Hypersonic effects in water

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1 Introduction

Supersonic in air is a well established term and it's when you travel faster then the speed of sound, also known as Mach 1. When the speed exceeds Mach 5 it's called hypersonic.
Since air is a gas the density and therefor the friction is very low. But, what is happening when we try to go supersonic in a liquid, like water?

2 Supersonic in air

Sound waves are pressure waves that travel in an elastic medium. The speed of which the waves are travelling are mostly dependent on the density and temperature of the medium. Since density, temperature and the composition of the air depends significantly on the altitude the speed of sound will vary. For an example is the speed of sound in dry air with a temperature of 20°C at sea level approximately 343 m/s while at an altitude of 10668 m it's 295.4 m/s. *Supersonic speed* [1].
For an object that travels near or faster than Mach 1 new auditory effects will occur. When an object is travelling at speeds underneath Mach 1, sound waves will be sent out in all directions while if the speed exceeds Mach 1 the object will travel faster than its own sound waves. At this point the sound barrier is broken, the sound waves becomes compressed by the object and it will result in sound waves with different intensities in different directions. This is when one will hear the famous shock wave, "the sonic boom" *Shock wave* [2]. It can be compared with the doppler effect where a traveling object that is emitting sound will compress the sound waves before it self and behind they will be elongated. *Doppler effect* [3].
Because a shock wave happens almost instantaneously and the total enthalpy along with temperature is constant the total pressure downstreams of the shock wave will be less than upstream *Shock Wave pressure drop* [4]. This pressure drop will sometimes force moist air around an object to reach its saturation level at which it can not "hold" its water any more. This will result in a temporary cloud, or a vapor cone. See Fig. 1.

Fig. 1 . Formation of a vapor cone around aircraft.

3 Supersonic in water

Since water is considered incompressible, the speed of sound is relatively high compared to air: approximately 1450 m/s at 20°C. So when you want to reach a hypersonic speed in water, you need to break the sounds barrier. Because of the high drag the water will cause, it takes a lot of energy to drive something through the water at this speed (in comparison: for common underwater vehicles the speed limited to about 40 m/s because of the high drag above this velocity). Theoretically it would maybe be possible to break the sounds barrier under water, but it has not been done yet neither we have the technology to do so right now.
In fact, before even getting close to reaching the speed of sound under water an other phenomena called cavitation will occur. Cavitation is the phenomena were small bubbles of vapour will form. Beside the other problems it will cause, it would also mean that the object would not be travelling through water anymore but instead through an bubble of a water/steam mixture. The effects of cavitation are explained extensively in section 4.

4 Hypersonic effects in water

4.1 Cavitation

Cavitation happens when a liquid is accelerated to high velocities, and is getting pushed away faster than it can react. This will leave behind an area of low pressure, often in the form of vapour bubble, the bubbles will expand as the pressure is reduced further. When the bubble reaches a high pressure area, it will violently collapse. These vapor cavities will cause a extremely high local pressure (about 800 MPa!). Usually objects are designed to avoid cavitation because of the damage it causes, but in some cases it can be used to our advantage (as explained is section 4.2). The effects of cavitation on a hydrofoil can be seen in Fig. 2.

Fig. 2 . Cavitation on a Hydrofoil.

To know when the cavitation will occur the cavitation number can be calculated by using a formula. This equation will estimate how close the pressure in the liquid flow is to the vapor pressure, which will tell if cavitation can occur or not. See Fig. 3. *Cavitation number* [5]

$$\sigma_{inlet} = \frac{P_{inlet} - P_{vap}}{\frac{1}{2}\rho V_{inlet}^2}$$

Fig. 3 . Formula for cavitation number.

4.2 Supercavitation

Beside its negative effects, cavitation can also be used as an advantage. Supercavitation is a technology used to increase the speed of an object moving trough the water. The nose of the object is used to create a bubble around the object. An example of this can be seen in Fig 4. This means that the object is no longer traveling through a liquid, but through a gas. This significantly reduces the skin friction drag on the object, enabling it to travel at higher speed. An example of the use of supercavitation is the supercavitation torpedo *VA-111 Shkval* [6]. Using this technology the torpedo was able to reach a maximum speed of about 100 m/s. This is not even close to going hypersonic.

Fig. 4 . Formation of supercavitation on an airfoil.

5 Conclusion

As it seems, it is impossible to achieve true hypersonic speed in water due to cavitational effects, which occur far before one will even reach supersonic speed in water. Even thought the use of supercavitation will help to reach higher velocities (for now up to 100 m/s) it wont be sufficient. We would need to find other methods or techniques to reach hypersonic speed in water, if it even is possible. To have some comparison: in 2005 the X-43 from NASA was able to break the speed record in air by going as fast a Mach 9.6!

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