in Fig. 3. This section was not taken from any "family" of

Table 1. Weight and center of gravity location.

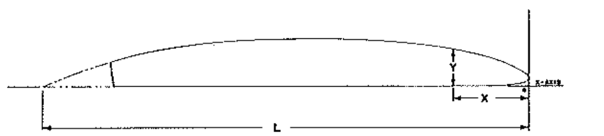
I. Full Gross Weight

Item	Weight lbs.	Percent Gross
Hull structure	5,630	44
Equipment	1,400	11
Engines	2,080	16
Stern-drives	720	6
Fuel and oil	2,000	16
Crew, 4 men	870	7
Full gross	12,700	100

II. C.G. Location

Horizontal: 7.5 ft. or 22 percent LOA fwd from transom.

Vertical: 2.8 ft. or 51 percent max height above keel.



DIMENSIONS

CHORD: 25.5 FT.
SPAN : 7.44 FT.
AREA : 189.7 SQ.FT.
ASPECT RATIO: 0.29

AIRFOIL COORDINATES		
X, %L	Y, %L	
0	1.8	(1)
10	6.6	(2)
20	8.4	
30	9.6	
40	9.9	
50	10.0	(3)
60	9.6	
70	8.7	
80	6.9	
85	5.4	(4)
90	4.0	
100	0	

NOTES

1) Y MEASURED FROM X-AXIS TO UPPER SURFACE. LEADING EDGE RADIUS 0.9% L.
2) LOWER SURFACE FLAT AFT OF 10% POINT.
3) MAXIMUM THICKNESS AT 50% L.
4) TRUNCATED AT 85% L.

Fig. 3. Wing data.

sections but is the result of wind tunnel tests conducted to develop a shape yielding a low pitching moment about the c.g. The lower surface of the wing is set at a 5 deg angle to the keel.

III. Structure

Estimation of the structural loads and the design of a structure to accommodate these loads proved to be the most critical factor in the design and development of the craft.

Concept. KUDU has a semi-monocoque hull design. Longitudinal bending loads are carried by the skin and large longitudinal members which form the side walls of the sponsons. Transverse loads are primarily carried by the transom and four main frames. Nine additional frames and variously spaced longitudinals complete the structure.

Initial Construction. Initially, all frames, the wing lower surface, and the inside wall of the sponsons were fabricated from 6061-T6 aluminum honeycomb. Three-quarter inch thick panels, having 0.250 in. and 0.125 in. Hexcel cores and 0.040 in. face sheets were employed. The sponson bottom and outboard sides, the decks, and the top surface of the wing were fabricated from marine plywood.

Loads in excess of those anticipated, and to a lesser extent delamination of the face-sheet to core bond due to salt water contamination, resulted in major structural failures in the after one-quarter of the craft. In April 1975, a major redesign and refurbishment program was initiated.

Current Structure. Despite a comprehensive search of the open literature, no realistic loads criteria could be found. A conservative, but arbitrary, figure of 100 psi was adopted as the distributed pressure in the areas subject to water impact. Analysis of the failures and careful consideration of the load path resulted in the structure illustrated in Fig. 4. The transom, the first solid frame forward of the engines, and three intermediate frames form a box which houses the engines and supports the balance of the structure. The transom was fabricated from one inch thick 0-90° 14 ply, maple plywood, onto which a 0.375 in. thick sheet of 6061-T6 aluminum has been bonded. The next four frames visible in Fig. 4 are 0.5 in. thick, ±45° bias, 7 ply maple plywood webs fitted with 18 ply caps of similar construction. The remainder of the craft retains the original construction.

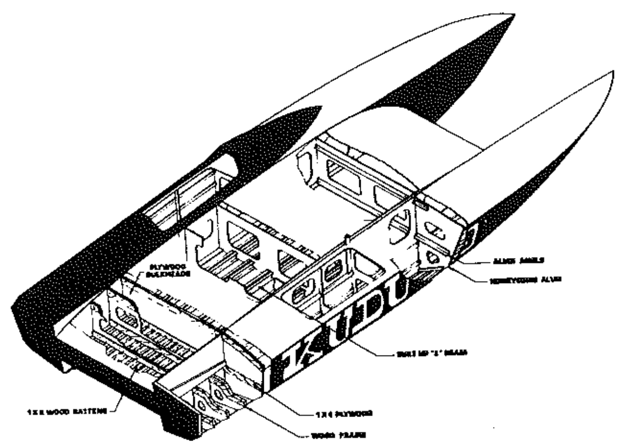


Fig. 4. Structure.

To date, the main structure has remained intact. Local failures, resulting from occasional unusually rough water impacts, have occurred in the intermediate frames.

IV. Propulsion

The craft is powered by two reciprocating internal-combustion engines located in the sponsons. Each engine is connected to a surface piercing propeller through a stern-drive assembly.

Engines. The engines were built from Model 427 Chevrolet V-8 truck blocks. When modified, these engines have the characteristics listed in Table 2. A dynamometer curve for a typical engine is provided as Fig. 5. Performance data are provided in Table 3.

Drivetrain. The drivetrain is illustrated in Fig. 6. Each engine is connected to a transmission fitted with reversing gears. The transmission

Table 2. Engine characteristics.

Cylinder arrangement:	V-8
Bore:	4.31 in.
Stroke:	4.25 in.
Displacement:	496 cu. in.
Compression ratio:	11.2 to 1
Fuel:	Aviation gasoline, 100/130 octane
Induction:	Naturally aspirated, fuel injected
Ignition:	Spark
Cycle:	Four stroke
Weight:	1040 lbs.

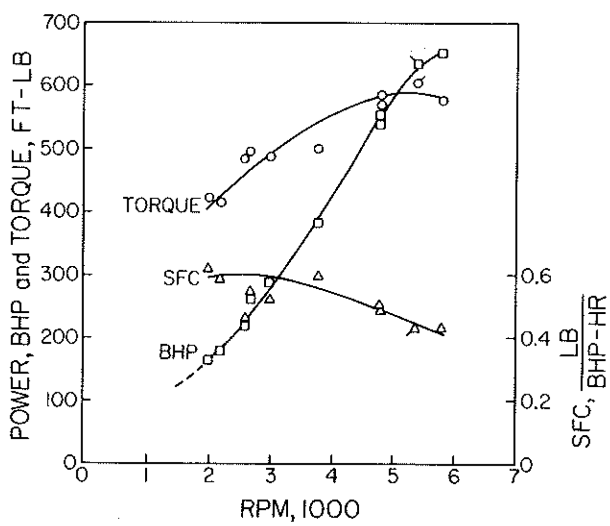


Fig. 5. Engine dynamometer curve for full throttle operation. Flagged points are double points.

Table 3. Engine performance based on measured data.

Power:	635 BHP
Shaft speed:	5,500 rpm
Torque:	606 ft-lb
Brake mean effective pressure:	184 psi
BHP/Displacement:	1.28 BHP/cu. in.
Specific fuel consumption:	0.43 lb/BHP - Hr.
Specific weight:	1.64 lb/BHP

is connected to the stern-drive through the use of a splined coupling fitted with universal joints at both ends. This coupling permits relative motion to take place between the engine and stern-drive. Two Mercury Marine Inc. "Mercruiser III Super Speedmaster" stern-drive units have been fitted to the transom. These units permit changes in the thrust angle to be made while the craft is underway. The unit may be pitched through an arc of from 7 deg nose up to 14 deg nose down, relative to the keel. A 1.33 to 1 reduction in shaft speed is accomplished in the stern-drive gearing. No change in shaft speed takes place in the transmission and both engines have the same direction of rotation. The propellers, however, are outboard turning. This change in rotation takes place in the stern-drive as illustrated in Fig. 6. Dynamometer experiments show that there is less than a 10% loss in power through the drive train.

Propeller. A three bladed propeller has been fitted to each stern-drive. Photographs of a propeller are provided in Fig. 7 where a one foot ruler has been introduced to provide a scale. The top view is of the bluff trailing edge. The mid view is a profile with the leading edge down, and the bottom view is of the sharp leading edge.

The propeller was manufactured by Mercury Marine, Inc. No data or characteristics, other than the pitch and diameter, are available. Data taken from direct measurement of the propeller are provided in Table 4. This propeller is commonly called a "cleaver" as the blade resembles a butcher's cleaver.

A view of the propeller and stern-drive mounted on the sponson is provided in Fig. 8. When planing, the propeller pierces the water surface and runs with approx. 85% of the disk area under water.

V. Operation

KUDU has competed in Offshore Power Boat Racing, Open Class IV, for four years. These races have provided an opportunity to gain experience in the operation of the craft and to make comparisons with conventional planing craft under similar competitive conditions.

Control. KUDU was designed for, and may be operated by one man. However, two men are usually used when running at high speeds in the ocean. The pilot stands in the port sponson and maintains the course. A "throttle-man" stands in the starboard sponson where he controls the throttles and regulates the trim of the stern-drives. A third man, a navigator, is sometimes used to complete the crew during offshore races.

The craft is started by trimming the stern-drives under the hull, i.e. negative ϵ. This places a pitch down moment about the c.g. and provides some assistance in passing the first resistance maxima or planing "hump" as it is commonly called (see Fig. 12). The throttles are carefully opened and, as the speed of the craft approaches the first resistance hump, additional throttle is applied to cause the propeller to "break loose" or begin cavitating operation. More thrust can be delivered at this craft speed when the engine is turning at the higher shaft speed necessary to cavitate the propeller. Care must be taken not to allow the speed of rotation to increase to the point where thrust breakdown will occur. Once over the hump, the craft accelerates rapidly to 48 kts. (55 mph). At this speed the trailing edge of the wing clears the water and the craft passes the second resistance hump. The stern-drive must then be trimmed out, i.e. positive ϵ, to apply a pitch up moment about the c.g. or too much of the forward end of the sponson will become immersed and the craft will become

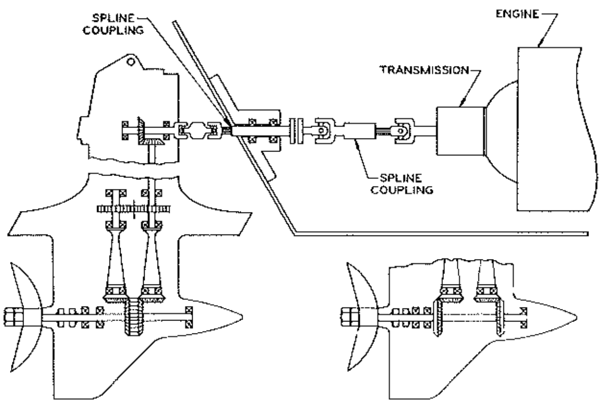


Fig. 6. Drivetrain. Not to scale.

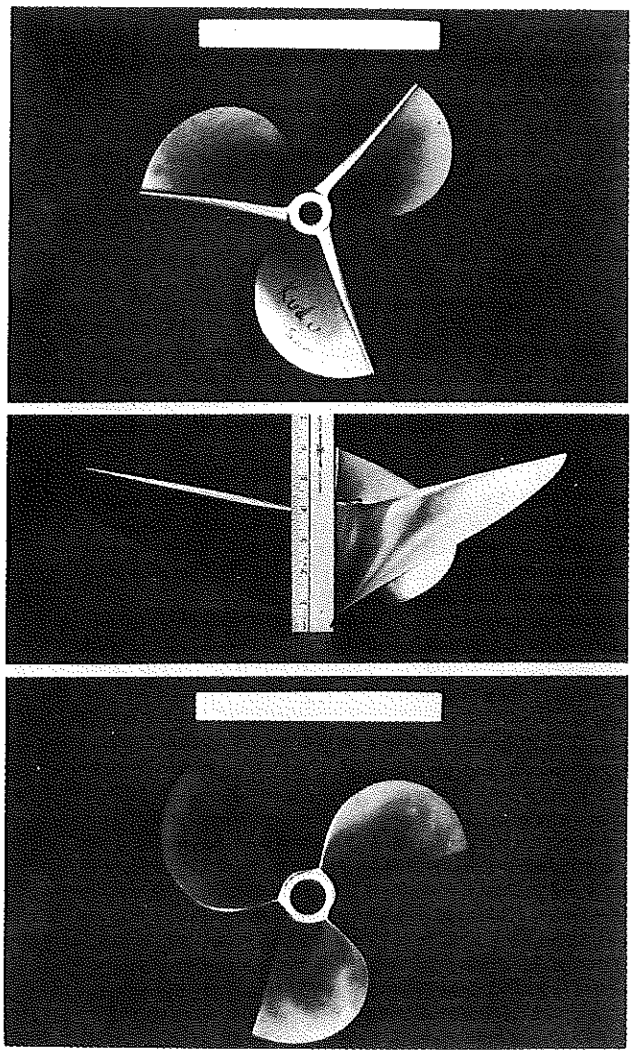


Fig. 7. Propeller

difficult to steer. During operation in heavy seas, the craft will become airborne when it flies off the top of a wave. As the craft starts to leave the water, the throttle must be closed to minimize the loads on the propulsion system due to sudden removal of the propeller load and subsequent reloading upon water entry. Continuous trimming of the stern-drives takes place

Table 4. Propeller characteristics.

Diameter:	16.5 in.
Pitch:	25.0 in.
Pitch-diameter ratio:	1.52
Developed blade area ratio:	0.54
Blade sections:	Supercavitating
Maximum developed blade chord:	6.2 in.
Location of max. blade chord:	0.6 R
Trailing edge rake:	10 deg. aft
Hub-diameter ratio:	0.12

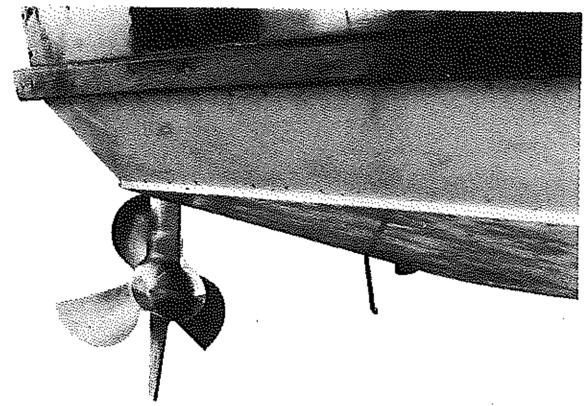


Fig. 8. Propeller-pod assembly viewed looking aft.

in an effort to seek an optimum compromise between speed and directional control. Sea state, wind speed and direction, and desired craft speed all influence the throttle and trim settings. When the craft is properly trimmed, one has the sensation of riding on a bubble of air as the craft exhibits small amplitude, long period oscillations in pitch and roll about a point located approx. midships.

Turns are best accomplished by coordinating the motions of the pilot and throttle-man. As a turn is entered, the throttle-man trims under the inboard stern-drive. This places the forward edge of the outboard sponson further in the water than that of the inboard sponson. The outboard sponson then acts as a fin about which the craft is turned. KUDU turns well inside conventional craft and can accomplish a 180 deg turn in three boat lengths at 69 kts. (80 mph).

Range-payload. KUDU cruises comfortably at 69 kts. (80 mph) in the open ocean. At this speed, the craft has a range of 295 nm (340 st. mi.). Assuming a two man crew, 2,400 lbs. are available for division between fuel and payload.

Seakeeping. KUDU provides a softer ride than a conventional planing hull when operating at the same speed in waves. While there is no quantitative data to substantiate this claim, personnel experienced in the operation of both craft and aerial motion pictures of both craft operating in heavy seas show a marked reduction in motions and accelerations.

VI. Performance

Performance trials were conducted in San Pedro Bay, California, along the measured mile markers available on the breakwater, see Fig. 9. Water depths along the breakwater are in excess of 40 ft., well out of the range where bottom effects could influence performance. Wind speeds were less than 10 kts. and the significant wave height was less than 1 ft. The craft weighed approx. 11,900 lbs. during the trials.

Instrumentation. A list of the instrumentation carried on board during the trials is provided in Table 5.* Most of the data were recorded on an oscillograph to permit simultaneous sampling of the variables. All the instruments were bench calibrated and, where possible, again after installation in the craft. Air and water speed readings were based on instruments which were calibrated by making timed runs along the measured mile. While most of the instruments are conventional, a few are noteworthy and are commented on below.

Craft trim, τ, and keel wetted length, L_K, proved to be the most difficult measurements to make. Craft motion caused the τ gyro to tumble and a bearing failure was encountered early in the program. This instrument was replaced by a viscously damped pendulum which also proved to be impractical due to vertical acceleration interactions. Finally, a viscously damped ball inclinometer was mounted in the craft and τ data were recorded by hand during steady state running periods. Keel wetted length was recorded by taking motion pictures of a pattern painted on the inside wall of the sponson at the keel. Under proper lighting conditions, good pictures were obtained and one could easily evaluate L_K at any given point in time. However, small changes in trim and draft made large changes in L_K. All values of τ and L_K were plotted against ϵ and V, and these values compared with calculated values based on draft. The values of τ and L_K presented below are best estimates based on smoothed average data.

Study of the stern-drive assembly, Fig. 10, revealed that the forces on the unit could be resolved into three components, i.e., two orthogonal forces and a moment. This was accomplished as follows: a conventional strain gage load cell having a sensitive axes in the direction F_1 was fixed to the gimbal pintal; a four-active-arm strain gage bridge pattern having a sensitive axes in the direction F_2 was bonded to the gimbal ring at the pivot point, P; the trim control rod ends were gaged to provide a signal proportional to the axial load, F_3. As the forces F_1 and F_2 are orthogonal, and as the F_3 force could be decomposed at the gimbal ring trim actuator pivot point into components along F_1 or F_2, it was possible to resolve the propulsive force into an X component, a Y component, and a moment all acting at point P.

*A list of nomenclature is provided on page 8.

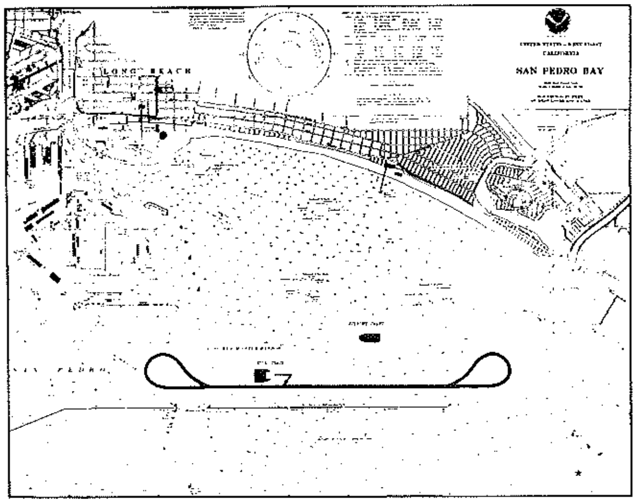


Fig. 9. Performance trials area.

Table 5. Instrumentation

Parameter*	Instrument	Recording
d	Total head rake	Visual
F_1	Strain gage load cell	Oscillograph
F_2	Strain gages applied to gimbal ring	Oscillograph
F_3	Strain gages applied to actuator ends	Oscillograph
L_K	Motion pictures	Color film
N_S	Magnetic induction	Oscillograph
P_K	Total pressure tube, pressure transducer	Oscillograph
q_A	Pitot-static tube, differential pressure transducer	Oscillograph
Q_S	Strain gage torque transducer	Oscillograph
ϵ	Linear potentiometer	Oscillograph
τ	Gyro stabilized inclinometer	Oscillograph

Results and Discussion. Figure 11 illustrates the effect changes in stern-drive trim, ϵ, have on gimbal forces and craft trim. As ϵ increases positively, F_1 increases negatively and the craft pitches up. This ability to adjust the thrust vector at will is essential to the operation of the craft and permits the crew to maximize speed over a wide range of operating conditions.

Figure 12 is a plot of total thrust, measured in the horizontal, vs. craft speed. If propeller-hull interactions are assumed negligible, this curve is equivalent to a total resistance curve as the data were recorded during

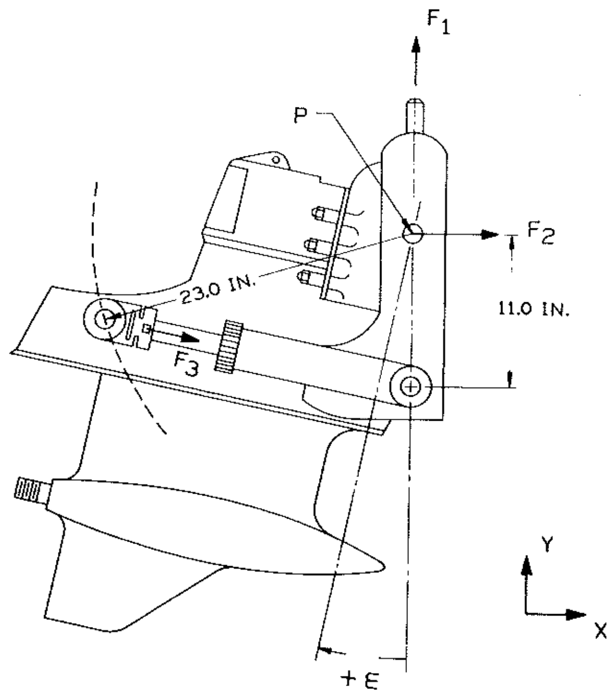


Fig. 10. Stern-drive instrumentation.

steady state conditions. Two resistance humps are apparent. The first is typical of all craft at the start of planing. This occurs at $V \cong 12$ kts. (14 mph) where $C_V = 0.946$ and $F_\nabla = 1.47$. The second hump, which occurs at $V \cong 45$ kts., $C_V = 3.82$ and $F_\nabla = 5.95$, takes place when the lower surface of the wing clears the water surface. Once this occurs, the resistance curve begins to exhibit a negative slope and the resistance to weight ratio drops below that for conventional planing craft. At this speed, the thrust available curve also has a negative slope and the intersection between the two curves is shallow. As a result, the speed of the craft is sensitive to changes in power.

Typical measurements, made during steady state operation with constant stern-drive trim, are provided in Table 6.

An analysis of the propulsion data is provided in Table 7. In this analysis, the relationship between the factors which link the power delivered by the engines to that required to overcome the total resistance of the craft under trial conditions is taken as

$$EHP = \eta_P \eta_M \, SHP$$

or

$$OPC = \eta_P \eta_M = \frac{EHP}{SHP}$$

where EHP, η_M, and SHP are based on measured data. The method used to calculate K_Q and K_T is provided as an appendix. The data appear to be in reasonable agreement with what little comparative data can be found in the open literature.

An Analysis of force and moment data for the case where V = 69 kts. (80 mph) is

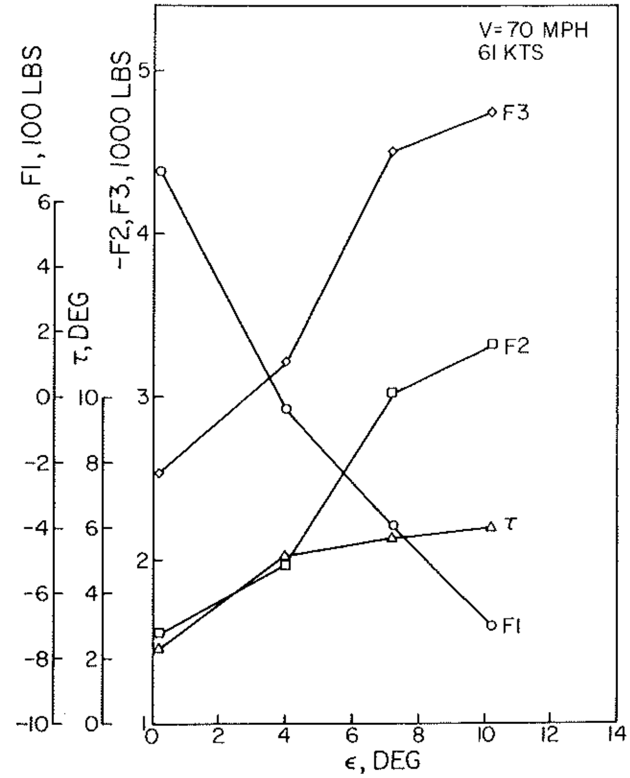


Fig. 11. Stern-drive trim effects.

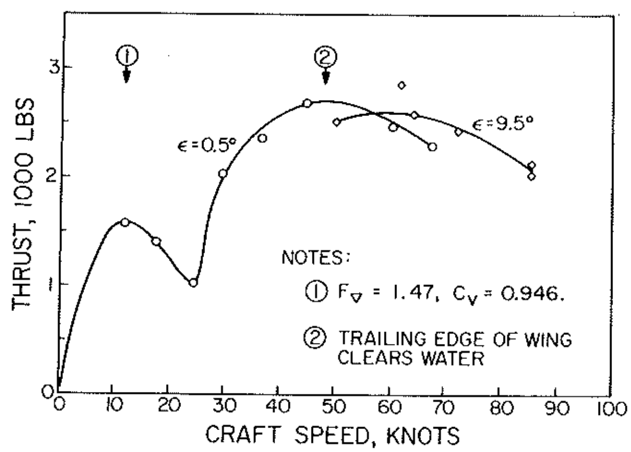


Fig. 12. Total thrust vs. craft speed.

provided in Table 8. Measurements of L_K and τ from Table 6 were used to calculate the lift, drag, and pitching moment about the c.g. contributed by the sponsons. A static equilibrium analysis about the c.g. was then performed, using measured propeller data and calculated sponson data, to evaluate the aerodynamic contribution. The value of C_{D_A} arrived at by this method is 5% higher, C_{L_A} is 26% lower, and C_{M_A} is 24% lower than values arrived at through wind tunnel tests. Given the errors inherent in the method used to arrive at L_A, D_A, and M_M, and the fact that the wind tunnel tests were performed on a small model of the craft in a slightly different configuration, this

Table 6. Measured data.

Param.	Units	Run		
V	mph	70	80	90
	kts	61	69	78
ϵ	deg	9.5	9.5	9.5
τ	deg	3.7	4.6	5.1
d	in	9	7	5
G	in	4	6	8
L_K	ft	11.2	7.0	4.5
N_S	rpm	4,370	4,900	5,550
Q_S	ft-lb	455	464	475
L_P	lb	-955	-1,493	-1,664
T_P	lb	2,592	2,439	2,274
M_P	ft-lb	19,749	23,826	24,656
η_M	---	91.2	91.3	91.5

Table 7. Propulsion parameters.

Param.	Units	Run		
V	mph	70	80	90
	kts	61	69	78
SHP	HP	379	433	501
EHP*	HP	243	259	272
OPC	%	64.1	59.8	54.3
n_P	rps	54.8	61.4	69.6
J	-	1.37	1.38	1.37
K_Q	-	0.019	0.016	0.012
K_T	-	0.061	0.046	0.033
η_P*	%	70.3	65.5	59.3
S	%	10.0	8.3	8.9
σ_7	-	0.055	0.043	0.034
σ_o	-	0.198	0.152	0.119

*See appendix for discussion.

degree of correlation may be expected. This comparison was made to show that the values presented are reasonable and to provide a measure of accuracy.

The aerodynamic center of pressure is located 8.3 ft. forward of the c.g. This means that when airborne, the craft will not be

Table 8. Equilibrium analysis.

Symbol	Parameter	Units	Value
V	Craft speed	mph kts	80 69
τ	Craft trim	deg	4.6
L_P	Propulsor lift, total	lb	-1,493
T_P	Propulsor thrust, total	lb	2,439
M_P	Propulsor moment, total	ft-lb	23,826
L_H	Hydrodynamic lift	lb	10,682
D_H	Hydrodynamic drag	lb	1,610
M_H	Hydrodynamic moment	ft-lb	-45,680
L_H/D_H	Hydrodynamic lift-drag ratio	-	6.7
L_A	Aerodynamic lift	lb	2,631
D_A	Aerodynamic drag	lb	828
M_A	Aerodynamic moment	ft-lb	21,854
L_A/D_A	Aero. lift-drag ratio	-	3.2
CP_A	Aero. center of pressure, % Chord aft of wing leading edge	% C	38
C_{L_A}	Aero. lift coef.	-	0.845
C_{D_A}	Aero. drag coef.	-	0.266
C_{M_A}	Aero. moment coef.	-	0.275
L/D	Craft lift to drag ratio	-	4.9

longitudinally stable. However, experience gained during the operation of the craft at high speeds shows this to be no real problem. The flight times are short and any rotations, either pitch up or down, are small. Motion pictures taken when KUDU races with conventional planing craft show KUDU to be far more stable.

At 69 kts. (80 mph), only the last seven feet of the sponson is wetted and the hydrodynamic lift produces a large pitch down moment about the c.g. This moment is balanced by the forward location of the aerodynamic center of pressure and the negative lift provided by the stern-drive. This negative lift amounts to 57% of the aerodynamic lift and to 12% of the craft weight. Improvements in performance could be realized by better alignment of the lift forces and the c.g.

A high-speed run was made in which the craft attained a speed of 85 kts. (98 mph). The stern-drive was trimmed to $\epsilon = 9.4$ deg and a thrust of 2004 lb. was required to propell the craft. At this speed, KUDU was operating at an overall thrust to weight ratio ($\approx L/D$) of 5.9. This ratio is superior to that for conventional planing craft operating at the same speed and moderately better than that for hydrofoil craft. A far more significant observation is that the slope of the resistance vs. speed curve is negative, while that for conventional planing craft is positive. Apparently, KUDU is just beginning to fly and the region of best performance is beyond 85 kts. (98 mph).

VII. Summary and Conclusion

Five years have passed since the decision was made to develop the ram-wing concept. Performance measurements and operating experience gained with KUDU II show that, in general, this concept has potential. In particular, the following observations may be made:

1. Efforts must be directed toward the formulation of a rational structural design technique;

2. The relationship between the c.g. and the configuration and orientation of the wing and sponsons is critical and requires investigation;

3. The use of a variable trim stern-drive is essential;

4. The potential for high L/D ratios at high speeds, and the apparent improvement in seakindliness, warrant further investigation into the ram-wing planing craft concept.

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Nomenclature

A = area of wing, ft^2

B = maximum beam, ft

BHP = brake horsepower of engine as determined by dynamometer, HP

c.g. = center of gravity of craft

C = wing chord, ft

C_{D_A} = aerodynamic drag coefficient, $D_A/q_A A$

C_{L_A} = aerodynamic lift coefficient, $L_A/q_A A$

C_{M_A} = aerodynamic moment coefficient, $M_A/q_A AC$

C_{P_A} = aerodynamic center of pressure

C_V = speed coefficient, $V/\sqrt{gB}$

d = draft, measured from intersection of transom with sponson keel, in

D = total fluid dynamic drag, $D_A + D_H$, lb

D_A = aerodynamic drag, lb

D_H = hydrodynamic resistance, lb

D_P = propeller diameter, ft

DHP = delivered horsepower, power delivered to propeller as determined by dynamometer, HP

EHP = effective horsepower, power required to overcome total drag under trial conditions, DV/550, HP

F_1 = stern-drive gimbal ring pintal force, positive upward, see Fig. 10

F_2 = stern-drive gimbal ring bending load, positive forward, see Fig. 10, lb

F_3 = stern-drive trim actuator load, positive forward, see Fig. 10, lb

F_∇ = volume Froude number, $V/\sqrt{g\nabla^{\frac{1}{3}}}$

g = acceleration due to gravity, 32.2 ft/sec^2

G = wing trailing edge gap, height of trailing edge above water surface, in

J = propeller advance coefficient, $V/n_P D_P$

K_Q = propeller torque coefficient, $Q_P/\rho(n_P)^2(D_P)^5$

K_T = propeller thrust coefficient, $T_P/\rho(n_P)^2(D_P)^4$

L = total lift, $L_A + L_H + L_P$, lb

L_A = aerodynamic lift, lb

L_H = hydrodynamic lift, lb

L_K = keel wetted length, ft

LOA = length over all, ft

L_P = lift due to propeller-pod assembly, lb

M = total moment about c.g., positive when tending to rotate bow upward, $M_A + M_H + M_P$, ft-lb

M_A = aerodynamic moment about c.g., positive when tending to rotate bow upward, ft-lb

M_H = hydrodynamic moment about c.g., positive when tending to rotate bow upward, ft-lb

M_P = moment about c.g. due to propeller-pod assembly, positive when tending to rotate bow upward, ft-lb

N_P = propeller rotational speed, rpm

n_P = propeller rotational speed, rps

N_S = engine shaft rotational speed, rpm

n_S = engine shaft rotational speed, rps

OPC = overall propulsive coefficient, EHP/SHP

P_K = hydrodynamic total pressure, lb/ft^2

P_L = local pressure, taken as absolute pressure at water surface, lb/ft^2

P_P = propeller pitch, ft

P_V = vapor pressure of sea water, lb/ft^2

q_A = aerodynamic pressure, lb/ft^2

Q_P = propeller torque, ft-lb

Q_S = engine shaft torque, ft-lb

R_P = propeller radius, ft

S = propeller slip, $1 - V/n_P P_P$

SHP = shaft horsepower, $N_S Q_S/5252$

T_P = total thrust delivered by stern-drives, measured in the horizontal, as resolved at point P in Fig. 10, lb

V = speed of craft through water, ft/sec

W = weight of craft, lb

X = direction measured along a line coincident with the sponson keel in the after portion of the craft, positive forward from an origin located at the intersection of the keel and transom, ft

Y = direction measured normal to X, positive upward from an origin located at the intersection of the keel and transom, ft

∇ = displacement of the craft, cu. ft.

ϵ = stern-drive trim angle, measure between Y axis and line through stern-drive strut at pivot point P in Fig. 10, positive when trimmed out as illustrated, deg

η_M = mechanical efficiency of drive train, DHP/SHP

η_P = propulsive efficiency, $EHP/\eta_M SHP$

ρ = mass density of salt water, $slug/ft^3$

σ_o = cavitation index based on speed of craft, $(P_L - P_V)/\frac{1}{2}\rho V^2$

σ_7 = cavitation index based on speed of propeller through water at 0.7 R_P, $(P_L - P_V)/\frac{1}{2}\rho\left[V^2 + (0.7\, n_P D_P)^2\right]$

τ = angle of sponson keel relative to horizontal positive bow upward, deg

APPENDIX

Propulsion Factors

The relationship between the factors which link the power delivered by the engines to that required to overcome the total resistance of the craft under trial conditions is taken as

$$EHP = \eta_P \eta_M SHP \tag{1}$$

with

$$OPC = \eta_P \eta_M \tag{2}$$

and the effective horsepower defined as

$$EHP = \frac{DV}{550} \tag{3}$$

Next, it is assumed that the thrust-deduction factor and the wake factor are equal to unity. The limited amount of supercavitating propeller data available indicates that the thrust-deduction factor is approximately one and a wake factor of one does not appear to be unreasonable considering installation shown in Fig. 8. Further, the measurements made do not justify any other assumption. Then, under the steady-state trial conditions, $D = T_P$ where T_P is the total thrust delivered by the propeller-pod assembly as measured at point P in Fig. 10. EHP may then be calculated from

$$EHP = \frac{T_P V}{550} \tag{4}$$

and values of the overall propulsive coefficient from

$$OPC = \frac{EHP}{SHP} \quad . \tag{5}$$

Values of the mechanical efficiency were evaluated by simultaneous dynamometer measurements of engine shaft power, SHP, and propeller shaft power, DHP, and the relationship

$$\eta_M = \frac{DHP}{SHP} \quad . \tag{6}$$

Values of the propulsive efficiency were calculated using the relationship

$$\eta_P = \frac{EHP}{\eta_M SHP} \tag{7}$$

and account for the open water efficiency of the propeller, and the effect of the interaction between the hull, pod-strut assembly, and the propeller.

Next, as delivered horsepower is defined as

$$DHP = \frac{N_P Q_P}{5252} \tag{8}$$

and

$$DHP = \eta_M SHP \quad . \tag{9}$$

DHP may be eliminated by substituting Eq. 8 into Eq. 9 and the torque delivered to the propeller evaluated from

$$Q_P = \eta_M Q_S \frac{n_S}{n_P} \tag{10}$$

where $n_S = 1.33\ n_P$. Values of the resulting propeller torque were reduced to coefficient form using the relationship

$$K_Q = \frac{Q_P}{\rho (n_P)^2 (D_P)^5} \tag{11}$$

and values of the propeller thrust coefficient were calculated using

$$K_T = \frac{T_P}{\rho (n_P)^2 (D_P)^4} \quad . \tag{12}$$

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