Fluid Dynamics in Freediving – a Qualitative Analysis

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Special Presentation for AIDA Instructor Course, 08-04-2013

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One very important aspect in freediving is to move as smoothly through the water as possible. This analysis is meant to give us an idea of how much of a difference body position makes, how skin friction affects us, as well as what kind of freediving equipment we should look for, to aid in our goal to become one with the ocean.

Calculation of increased drag due to bad head position

Assumptions

- 1.8 m diver
- All propulsion from fins, fins not part of body
- Diver's head considered being a 0.11 m radius sphere
- Area of diver head first, A=0.2m^2 (1)
- Salt sea water, 35g NaCl/kg, 20°C. Dynamic viscosity,μ=1.08*10^{-3} Pa*s. Density, ρ=1025kg/m^3 (2)
- Diver swimming speed, v= 0.9 m/s

Drag force can be calculated by the drag equation (3):

$$F_{drag}=\frac{C\rho A v^2}{2}$$

Where C is the drag coefficient. This number will in this case mainly depend on the shape of the body, which will be around 0.7 for an average human. (1)

ρ is the density of the fluid, which we have assumed being 1025 kg/m^3

A is the area of body, assumed being 0.2 m^2

v is the velocity of the fluid compared to the solid body, assumed being 0.9 m/s

$$F_{diver}=\frac{0.7*1025\frac{kg}{m^3}*0.2\,m^2*0.9\frac{m}{s}}{2}=58.1175\,N$$

Considering the head as a point of additional drag

So what happens with this drag force if the diver were to tilt his head upward, placing the centre of the head 12 cm above alignment with the rest of the body?

For a sphere, which we consider the head to be, the drag coefficient, C, is largely dependent of the Reynolds number. The Reynolds number is a dimensionless number that quantifies the ratio between the inertial forces, and the viscous forces. It is an important tool in fluid dynamics for determining certain flow characteristics among other things as we soon will see.

$$Reynolds\ number,\ \Re=\frac{vL\rho}{\mu}$$

Where we already have defined *v*,*ρ* and *μ* as the relative fluid velocity, fluid density and dynamic viscosity respectively. *L* is the characteristic length, usually the length of the solid body in the axis of motion. For sphere, the usual convention is to set *L* as the diameter, thus 0.22 m.

$$\Re_{head}=\frac{0.9*0.22*1025}{1.08*10^{-3}}\approx 188000$$

This Reynolds number should give something called von Karman trails, resulting in vortices appearing after the sphere with fast alternating directions (4). These vortices exert forces on the sphere resulting in a zig-zag movement. You may have seen this when dropping something small and round in water that either sinks or floats up fast, or felt your head wiggle a bit from side to side while swimming under water with this kind of head position.

In these conditions, *C*, will be around 0.47 (5) for a sphere, and the reference area will for a sphere be $r^2*\pi$

$$F_{head}=\frac{0.47*1025\frac{kg}{m^3}*(0.11\,m)^2*\pi*0.9\frac{m}{s}}{2}=7.417\,N$$

F_{head}/F_{diver}=58.1175 N/7.417 N=0.1276≈0.13

So around 13% more force from the fins is needed to keep the same velocity when facing the direction of motion. However, the drag force acting on the head is not like the rest of the streamlined body in average exerted in the level of the mass centre, but instead 12 cm above this. Therefore we get a momentum, M. M=F*l=7.417 N*0.12 m=0.89 Nm

The force from the fins, F_{fins}=58.1175 N+7.417 N=65.535 N, will need to compensate for this momentum by acting on the diver in a way that the momentum is cancelled out.

$M=F_{fins}*l_{fins} \Rightarrow l_{fins}=M/F_{fins}$=0.89 Nm/65.535 N=0.01358 m≈1.4cm

Meaning that the fins will need to exert the force 1.4 cm higher up towards the back, without changing direction, probably resulting in worse swim technique, which will be complicated to calculate without empirical studies and/or computer simulations.

Considering the upper body acting as a hydrofoil

When tilting the head to look in the direction of motion, probably more than just the head will move as in previous example. The neck, chest and stomach will likely bend, resulting in the surrounding water being deflected by the body. This induces a force with its components directed perpendicular and against the direction of motion, a lift force and drag force respectively, thus the upper body can be considered a hydrofoil.

The lift force and the drag force from a hydrofoil can be calculated with the Lift Equation (3):

$$F_L = \frac{\rho v^2 A C_L}{2}$$

Where A is the area of the lifting surface and C_L is the lift coefficient. We approximate the area A to be 0.2 m^2. C_L is commonly determined experimentally, as it depends on many complicated factors. We can however get a very rough approximation using thin airfoil theory to estimate C_L (6).

$$C_L = 2\pi\alpha$$

Where α is the angle of attack in radians. In this example we can estimate the tilt of the upper body to be 5 cm, starting 50 cm lower on the upper body. The angle of attack would then be arcsin(5/50)≈0.1

We can now calculate the lift force.

$$F_L = \frac{1020 * 0.9^2 * 0.2 * 2 * \pi * 0.1}{2} = 52.3\,N$$

As mentioned before, we will also get drag force from the body acting as a hydrofoil. The formula for induced drag force is quite similar to lift force:

$$F_{ID} = \frac{\rho v^2 A C_D}{2}$$

Where C_D is the drag coefficient, for which we once again can approximate with thin airfoil theory. (6)

$$C_D = \frac{{C_L}^2}{\pi e A_R}$$

Where e is the Oswald efficiency number and A_R is the aspect ratio. We set e=0.9 simply because I can’t find a way to approximate it, and the fact that a value of 0.85 to 0.95 is common. The aspect ratio is another matter of very rough approximations where I consider the lifting surface on the chest having the shape of a square, thus AR=1.

$$C_D = \frac{(2\pi\alpha)^2}{\pi * 0.9 * 1} \approx 0.14$$

$$F_{ID}=\frac{1025*0.9^2*0.2*0.14}{2}\approx 11.65\,N$$

Total force from the fins to keep the freediver at constant velocity of 0.9m/s forward can be determined using Pythagoras's theorem.

F_{fins}/F_{diver}=87.2 N/58.1175 N=1.5003

It is therefore required 50 % more force to swim with upper body slightly tilted upwards.

Conclusion

Even though many of the parameters for the calculations probably are quite far from actual values, and makes the results rather arbitrary, it does give us an explanation of how some major fluid dynamic forces change with body position. This points us back to what we already knew: Body position has a very large impact on how we will experience freediving

Skin friction in freediving

When freediving, drag mainly consist of form friction and skin friction. Skin friction arises when a solid body is moving through a fluid. The moving body will then alter the movement of the fluid closest to the surface of the body. Therefore force is needed to accelerate the fluid, which in its turn is acting with an equal force on the skin of the freediver according to Newton's Third law of motion: *To every action there is an equal and opposite reaction*, making it more difficult to move the body.

Importance of skin roughness

So, how much does skin friction affect us while freediving? One important thing to know is if we are dealing with laminar or turbulent flow. Laminar flow is characterized by the fluid moving like very thin sheets, sliding over each other at slightly different velocities. If we have laminar flow all over our bodies while swimming, the skin friction is proportional to the total wetted area, which for me can be calculated to 1, 94 m^2 (7). An additional factor other than the wetted surface is the roughness of the surface. However, we will in all laminar flow cases witness that the fluid closest to the skin always move at the same velocity as the skin, roughness doesn't affect skin friction in those cases. Very rough surfaces, or surfaces with relatively large protrusions, like body hair, can be considered giving the surface a larger wetted area. This will in its turn contribute to larger skin friction as well as earlier conversion to turbulent flow. When we have turbulent flow, surface roughness can on the other hand affect the skin friction. As turbulent flow is characterized by chaotic motion of fluid particles, those particles closest to the surface (who on an average won't travel in the same direction as the object) will hinder the movement of the object as particles are more prone to collide with the rough surface.

So is the flow around our bodies while freediving laminar or turbulent? We can do a quick control by calculating the Reynolds number:

$$\Re = \frac{\rho L v}{\mu}$$

Where ρ=the density of the fluid=1025 kg/m^3

L=characteristic length=1. 8m

v=fluid speed compared to object=0.9m/s

μ=dynamic viscosity=0, 00108 Pa*s

Re=1025*1.8*0.9/0.00108=1, 537, 500≈1.5*10^6

For Re> 3.5*10^5 we are likely of having turbulent flow. However, it is from this number not known over how large part of the body turbulent flow will be present. In athlete swimmers, laminar flow is often observed on part of the abdomen and thighs, as those are relatively flat. As freedivers roughly swim at only half the speed of a swimmer during a max performance, we should have a larger percentage laminar flow. Also, when using fins, we don't move our arms much, so at least the front most part of our arms should have laminar flow.

We can calculate if the surface roughness has any significant impact on skin friction. (Remember, this may only apply to surfaces with turbulent flow)

k=100**l*/Re (3)

Where k=roughness large enough to increase skin friction

l=boundary layer thickness

We have to calculate *l*, which can be approximated with this formula describing a flat plate in turbulent flow.

l=0.382 L/Re$^{0.2}$ (6)=0.04m

But since most freedivers don't look very much like flat plates, we can compare with a swimmer instead. Swimmers have roughly the double velocity which gives them twice as large Re, and a boundary layer of 0.25 m is an average in experiments (8).

1$^{0.2}$/2$^{0.2}$*0.25=0.218 m

k= 100*0.218/1.5*10^6=1.45^{-5} m=14.5 μm

14.5 µm is actually about the same roughness as human skin, ranging from about 10 to 20 µm (9). We must remember that it is not only the absolute value of roughness that matters, but also the topography of the surface. This is too complicated to take into consideration right now, as this is more meant to get a rough idea.

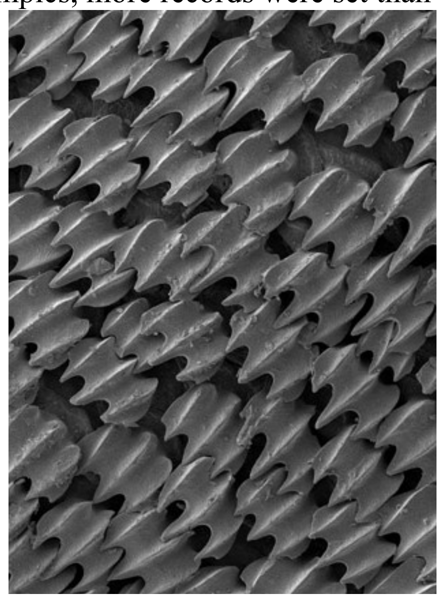
Conclusion

These results do however imply that getting a suit only for the sake of reducing skin friction with water, will at most have a non significant or no impact whatsoever, as our skin is already smooth enough. Even though this research does not cover the impact of body hair, it is very likely removing body hair or wearing a swim cap will reduce skin friction noticeably.

The shark suit

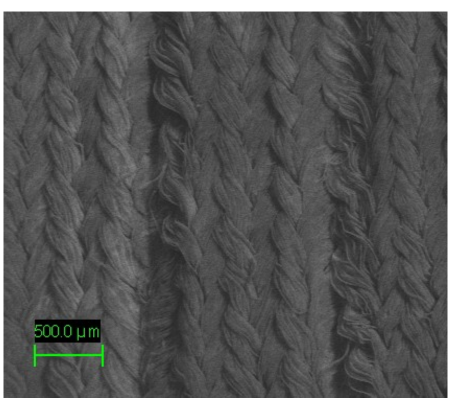
As you probably remember, during the 2008 swimming Olympics, more records were set than ever before. This was also the first time the now banned full-length "shark suit" were worn by many of the competitors. According to Speedo who developed the shark suit, or FSII as the model name is called, the suit's outer surface mimics that of shark skin, reducing skin friction.

It is suspected that sharks somehow seem to move easier through water compared to other bodies of similar shape. If you have ever touched a shark or ray, you know that their skin is not smooth like a dolphin's, but instead coarse. This is because shark skin is covered with microscopic ridges, called dermal denticles, with a structure similar to teeth. So in some way, having a rough skin can, at least for a shark, make swimming easier.



Bull shark skin (16)

The FSII "Shark Skin" (10)



The hydrodynamic function of shark skin

Last year (2012) Johannes Oeffner and George V. Lauder at Harvard University published a report (10) describing how sharks use the dermal denticles, and also how the FSII suit functions in comparison. Studies like this has been done before, but what those scientists did differently was testing how the surfaces affected swimming speed when they were used in propulsion, contrary to other studies which only used steady flow on rigid bodies. In the study, rigid plates with steady flow, rigid plates that self-propelled and flexible self-propelling foils where used. For the surface material, shark skin, FSII fabric, ridged silicone made to mimic shark skin and sanded shark skin (shark skin that had its dermal denticles sanded down) where attached to the plates and foils. These were then in various velocities tested to evaluate self-propelled speed and hydrodynamic drag.

Results

The tests resulted in that for the rigid plates, and the rigid moving plates, the sanded shark skin actually had lower drag and higher self-propelling speed, compared to the un-sanded skin. However, when attached to a flexible moving foil, the self-propelling speed increased on an average of 12.3%, for the skin with the denticles still attached. For certain frequencies, the shark skin was 20% faster than the sanded shark skin.

Similar, but not as dramatic results were observed in the shark replicating silicone ridged material. For the rigid and rigid moving plates, the smooth "back side" of the silicone produced least drag and higher self-propelled speed. But for the flexible foils the ridged surface showed an increased self-propelled speed: 7.2% with the ridges perpendicular to the axis of motion, but as well to some extent with the ridges parallel, indicating that surface roughness alone is a beneficial factor.

With the Speedo FSII no consistent self-propelling speed or drag reduction were noticed. Having the seams the "wrong" way or even using the inside of the suit instead over the different flow velocities had in average no impact.

Discussion

From the results there are no doubts about the importance for shark-like skin actually bending as it moves through water. And this is also the way sharks swim in real life: Basically their whole body bends, and even large sharks are quite flexible. The exact reasons how this works has not been proven yet, but the denticles seems to make the so called leading edge vortex closer to the fin, increasing thrust. A leading edge vortex makes a local pressure drop at the backside of a fin moving through a fluid, creating suction that in this case is beneficial for locomotion.

As we can see from the results, the FSII is nothing like shark skin. From the pictures it looks very similar to fabric used in other suits. And even if it had the shark skin properties, it is very unlikely we would see any gain in a human swimming with this kind of surface. As we just have learned, shark skin only works when the propelling parts bend. As humans swim without fins, it is mainly our arms and legs moving us forward, and these only bend at a few joints, making the use of a "shark suit" rather obsolete. Now we might ask ourselves, why did we see so many records being broken those 2008 Olympic Games? The answer seems to lie in other areas than surface properties. The suits are very tight, and the athletes are really squeezed in them. This pressure could help the veins return blood to the heart easier, increasing the blood flow and therefore giving more oxygen for the muscles to work with. Probably an even greater benefit of the suits is that they alter body form and helps having a good posture, even when tired. This gives the body less form drag, which for humans, who aren't very streamlined, could make a great difference.

Conclusion

When using a suit for freediving, the surface is not really important, as long as it is not very rough. Feeling comfortable and being able to use good technique is much more important. What might be something to look for instead of "shark suits" could be "shark fins". Freediving fins, just as a shark's body bend when used for swimming, meaning with some bio mimicry in fins, we might get more power with every stroke. They would probably have an undetectable bit of extra drag in freefall, but utilising the energy better for swimming, giving us more time and distance. Maybe something to look for in dive shops in a couple of years.

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