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THE ENERGETICS OF HOVERING IN THE MANDARIN FISH (*SYNCHROPUS PICTURATUS*)

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SUMMARY

The influence of the ground effect on the energetics of hovering in *Synchropus picturatus* Peters, a negatively buoyant, demersal teleost was studied. Changes in pectoral fin kinematics, the ultimate water velocity in the wake below the fins, the calculated minimum induced thrust and power required to hover are related to the height at which the animal hovers above the substrate. The profile power required to overcome the frictional drag on the fins has been calculated for the case of both a laminar and a turbulent boundary layer over the fins. Reductions in the total power needed to hover (as compared with that required out of ground effect) of 30–60% have been calculated for *Synchropus* when hovering at commonly observed heights above the bottom. Results are discussed in relation to the hovering flight of birds, insects and helicopters.

INTRODUCTION

Most of the papers on fish locomotion are concerned with streamlined, pelagic and nektonic fish that are either neutrally buoyant or have a buoyancy close to neutral. Studies on the swimming of negatively buoyant fishes have concentrated on the hydrostatic equilibrium and forward motion of pelagic and nektonic Selachii (e.g. Harris, 1936, 1937; Alexander, 1965) and Scombroidae (e.g. Magnuson, 1970; Weihs, 1974). In this paper the kinematics and energetics of hovering in *Synchropus picturatus* (Callionymidae), a negatively buoyant demersal fish, is considered.

Much work has been done recently on the hovering flight of insects (e.g. Weis-Fogh, 1972, 1973; Bennett, 1976; R. Norberg, 1975), birds (e.g. Pennycuick, 1968; Weis-Fogh, 1972; Hainsworth & Wolf, 1972) and bats (e.g. U. M. Norberg, 1970). From a fluid dynamical point of view we can treat hovering, negatively buoyant fish, birds, bats and insects as a single functional group. This enables us to make comparisons between animals of different grades of organisation engaged in essentially the same task.

S. picturatus habitually hovers near the bottom and the effect that this has on the final wake velocity below the fins, the induced thrust and power required in hovering is considered.

MATERIALS AND METHODS

Much information on the kinematics of the undulatory pectoral fins was gained from still photography (see Fig. 5). An Asahi Pentax 35-mm, single lens reflex camera and Pan F film was used. The camera was linked to three electronic flash units. The 135 mm lens used was fitted with a stereo-attachment (Ellington, in preparation). A single specimen of *Synchropus picturatus* was filmed against a grid (25 mm squares) in a tank (0·3 × 0·3 × 0·3 m) which was maintained at 26 °C.

Further information was gained from cinematography. A Bolex H 16 camera and 16 mm, Pan F film was used. The film was shot at a nominal rate of 64 frames s^{-1} at f 5·6. Each film was calibrated before use.

A suspension of polystyrene spheres (diameter = 0·2 mm, S.G. = 1·05) was used to measure flow velocities around the fins. The sinking velocity of the particles in still water is low (about 0·05 cm s^{-1}) compared to observed velocities as they left the fins (about 20 cm s^{-1}). Particles attained their ultimate wake velocity very close to the trailing edges of the fins. The particles were filmed at 64 frames s^{-1} as they were entrained and accelerated by the action of the fins. Only particles which remained in sharp focus were considered.

The animal was weighed in air (= $8·1 \times 10^{-3}$ kg) and in sea water (= $0·66 \times 10^{-3}$ kg), the density of which was measured by a hydrometer at 26 °C as 1025 kg m^{-3}. The displacement volume (weight in air − weight in sea water/density of sea water) is calculated to be 7·26 cm^3, giving an S.G. of about 1·12.

The application of the actuator-disc theory to the undulating fin system

The momentum principle is a fundamental concept in fluid mechanics which is of great use in the analysis of flow problems where the determination of forces is involved. Below a simplified model of the action of an undulating fin is developed based on actuator-disc theory, a special way of applying the momentum principle. The actuator-disc is an idealized device which produces a sudden pressure rise in a stream of fluid passing through it. This pressure rise, integrated over the whole area of the actuator-disc gives the thrust force associated with the driving mechanism, in this case the pectoral fins. Initially we will assume:

(1) That the pressure increment and thrust loading is constant over the whole disc.

(2) That there are no rotational velocities in the wake.

(3) That there is no discontinuity in velocity across the disc.

(4) That a well-defined wake boundary separates the flow passing through the actuator-disc from that outside it.

(5) That ahead and behind the fins the static pressure in and out of the wake is equal to the free-stream static pressure.

The pectoral fin is considered to be an actuator-disc, far upstream from which the pressure is p_0 and the velocity V. Just upstream of the disc the velocity is assumed to have increased to $(V+v_1)$ and in accordance with Bernoulli's Theorem the pressure has fallen to p. Just downstream of the disc the pressure has been increased by Δp to $(p+\Delta p)$ due to the action of the actuator, while the velocity is unchanged. At a distance far downstream from the actuator-disc the pressure has returned to p_0, whil the velocity is $(V+v_2)$. By applying Bernoulli's Theorem to the region in front of the disc, we have:

$$p+\tfrac{1}{2}\rho(V+v_1)^2 = p_0+\tfrac{1}{2}\rho V^2 \quad (1)$$

and doing the same to a region behind the disc:

$$p+\Delta p+\tfrac{1}{2}\rho(V+v_1)^2 = p_0+\tfrac{1}{2}\rho(V+v_2)^2 \quad (2)$$

The thrust (T) is given by:

$$T = \Delta pA = A\rho v_2(V+\tfrac{1}{2}v_2) \quad (3)$$

where A is the area of the actuator-disc ($= \theta D^2$, where θ is the angle through which the fin rays sweep and D is the span of the fin). The rate of mass flow is $\rho A(V+v_1)$ and therefore the rate of increase in momentum of the wake is $\rho A(V+v_1)v_2$ and the thrust equals the rate of change in momentum:

$$A\rho v_2(V+\tfrac{1}{2}v_2) = \rho Av_2(V+v_1) \quad (4)$$

and

$$v_2 = 2v_1 \quad (5)$$

The disc loading (D_d) is given by:

$$D_d = W/2A \quad (6)$$

where W is the effective weight of the animal in sea water. The factor 2 arises from the operation of two fins.

When hovering $V = 0$ and:

$$T = \tfrac{1}{2}\rho Av_2^2 \quad (7)$$

the minimum induced power (P_i) is:

$$P_i = Tv_1 = T^{\frac{3}{2}}/\sqrt{(2\sigma A)}. \quad (8)$$

RESULTS

1. *Pectoral fin kinematics, wake velocity and fin loading in relation to ground effect*

In the empirical analysis of the ground effect on the performance of helicopters (Bramwell, 1976) the ratio of rotor height and diameter is used as a basic parameter. The variation in the mean amplitude $(\bar{a})$ and frequency $(\bar{f})$ of the pectoral fin waveforms during hovering is plotted against the ratio of mean fin height $(\bar{H})$ above the bottom and the maximum fin span (D) on Fig. 1. Fig. 5 gives a good impression of the form of the waveforms which pass down the fins.

Mean amplitude decreases from about $1{\cdot}85\times10^{-2}$ m at $\bar{H}/D = 0{\cdot}25$ to about $1{\cdot}1\times10^{-2}$ m at $\bar{H}/D = 3{\cdot}0$, a total reduction of about 40% most of which (about 65% of the total decrease) occurs between $\bar{H}/D = 0{\cdot}25$ and 0·8. The value of $-d\bar{a}/dt$ changes little after $\bar{H}/D = 2{\cdot}0$. The mean frequency at which waveforms pass down the pectoral fins increases steadily as $\bar{H}/D$ increases from about 6·5 Hz at $\bar{H}/D = 0{\cdot}25$ to about 8·5 Hz at $\bar{H}/D = 3{\cdot}0$, a total increase of approximately 23%.

Fig. 2 shows the increase in the fin loading and ultimate wake velocity with increasing $\bar{H}/D$. Values of v_2 range from about 0·17 m s^{-1} at $\bar{H}/D = 0{\cdot}25$ to about [illegible]3 m s^{-1} at $\bar{H}/D = 3{\cdot}0$, a total increase in v_2 of about 35%.

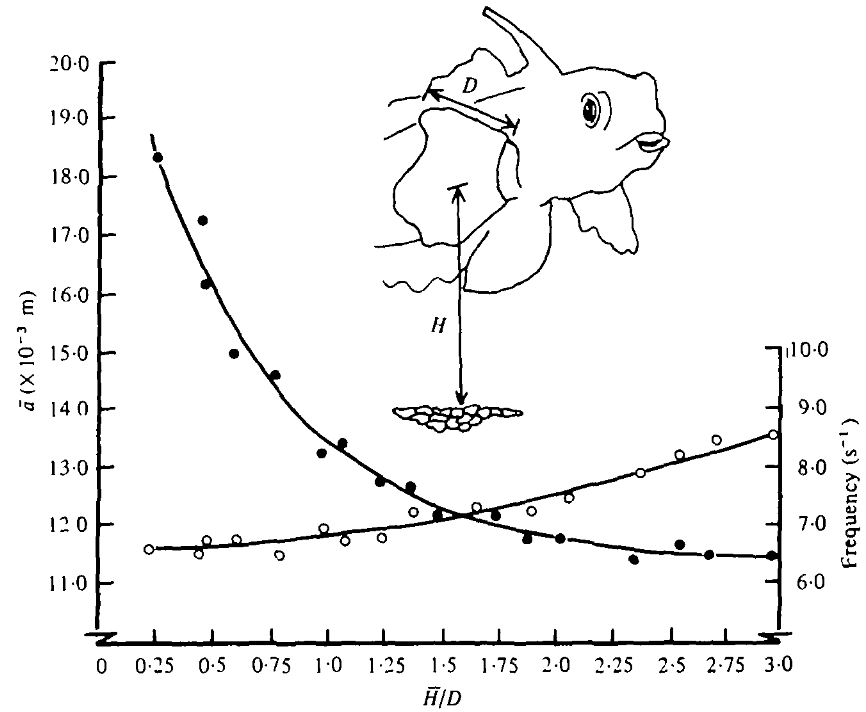

Fig. 1. Mean amplitude ($\bar{a}$) (●; average values of amplitude, measured over ten cycles at the trailing edge of the fin from cine-film records) and frequency (○; average of values measured over ten cycles) of waveforms on the pectoral fins in relation to the ratio of the mean height of the fin above the bottom ($\bar{H}$) and maximum fin span (D) (see inset).

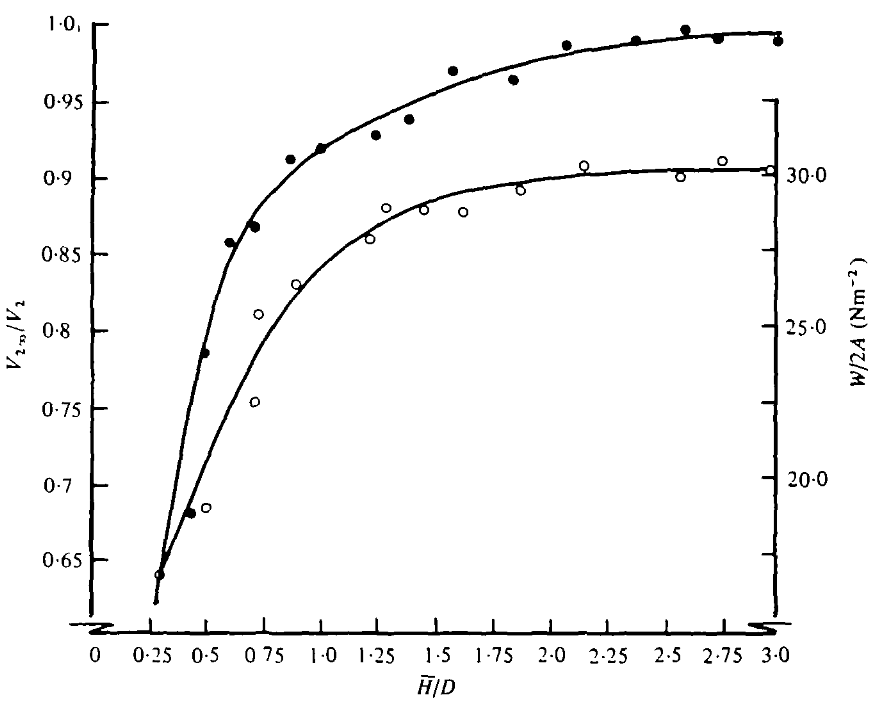

Fig. 2. The ratio of the wake velocity (v_2) at various values of $\bar{H}/D$ to that out of ground effect ($v_{2\infty}$) (●) and the change in fin loading ($W/2A$) in relation to $\bar{H}/D$ (○).

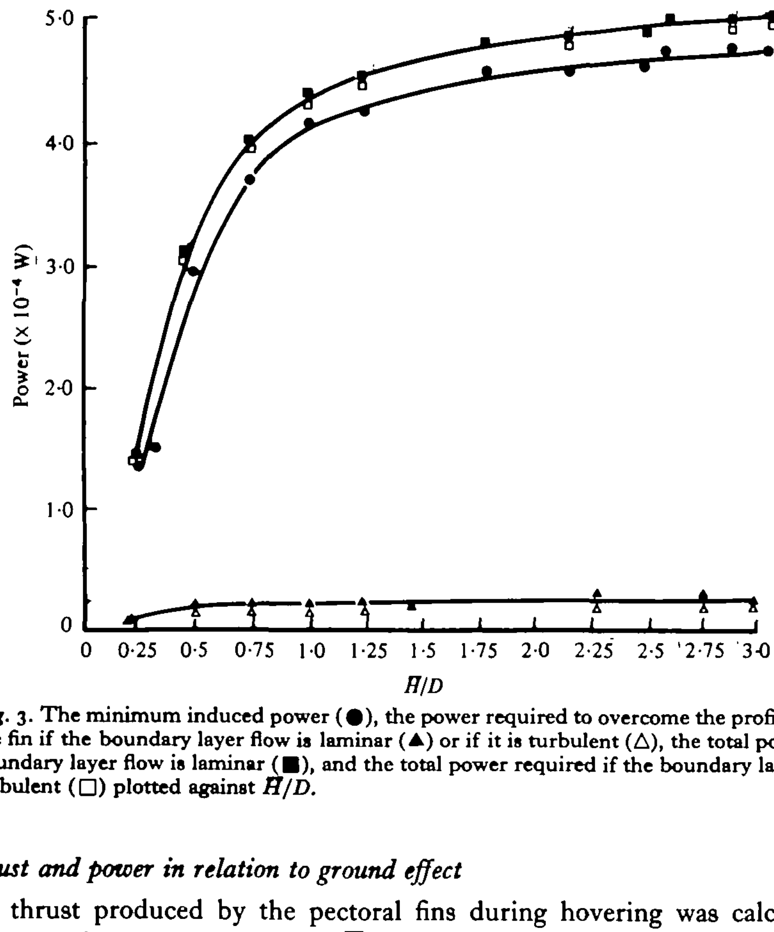

Fig. 3. The minimum induced power (●), the power required to overcome the profile drag on the fin if the boundary layer flow is laminar (▲) or if it is turbulent (△), the total power if the boundary layer flow is laminar (■), and the total power required if the boundary layer flow is turbulent (□) plotted against $\bar{H}/D$.

2. *Thrust and power in relation to ground effect*

The thrust produced by the pectoral fins during hovering was calculated from equation (7) for various values of $\bar{H}/D$ (values of A ranged from $7{\cdot}5 \times 10^{-5}$ m^2 at $\bar{H}/D = 0{\cdot}25$ to $1{\cdot}1 \times 10^{-4}$ m^2 at $\bar{H}/D = 3{\cdot}0$). When out of ground effect ($\bar{H}/D \geqslant 3{\cdot}0$) the thrust force produced by the pectoral fins in hovering must be equal to the weight of the animal in sea water; which was 0·66 gf ($\approx 6{\cdot}5 \times 10^{-3}$ N), and therefore each fin must have been producing about $3{\cdot}25 \times 10^{-3}$ N of downwardly directed thrust. A value of $T = 3{\cdot}39 \times 10^{-3}$ N was calculated for $\bar{H}/D = 3{\cdot}0$.

Values of the minimum induced power (P_i) were calculated from equation (8) and are shown on Fig. 3.

Up to now we have only considered the theoretical minimum induced power required for the fish to hover. A more realistic estimate of the power needed to hover can be gained by taking into account:

(1) The extra power needed due to tip losses and the departure of the induced velocity distribution from constant.

(2) The additional power required to overcome the profile drag of the fins.

In the case of well-designed helicoptor rotors and propeller blades, (1) necessitates an increase in power of about 15% beyond P_i (Bairstow, 1939; Brotherhood, 1947; Stewart & Burle, 1950). A similar value has been found analytically by J. M. V. Rayner (in preparation) for hovering birds. However, we cannot assume that the data on the flight of helicopters and birds can be applied directly to the case of an undulatin fin.

The power required to overcome the profile drag on the fin (P_p) is:

$$P_p = \tfrac{1}{2}\rho S_w v_1^3 C_f \tag{9}$$

where S_w is the total wetted surface area of the fin ($= 3{\cdot}26 \times 10^{-4}$ m^2) and C_f is a frictional drag coefficient. The value of C_f depends on the fin's boundary layer flow regime. For laminar boundary layers over flat plates and rigid streamlined bodies, C_f can be calculated from Blasius's equation:

$$C_{f\,(\text{lam})} = 1{\cdot}33 R_e^{-0{\cdot}5} \tag{10}$$

where R_e is the Reynolds Number ($R_e = LV/\nu$, where L is a characteristic length, V a velocity and ν the kinematic viscosity of the fluid). The fin operates at $R_e \approx 2{\cdot}0$ to $3{\cdot}0 \times 10^3$ and assuming equation (10) to be applicable, $C_{f\,(\text{lam})} \approx 0{\cdot}02$ for most values of $\bar{H}/D$. Therefore, the power required to overcome the profile drag on the fin, if the boundary layer flow is laminar is:

$$P_{p\,(\text{lam})} = \tfrac{1}{2}\rho S_w v_1^3 (1{\cdot}33 R_e^{-0{\cdot}5}) \tag{11}$$

$P_{p\,(\text{lam})}$ is plotted against $\bar{H}/D$ on Fig. 3.

For turbulent boundary layers the value of C_f can be calculated from Prandtl's equation:

$$C_{f\,(\text{turb})} = 0{\cdot}072 R_e^{-0{\cdot}2} \tag{12}$$

and for a turbulent boundary layer the profile power will be:

$$P_{p\,(\text{turb})} = \tfrac{1}{2}\rho S_w v_1^3 (0{\cdot}072 R_e^{-0{\cdot}2}) \tag{13}$$

which is plotted against $\bar{H}/D$ on Fig. 3.

The total power required in hovering (P_t) (excluding any corrections for tip losses and the departure of the induced velocity distribution from constant) can be calculated from:

$$P_{t\,(\text{lam})} = P_i + P_{p\,(\text{lam})} = Tv_1 + \tfrac{1}{2}\rho S_w v_1^3 (1{\cdot}33 R_e^{-0{\cdot}5}) \tag{14}$$

for a laminar boundary layer, and

$$P_{t\,(\text{turb})} = P_i + P_{p\,(\text{turb})} = Tv_1 + \tfrac{1}{2}\rho S_w v_1^3 (0{\cdot}072 R_e^{-0{\cdot}2}) \tag{15}$$

for a turbulent one. Values of $P_{t\,(\text{lam})}$ and $P_{t\,(\text{turb})}$ are also plotted on Fig. 3.

The ratios of $P_{t\,(\text{lam})}$ and $P_{t\,(\text{turb})}$ to their respective values of the total power required to hover out of ground effect are plotted against $\bar{H}/D$ on Fig. 4.

We can define a figure of merit for the undulatory find system in hovering (M_h) as:

$$M_{h\,(\text{lam})} = \frac{P_i}{P_i + P_{p\,(\text{lam})}} = \frac{Tv_1}{Tv_1 + \tfrac{1}{2}\rho S_w v_1^3 (1{\cdot}33 R_e^{-0{\cdot}5})} \tag{16}$$

and

$$M_{h\,(\text{turb})} = \frac{P_i}{P_i + P_{p\,(\text{turb})}} = \frac{Tv_1}{Tv_1 + \tfrac{1}{2}\rho S_w v_1^3 (0{\cdot}072 R_e^{-0{\cdot}2})} \tag{17}$$

for the laminar and turbulent boundary layer flow cases respectively. Values of M_h

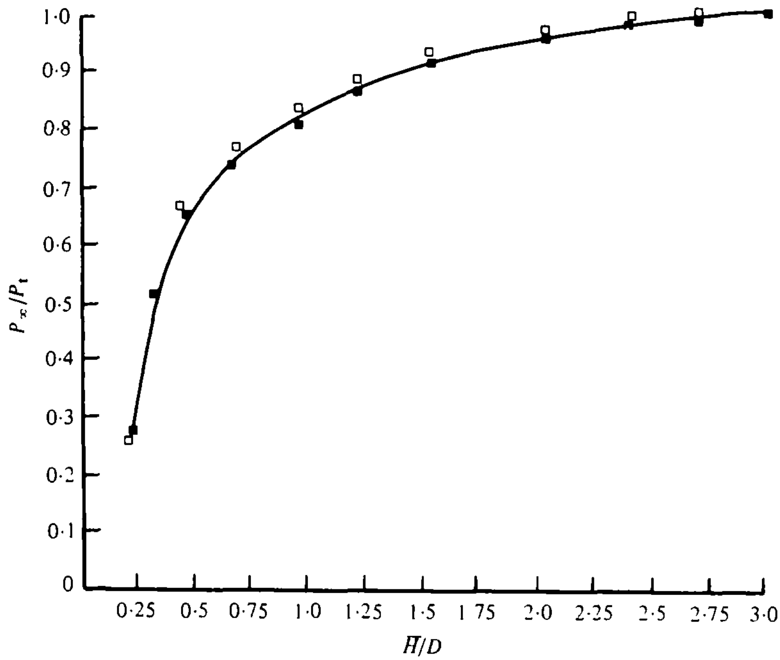

Fig. 4. The ratio of the total power required to hover at various values of $\bar{H}/D$ to that out of ground effect for the case of a laminar (■) and for a turbulent (□) boundary layer over the fin.

are not very sensitive to changes in $\bar{H}/D$ for $\bar{H}/D > 0{\cdot}75$, with $M_{h(\mathrm{lam})}$ and $M_{h(\mathrm{turb})}$ at about 0·95.

DISCUSSION

Ellington (1978) has recently discussed the advantages and disadvantages of the application of the actuator-disc theory to insects in normal hovering (Weis-Fogh, 1973). He concludes that the main advantage of the theory is its simplicity, in that it ignores the particular kinematics of the operating mechanism. However, he also points out that this can be a disadvantage if frictional drag and tip losses are high.

Weis-Fogh (1973) found that the power necessary to overcome the frictional drag of the wings in insects in normal hovering could be as great as the induced power and therefore must be taken into account. If the pectoral fins of *Synchropus* can maintain a laminar boundary layer over their surface the profile drag is only going to be about 4% of the minimum induced power. The pectoral fins operate at a Reynolds Number of the order of 10^3 and therefore it is probable that the fins can maintain a laminar boundary layer over their surface and that $P_{t(\mathrm{lam})}$ and $M_{h(\mathrm{lam})}$ apply.

The density difference between air and water ($\rho = 1000$ kgm^{-3} and 1·3 kgm^{-3} for water and air respectively at 20 °C) accounts for the low specific induced power (induced power/effective weight) of the specimen of *Synchropus* studied here (about 0·075 WN^{-1} when out of ground effect) compared with hovering insects (e.g. values of 0·4, 1·71, 2·04 and 2·1 WN^{-1}, calculated for *Tipula*, *Sphinx*, *Helicopris* and *Bombus* respectively from the data of Weis-Fogh, 1973) and birds (e.g. values of 3·0 and 2·2 WN^{-1} calculated for *Columbia livia* and *Archilochus colubris* respectively from the data of Pennycuick, 1968).

In captivity, *Synchropus* habitually hovers very close to the bottom or to coral branches whilst feeding. Its mouth is small, downwardly directed and terminal, and it makes sudden 'pecking' movements at small crustaceans and algal growths on which it feeds. Both *S. picturatus* and the closely related *S. splendidus* (personal observations) will sometimes spend hours moving slowly over a branch of dead coral, hovering for long periods whilst methodically pecking at algal growths. Typically $\bar{H}/D$ falls between 0·25 and 0·5 (equivalent to about 0·5–1·0 cm above the bottom) and savings of the order of 30–60% on the power required to hover can be expected. The ratio of the rotor height to its distance above the ground in a typical helicopter at take-off is about 0·3 representing a reduction of about 33% on the total power required (Bramwell, 1976).

Although, large energy savings can be made by hovering in ground effect the mechanism itself operates at essentially the same efficiency (i.e. M_h varies little about 0·97 for the laminar and the turbulent flow cases at all values of $\bar{H}/D$) 'in' or 'out' of ground effect.

Fig. 4 shows that *Synchropus* can make substantial energy savings when hovering close to the bottom. The effect that the presence of the ground makes on power consumption during forward progression will probably not be as great. Withers & Timko (1977) have discussed the significance of ground effect for the flight energetics of the black skimmer (*Rhyncops nigra*) and have pointed out that the component of the total power required for flight due to the induced power increases at lower velocities where the ground effect results in a greater percentage reduction in the total power required to fly.

I suspect that future studies will show ground effect to be a significant factor in determining the energy budget of many insects, birds, bats and demersal, negatively buoyant Selachii (e.g. Batoidei) and Teleostei (e.g. Callionymoidei, Heterosomata), especially in hovering.

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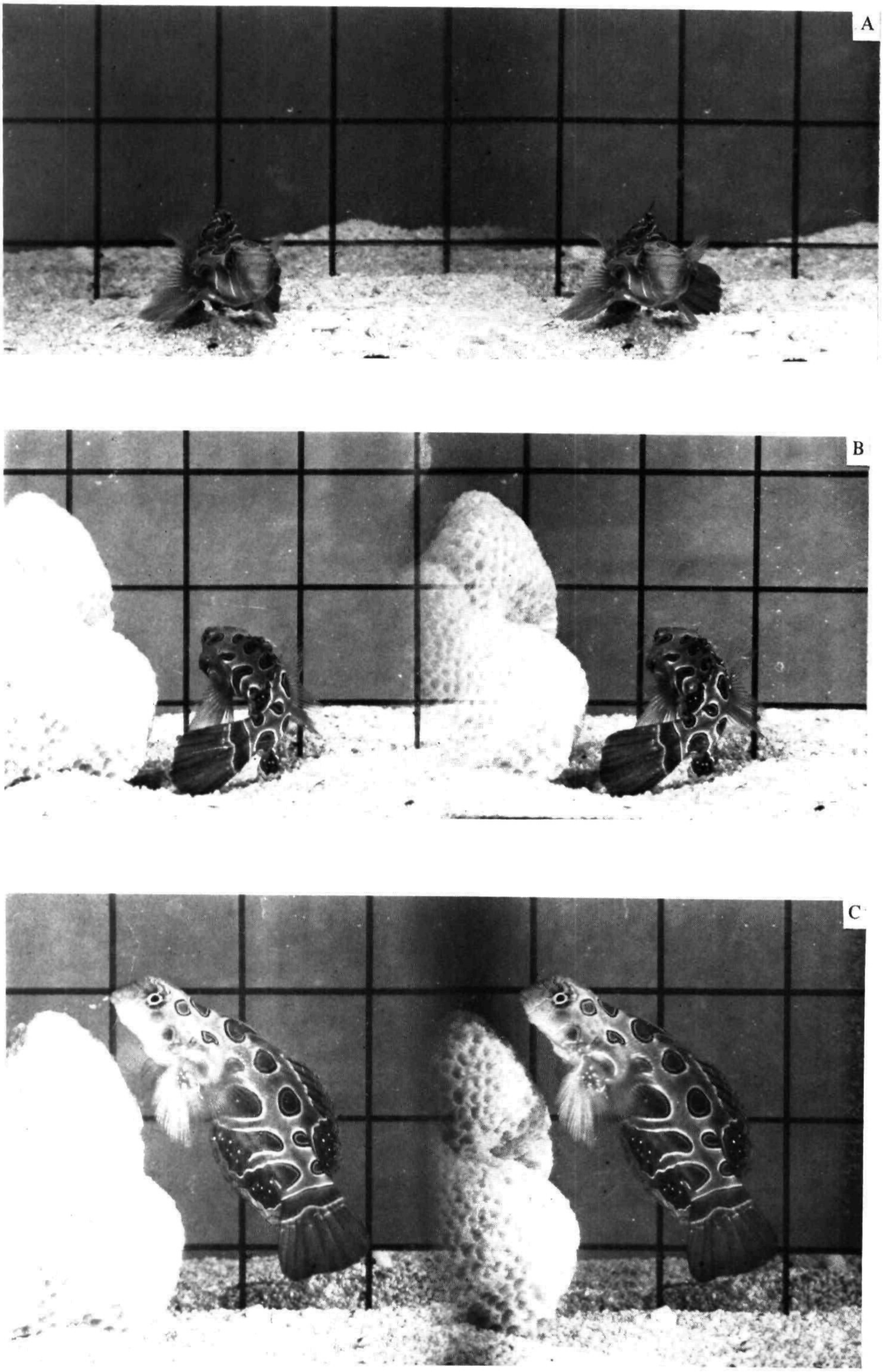

Fig. 5. Stereoscopic pairs of photographs of *Synchropus picturatus* hovering in front of a grid (25 mm squares) in (*A* and *B*) and out (*C*) of ground effect.

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