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Hydrodynamics of an Extinct Amphibian

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ABSTRACT

The Paleozoic amphibia known as Diplocaulus, of the order Nectridia, are characterized by long tabular horns similar in planform to the wings of a modern jet airliner. Previous research on the hydrodynamics of the head were established from wind tunnel tests but with a fixed body position placed at zero incidence. The current paper examines the hydrodynamics and stability if both the head and body change incidence, in order to obtain an improved understanding of the overall hydrodynamics. It is found that the conditions would result in unstable motion indicating a high level of maneuverability. Under certain conditions of head and body orientation the situation is one of static equilibrium, assuming the drag is countered by the thrust produced by the tail. Assumptions are made regarding the densities of the body and head in order to determine buoyancy effects.

Keywords: Wind tunnel testing; hydrodynamics.

NOMENCLATURE

C_L	lift coefficient	β	angle of incidence
C_D	drag coefficient	ρ	fluid density
C_M	pitching moment coefficient	V	velocity

1. INTRODUCTION

Because of the marked similarity in the planform of the creatures head to the swept wing profile of modern aircraft the flight characteristics has also attracted interest from aerodynamicists. Fairly intact fossils have been found in the lower Permian Clear Fork Group of North Central Texas and a fairly definite idea of the anatomical structure of the creature has resulted. A reasonably clear description has been given by Douthitt (Douthitt 1917) with the skeletal outline shown in Fig. 1.

A variety of views have been put forward in attempts to explain the functional significance of the tabular horns. Suggestions have been made that these were for protection of external gills (Williston 1917), for counter balancing the head (Douthitt 1917), locomotion and protection (Olson 1951), ballast stabilization and as respiratory adaptation (Beerbower 1963). Cruickshank and Skews (Cruickshank and Skews 1980) examined the possibility that the head was a balanced hydrofoil by undertaking a series of scaled wind tunnel experiments on the head, due allowance being made for limited interference effects of the body. Measurements were made of the forces perpendicular to the direction of motion (the lift force), that parallel to the stream direction (the drag force) and the moment (pitching moment) referenced to the axis of rotation of the head about the occipital condyles (pivot point between head and body). They found that the head had very interesting hydrodynamic properties which were entirely consistent with the animal being a mid-water feeder rather than a bottom dweller as had been assumed previously. Both the lift and pitching moment were zero at small negative incidence (-1°) resulting in minimal strain on the neck muscles. In addition the head exhibited the very interesting property that the position of the center of pressure coincided with the aerodynamic center and was fixed with respect to the occipital condyles. Thus the tension in the neck muscles was directly proportional to the lift force being generated. In these tests only the forces on the head were measured and it was found to be hydrodynamically unstable i.e. an increase in incidence would increase the nose up pitching moment which would tend to increase the incidence still further.

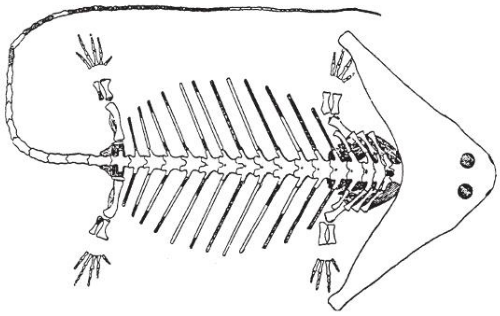

Fig. 1. Diplocaulus skeleton (Douthitt 1917).

In order to be able to assess the stability more thoroughly it is necessary to evaluate the forces acting on the whole animal. This is the purpose of the current investigation. Data regarding the maneuverability and stability of the animal might be of value to palaeontologists trying to determine more definitely its habits, diet and anatomy. An indication of the hydrodynamic forces acting on the surface of the animal might allow more accurate estimations of muscle size and conversely consideration of muscle size in conjunction with drag data could lead to satisfactory predictions of the animal's speed range.

2. MATERIAL AND METHOD

The model head used was that used in the previous investigation (Cruickshank and Skews 1980). It is largely based on the casts kindly made available by the Field Museum of Natural History, Chicago, and the fairly unambiguous descriptions and reconstruction given by Douthitt (Douthitt 1917). The shape of the body is less clear. The plan outline was assumed to be defined by the end points of the ribs as given in his reconstruction. It is possible however that a peripheral flap of tissue existed on parts of the circumference perhaps even connecting to the rear of the skull. This would have had significant effects on the stability and lift of the animal, particularly when the head and body are at incidence. There is no additional evidence available from which to estimate such effects, because of the paucity of specimens, only having skeletons available on which to base assumptions. However without any evidence of such a possibility the skeletal remains were used. There is also some doubt as to the dorsoventral thickness of the body at various points. Scaling up of vertebrae of the anterior portion, the body was about 30mm thick in the area of the neck tapering to about 25 mm toward the rear. In the model it was assumed that there was little thinning out of the body in the lateral direction and as a result the lateral cross section was roughly rectangular. It should be noted that the form of the ribs with a deep double rooted attachment to the spine and thin single shafted lateral extensions could have resulted in a lateral cross section which was thinned towards the edges.

The model body was made of Jelutong wood sand-papered to a smooth finish. A worm and gear was fitted to the head body articulation to allow fine adjustment of head angle with respect to the body. The body was attached to the wind tunnel balance which allowed the body-head assemblage to be rotated in pitch with respect to the airstream. The supporting struts were fitted with windshields so as not to influence the measured forces. The tail and legs were not included in the model.

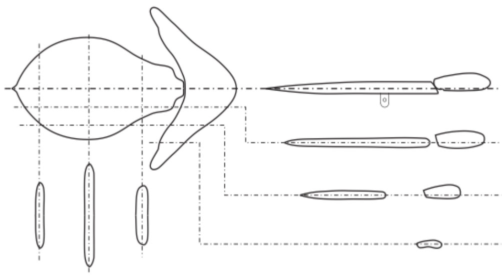

Fig. 2. Sketch showing cross-sections of the model. The distance from the nose to the base of the skull is 11.8cm and the span measured across the tips of the horns is 35cm.

For dynamic similarity between the flow in air in the wind tunnel and that in water the ratio of inertia forces to viscous forces, the Reynolds number, must be kept constant. For the purpose of this investigation it was assumed that Diplocaulus had a speed range of between 0 and 3*m/s*. In order to obtain equivalence in Reynolds number this meant that tests in air at about 50*m/s* were required to ensure similarity between the flows. Tests were run at three wind tunnel velocities corresponding to speed in water of about 0.9, 1.8, and 2.6*m/s* corresponding to Reynolds numbers of 73000, 147000, and 213000. Similarly for the determination of the relationship between forces on the model in air and the equivalent force in water, force and moment coefficients are defined. Thus the measured lift and drag coefficients are divided by the dynamic pressure, $\rho V^2 / 2$, where ρ is the fluid density and V the velocity, and a characteristic area. In the previous work this area was taken to be the planform area of the head (0.02635 m^2). The pitching moment coefficient is obtained by dividing the measured moment by the dynamic pressure, the above area, and a further characteristic dimension; in this case the root chord of the head (0.0775*m*).

3. ANALYSIS

The body was rotated about the pivot point situated on its underside as indicated in Fig. 2. This did not coincide with the resolving center of the wind tunnel balance thus influencing the calculation of the pitching moment. Normal convention is to specify the moment about the center of gravity, however in this case because of buoyancy effects the actual center of gravity with the animal submerged would depend on assumptions regarding the density of the components. For convenience, moments are taken about the centroid of the displaced volume of water. By immersing the components in water it was established that the volume of the head is 650 cm^3 and that of the body, 895 cm^3. From balance measurements the corresponding distances of the center of gravity from the head's leading edge (nose) were 103 and 327*mm*. Thus the centroid of the displaced water is calculated to be 232.76*mm* from the leading edge when the head and body are in line as shown in Fig. 3. This will be retained as the characteristic length for purposes of calculation but as the head rotates relative to the body this will move slightly.

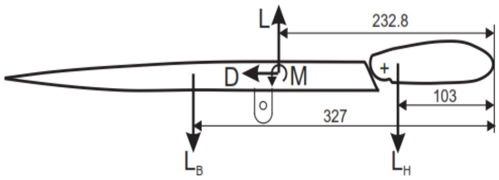

Fig. 3. Sketch showing position of centroid of displaced water.

Forces and moments are measured at the resolving center of the wind tunnel balance, marked R in Fig. 4. These are the lift, L, drag, D, and pitching moment, M. For the variation of the pitch of the chord of the body, β, these can be converted to act at the centroid, C. P is the pivot point about which the model rotates. From these the force and moment coefficients are determined as indicated above. Measurements are given so that the stability and control issues may be examined by including the effects of buoyancy, by assuming density values of the components. The density of the head, which is predominantly bone is probably between 1.7 and 1. 9 $g\,/\,cm^3$, whereas that of the body is less certain and could even be assumed to be neutrally buoyant. This will be discussed further later.

4. RESULTS

Tests were conducted at the equivalent of three swimming speeds and nominal Reynolds numbers of 73000, 147000, and 213000, with a variation of about 1% between tests at each speed. Results are given in Fig. 5 for changes in body angle and a fixed head angle of 0°. It is noted that there is very little change with Reynolds number, with a slight change at the lowest value and almost identical results for the medium and high speed tests. Thus it will be assumed that for realistic swimming speeds the effect of Reynolds number is minor. This is similar to the findings on the original tests on the head alone (Cruickshank and Skews 1980). For this reason results will be presented for the detailed tests at the middle value only, corresponding to a swimming speed of 1.85*m/s*.

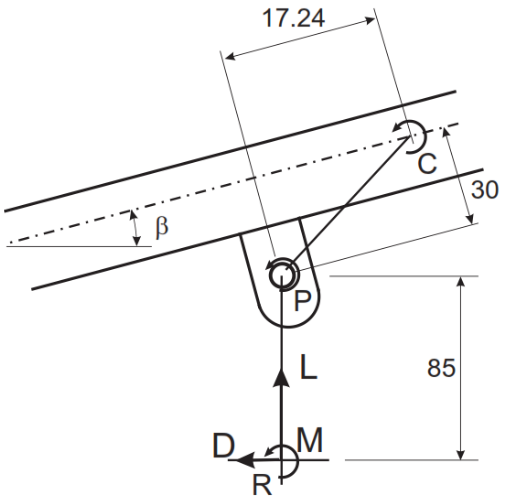

Fig. 4. Geometry for force and moment changes (not to scale).

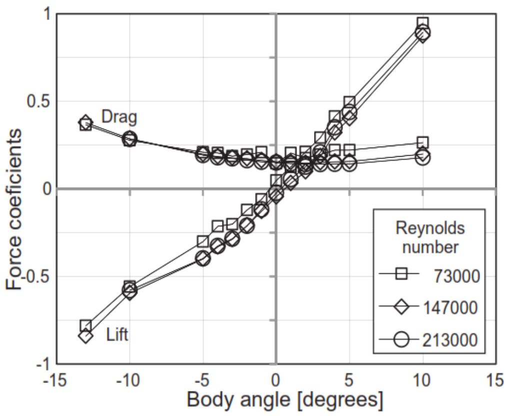

Fig. 5. Lift and drag coefficient variation with Reynolds number for fixed head inclination of 0◦ relative to the body.

The force and moment coefficients are presented in Figs. 6, 7 and 8. This data represents the hydrodynamic forces and pitching moment coefficients due to the motion of the animal through the water only, with the actual values of lift, drag, and moment determinable by substituting the density of water and the scaled velocity into the coefficient equations, together with the known geometrical properties since the wind tunnel model is full scale. The overall equilibrium conditions including buoyancy effects is considered later.

The lift variation is approximately linear, Fig. 6, with increasing pitch in both the body and head resulting in increasing lift, as expected. However, it is interesting to note that with the body at negative pitch the head incidence becomes increasingly less effective, with the body at less than -10° the head incidence has no effect. Furthermore, positive head pitch contributes significantly to the lift whereas negative pitch has minimal effect with the lift primarily determined by the body pitch.

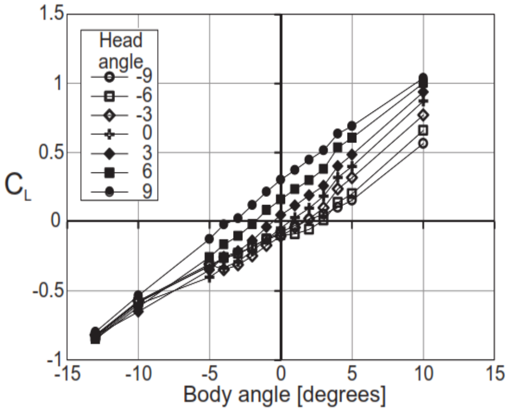

Fig. 6. Lift coefficient as a function of body and head angles.

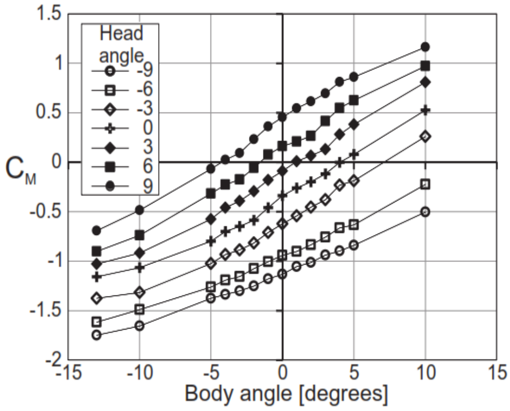

Fig. 8. Moment coefficient as a function of body and head angles.

The drag curves exhibit the expected bucket shape, but with the minimum drag point occurring at higher body angles as the head angle decreases. This may be a result of the wake from the head shielding the body flow to some extent. On the other hand, high head angles have a much smaller effect on the drag curves, with the minimum drag occurring close to zero body angle and head angles above zero degrees. The major influence on drag is with negative head angles.

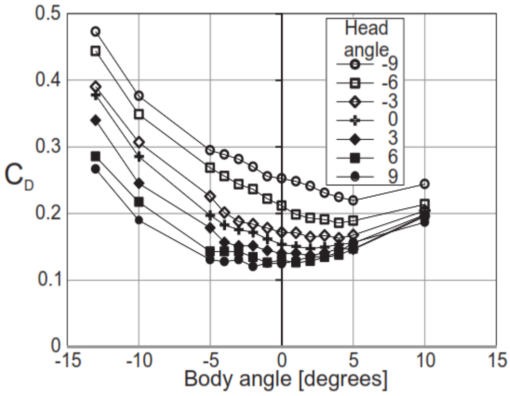

Fig. 7. Drag coefficient as a function of body and head angles.

The pitching moment curves all have positive slope with a slight increase in slope as the head angle increases as could be expected. This is an unstable situation since a small increase in pitch results in a larger moment which will tend to increase pitch further. This is a feature associated with highly maneuverable bodies, and does suggest the animal could use this to advantage. It is interesting that the pitching moment is zero for a 3 degree head incidence and zero body incidence, very nearly corresponding to when the lift is also zero. This would suggest this would be the resting condition of the animal in a steady stream. Because of the negative bouyancy due to the weight of the body and head this would allow the animal to sink to the bottom, with any drag being countered by tail thrust.

5. DISCUSSION

The basic hydrodynamic forces and moments discussed above do not account for the equilibrium situation for the animal submersed in water. This will depend on assumptions relating to the density of the head and body so as to account for the effects of buoyancy. Without specific knowledge of the density and its distribution within the animal and thus its center of gravity and corresponding center of buoyancy, only some rough estimates of these effects can be made.

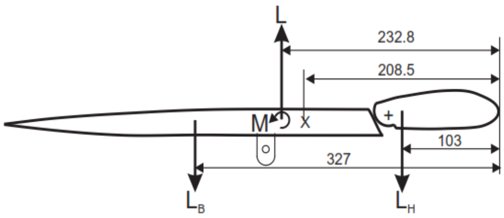

Fig. 9. Schematic of buoyancy effects.

Estimates of bone density vary between 1.7 and 1.9 g / cm^3 and because of the probable amount of soft tissue the lower value for the head will be assumed. As for the body, the density could range from being that of water to a value slightly above to take care of the bone content. A value of 1.1 g / cm^3 is initially assumed. The buoyancy force acting at the center of volume for these two components may be calculated. In both cases because density larger than that of water is assumed the net force will be downward. The actual equilibrium situation is as indicated in Fig. 9 for the case of both the head and body at zero incidence, for purposes of illustration. The cross in the head indicates the position of the occipital condyles which is the point at which the head rotates relative to the body and is positioned 118 mm from the nose. The X marks the position of the center of gravity of the combined bodies with the density assumptions made. L_B and L_H are the forces due to buoyancy and are both negative. L and M are the hydrodynamic lift and moment about the centroid as established earlier. The net result is a decrease in lift and also in moment because L_H is somewhat larger than L_B due to the larger head density.

As an example consider the case of the body aligned with the stream i.e. at 0° with only the head moving. This could represent a very natural positioning in watching for prey, with the position in the stream being held through thrust from the tail in order to counter the drag. The magnitude of the buoyancy forces can easily be calculated as can their moments, since the difference in density between body and water, the body volume, and the known distance to the body's center of gravity are all known. The very small change in the pitching moment arm as the head rotates has been neglected. Since the lift coefficients due to the hydrodynamic forces in air are the same as that in water, at the same Reynolds number, the lift coefficient due to buoyancy is simply added to give the effective value. A similar argument applies to the moments.

The net result for this case is given in Fig. 10 in coefficient form, non-dimensionalised as before, and for the same Reynolds number. Both the lift and pitching moment decrease, the lift because the buoyancy force is negative for both the body and head, and the moment because of the largest buoyancy force is due to the mass of the head, which results in a pitch down moment, in contrast to that of the body. If the body were to be neutrally buoyant the lift would increase slightly and the pitching moment would decrease. Sufficient data has been included so that other cases could be examined. If more accurate knowledge of the distribution of density became available the results could also easily be extended.

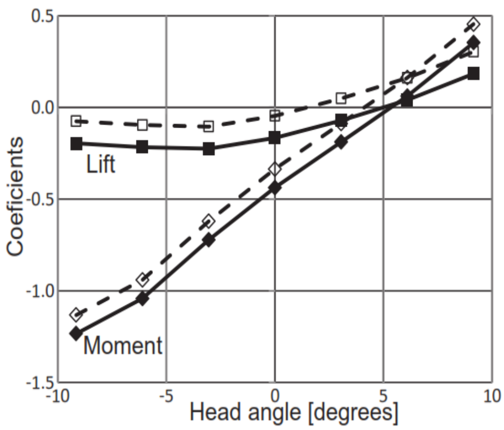

Fig. 10. Schematic of buoyancy effects. solid line: hydrodynamics with bouyancy. dashed line; hydrodynamics alone. Body angle at zero incidence.

An interesting feature noted in Fig. 10 is that both the pitching moment and lift are zero at a head angle of about 5 degrees. This indicates that the hydrodynamic lift force is balanced by the negative buoyancy force and the hydrodynamic positive pitching moment is balanced by the negative pitching moment due to weight of the head. Under these circumstances the animal is in equilibrium and the only force acting on it is the drag, which would need to be balanced by the thrust from the tail if the position in the flowing stream were to be maintained. This is also close to the point of minimum drag. Higher thrusts would move the body forward and an increase in head angle would cause an increase in body angle and result in a rapid increase in elevation, which could be counteracted by a decrease in head angle. These factors suggest a highly maneuverable behaviour. However, the contributions of the feet and tail in this regard have been ignored. Whilst it is indicated that the tail was flattened in the vertical plane it could have had a horizontal components which could have been use to add some control in pitch. The skeletal remains show the feet to be rather small and are unlikely to have contributed as a control surface.

6. CONCLUSION

Estimates are made of the hydrodynamic features of the extinct amphibian Diplocaulus, using wind tunnel data to model the hydrodynamic forces and moments, followed by consideration of buoyancy effects. It is shown that the animal was unstable, resulting in a high degree of maneuverability. Once more accurate estimates of density distribution and assumptions about items such as the tail are available more definite estimate of the dynamics of the animal under various orientations may be made.

ACKNOWLEDGMENTS

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