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ORIGINAL PAPER

Flow simulation along a seal: the impact of an external device

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Abstract An increasing number of marine mammal studies on physiology, behaviour and ecology rely on data, which have been collected from back-mounted devices, such as bio-logging tags and satellite transmitters. However, external devices may influence an animal's hydrodynamics, behaviour and energy expenditure and, therefore, can impede the individual animal. To investigate the influence of external devices on seals, the water flow along a grey seal was simulated using computational fluid dynamics calculations. The simulations revealed several changes in forces and moments and thus balance, due to this device. The investigated satellite transmitter creates an average 12% increase of the drag coefficient. Additionally, there are significant relative transmitter-induced increases in pitching moment (32%) and lift (240%). The simulations also showed that the transmitter generates areas of decreased wall shear stress on the seal's back. The results of this study demonstrate that external devices can change the hydrodynamics of the seal, which is expected to alter the seal's physiology and behaviour and its use of the ecosystem. Long-term attachment may have adverse effects on the animal's welfare. It is important to take these effects into consideration when studying tagged seals; otherwise, the value of the data obtained will be poor. Therefore, interpretations and extrapolations regarding 'natural behaviour' of animals in their 'natural environment' should only be made with great caution.

Keywords Computational fluid dynamics (CFD) · Telemetry · Animal welfare · Satellite transmitter · Grey seal (*Halichoerus grypus*)

Abbreviations

CFD	Computational fluid dynamics
Cd	Drag coefficient
Cl	Lift coefficient
Cm	Pitching moment coefficient
D	Drag force (N)
L	Lift force (N)
M	Pitching moment
ρ	Fluid density (kg m^{-3})
U	Swimming speed (m s^{-1})
A	Frontal projection area (cm^2)
α	Pitch angle (°)
N	Kinematic viscosity (m^2 s^{-1})
WSS	Wall shear stress (N m^2)

Introduction

Throughout the past few decades, a variety of telemetry devices, such as bio-logging tags (e.g. Block 2005; Kooyman 2004; Naito 2004; Ponganis 2007) and satellite transmitters (e.g. Culik and Luna-Jorquera 1997; Matthiopoulos et al. 2004; Myers et al. 2006), have been used on various animal species to investigate a wide range of ecological and conservation questions. These include systems to study physiology (such as body temperature), behaviour (such as diving and foraging behaviour) and use

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of the ecosystem (such as seasonal and diurnal migrations). In particular, these telemetry instruments have been used to obtain information on animals, such as diving birds and marine mammals, which have a wide range and are difficult to observe because they spend a considerable amount of time under water.

To date, biological telemetry studies have been carried out on various species of the marine environment, such as cetaceans (e.g. Gifford et al. 2007; Read and Westgate 1997), seals (e.g. Call et al. 2007; Matthiopoulos et al. 2004), marine turtles (e.g. Lohmann et al. 2008; Watson and Granger 1998), penguins (e.g. Clarke and Kerry 1994; Ponganis et al. 2004; Ropert-Coudert et al. 2001), other diving birds (e.g. Benvenuti and Dall'Antonia 2004; Paredes et al. 2005; Whidden et al. 2007), fish (e.g. Gifford et al. 2007; Koed and Thorstad 2001) and even jellyfish (Hays et al. 2008). More recently, marine mammals have also been used solely as instrument to transport physical telemetry devices to gain information on physical environmental parameters, for instance salinity and water temperature (Fedak 2004; Hooker and Boyd 2003).

To contribute successfully to new insights on animal physiology, behaviour and ecology, telemetry studies require instrumentation that does not alter the animal's behaviour, either in time (e.g. time spent foraging) or in space (e.g. foraging locations, diving depths). However, attaching external devices to or even implanting devices in animals may influence their hydrodynamics or physiology and alter behaviour and energy expenditure (Bannasch et al. 1994; Croll et al. 1991; Wilson et al. 1986). A wide range of hydrodynamical and behavioural effects of carrying devices have been documented, for example in diving birds (Hamel et al. 2004; Igual et al. 2005; Paredes et al. 2005; Whidden et al. 2007), penguins (Culik et al. 1994; Taylor et al. 2001; Wilson et al. 1986, 2004) and fish (Koed and Thorstad 2001; Thorstad et al. 2001). In the long term, the hydrodynamic effects of external devices may have serious consequences for the animal's welfare.

Seals have a highly streamlined body, which is a prime example of convergent evolution in their design to minimise drag for locomotion in the water (Howell 1930). The effect of animal-carried systems is particularly important in marine animals (e.g. Bannasch et al. 1994; Culik et al. 1994; Watson and Granger 1998) because the drag caused by moving non-streamlined units through the dense medium, i.e. water, may lead to substantial increases in energy expenditure.

There are several methods that can be used to explore the issue of how external devices influence diving animals. In some studies, the behaviour of animals with an external device was observed in captivity (Healy et al. 2004; Petrie and Rogers 1996; Simeone et al. 2002; Stewart et al. 1989). Captive studies are, however, of limited value given that most animals in captivity do not usually exhibit normal diving and foraging behaviour. The consequences of a reduction in the ability to forage may not be significant in laboratory animals, but could prove to be severely debilitating or even fatal for free-ranging wild animals (Hawkins 2004). In some studies, the behaviour of free-ranging animals with and without devices has been compared (Croll et al. 1991; Whidden et al. 2007; McMahon et al. 2008). The most common approach to study the hydrodynamic effects of external devices on swimming animals is to experimentally investigate the generated forces on models. There are a few methods by which models can be studied: water tunnels, wind tunnels and flow simulations. All these methods share the same disadvantage, namely the modelled animal has a rigid body and it is not a deforming swimming animal. Most of the studies with models have been performed in wind tunnels because of the ease of measuring the forces on the model in a steady flow compared to water tunnels and towing tanks. However, when conducting tests in air instead of water, it is necessary to compensate the different viscosities of air and water with the flow velocity (Reynolds analogy). This means that the velocity in the wind tunnel needs to be about 11 times greater than the investigated swimming speed in water to achieve a comparable flow situation (5 ms^{-1} swimming speed leads to 55 ms^{-1} wind tunnel velocity). Water tunnel tests are usually too small to investigate a seal model on a real scale. Akin to the viscosity of different fluids, the scale of the model can be compensated by flow velocity. Here, the smaller the model is, the larger the velocity has to be (again Reynolds analogy).

Although external devices may have various impacts on the seals, as lined out above, our study focused specifically on the issue of hydrodynamics. In the present study, we chose to use a flow simulation model on a real scale as well as the characteristics of water, using computational fluid dynamics (CFD). The CFD models were introduced in the 1990s to study insects and birds during flight (Liu 2002). If the simulations are performed with care, an equivalent or even greater accuracy to the wind tunnel test can be achieved. In addition, flow simulation using CFD can generate a large quantity of data and is very time- and cost-effective.

The aims of the present study were:

1. To identify and describe the effects of an externally attached satellite transmitter on velocity distribution, drag, lift, pitching moment, static pressure and wall shear stress at different swimming speeds of a grey seal
2. To describe the effects of transmitter-induced changes in the hydrodynamics on the physiology, behaviour, ecology and welfare of seals

Materials and methods

Computational fluid dynamics

To address the issue of how a transmitter influences seals, the water flow along a grey seal (*Halichoerus grypus* Fabricius, 1791) with and without a transmitter was simulated using CFD calculations. CFD methodology consists of a mathematical model applied to the fluid flow. It is based on the numerical solution of partial differential equations expressing local balances of mass, momentum and energy, which may eventually couple to transport equations of non-reactive or reactive flows for given operating conditions. To do so, we used the FLUENT™ software, which has been developed for simulation, visualisation and prediction of fluid flow and heat and mass transfer.

With a system of equations representing turbulent models, it is not feasible to predict details of an unsteady flow like the flow around structures, not even when including a low Reynolds number (*Re*). To overcome this problem, we used the standard k-epsilon (κ-ε) model in the FLUENT™ software.

Model

A model of a seal in the steady gliding position, with minimal fluid dynamical drag, was set. The three-dimensional geometrical model of the grey seal created for the simulation was based on post mortem measurements, photographs and observations of swimming grey seals.

The model was designed without complex details such as front flippers and eyes. The three-dimensional model of the device was based on a commonly used Argos Satellite Relay Data Logger. The location of this satellite transmitter was dorsal, close to the head, which is the most frequently used place to attach these transmitters on seals. A 'best case scenario' was simulated, in which the effect of the device on the fluid dynamical drag should be as little as possible (Fig. 1).

A three-dimensional computational calculation domain was used, consisting of about one million grid cells, most of them close to both the surface of the seal and the transmitter to achieve maximum accuracy (Fig. 2).

For this simulation, the following values and settings were used:

Fluid mechanical settings:

Fluid: seawater
Kinematic viscosity: $\nu = 1.06 \times 10^{-6} \mathrm{m^2 s^{-1}}$
Density: $\rho = 1{,}028\ \mathrm{kg\ m^{-3}}$

Computer settings:

Mesh: three-dimensional, 1×10^6 grid cells
Turbulence model: k-epsilon (κ-ε) model

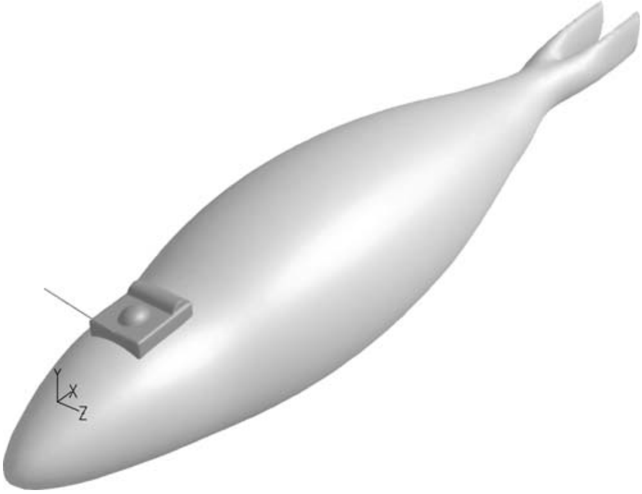


Fig. 1 Three-dimensional geometrical model of seal in steady gliding situation

Seal model:

Frontal cross-sectional area A, 800 cm^2
Pitch angles α, 0°

Hydrodynamics

Flow velocity, forces and moments

The water flow was simulated, and then distribution velocity, the different forces and moments acting on the seal with and without a transmitter were investigated. The forces and moments have been computed for a swimming seal, for each swimming velocity between 1 and 5 $\mathrm{m s^{-1}}$, which is within the normal range (Gallon et al. 2007; Orthmann 2000; Thompson and Fedak 1993). The drag, lift

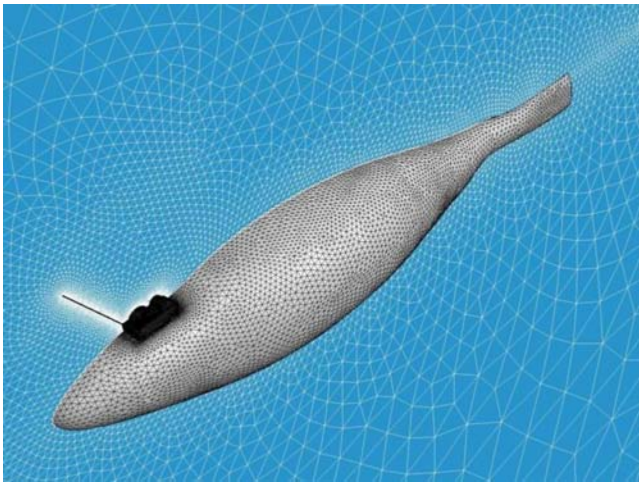


Fig. 2 Three-dimensional mesh

and pitching moment have been calculated and will be described as dimensionless coefficients (Fig. 3).

The drag coefficient, lift coefficient (Cl) and the pitching moment coefficient (Cm) were computed using the following equations:

$$\mathrm{Cd} = D/(0.5 \cdot \rho \cdot U^2 \cdot A)$$

$$\mathrm{Cl} = L/(0.5 \cdot \rho \cdot U^2 \cdot A)$$

$$\mathrm{Cm} = M/(0.5 \cdot \rho \cdot U^2 \cdot A \cdot L)$$
$$U = 1 - 5\ \mathrm{ms}^{-1}$$

where D is the drag force, L is the lift force, M is the pitching moment, ρ is the fluid density, U is the swimming speed and A is the projection surface of the model (this is the area of the seal perpendicular to the direction of the fluid motion).

The centre of gravity of the seal is assumed to be found at maximum girth.

Static pressure

The static pressure is the pressure at a nominated point on the seal model moving with the water. The changes in static pressure, which are due to the transmitter, were simulated.

Wall shear stress

A viscous fluid-like water moving along a solid body will incur a shear stress along the surface. At the surface, the velocity of the fluid is zero, but at some height from the surface, the flow speed increases asymptotically to the outer flow velocity. The region between these two points is called the boundary layer. The tangential frictional force along the surface is called wall shear stress. The integral of this wall shear stress along the entire surface of the body determines its friction drag, which limits its gliding speed and length and therefore its energy consumption. The wall shear stress was calculated for a seal with and without a device.

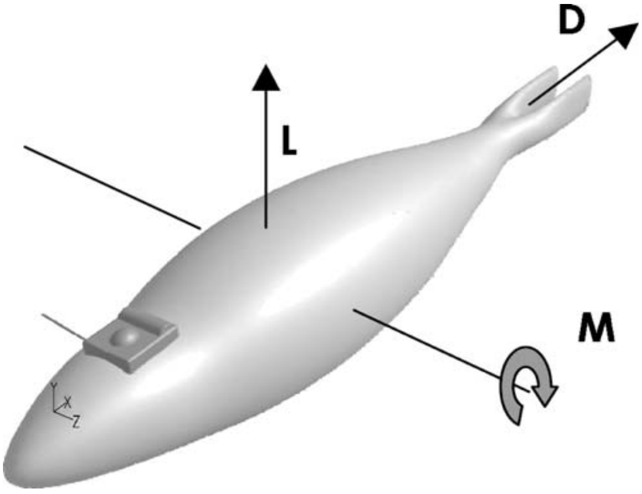


Fig. 3 Lift, drag and pitching moment

Results

The CFD simulation identifies several effects of the external device on the hydrodynamics of the seal, including velocity distribution, drag, lift, pitching moment, static pressure and wall shear stress.

Velocity

The simulation of the velocity magnitude reveals that a seal without a device is a highly streamlined object, where no flow separation or backflow occurs. Figure 4a shows the velocity vectors 1 cm from the object's surface coloured by velocity magnitude (metre per second). A seal object with a device shows a decrease in average velocity magnitude on the back of the seal (Fig. 4b). In addition, vortices and backflow can be found near the device.

Forces and moments

With flow simulation using CFD, it was not only possible to determine the drag, but also to calculate lift force and pitching moment. The results revealed several changes in forces and moments due to the device (Table 1).

The investigated satellite transmitter created an average increase of the drag coefficient of 12% (Fig. 5). The simulated drag coefficient varied between 0.08 and 0.1.

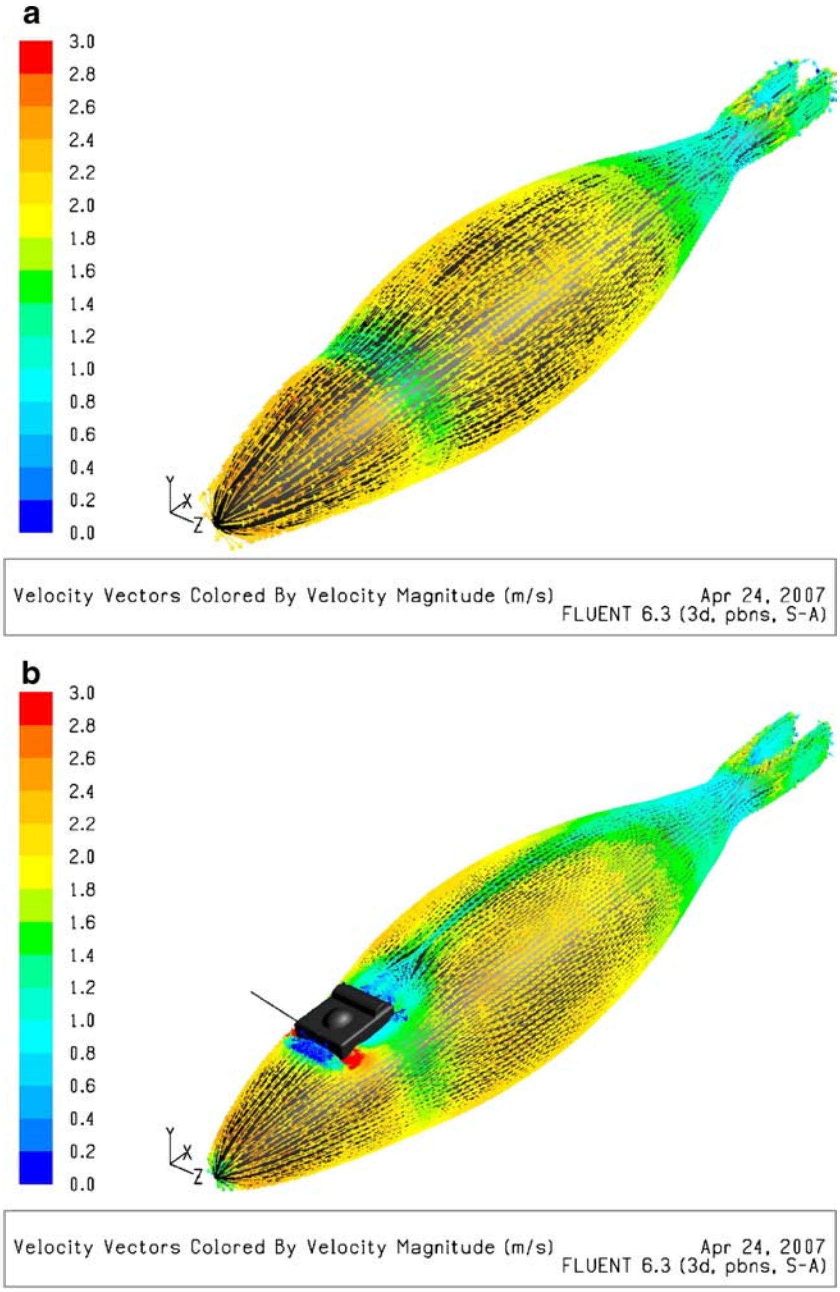
The absolute values for the lift force are rather small compared to the drag force; the lift was about 6% of the drag for a seal without an external device. We found that the transmitter created a significant average increase in the coefficient of the lift force of 240% (Fig. 6). There was a remarkable and sudden increment between a swimming speed of 2 and 3 ms^{-1}.

The pitching moment of the swimming seal was determined and revealed a significant average transmitter-induced increase of 32% in the pitching moment coefficient (Fig. 7).

Static pressure

The simulation showed that the transmitter changes the distribution of the static pressure slightly, but only in the vicinity of the transmitter and near the nose of the seal model. Large values for the static pressure could be found at the front face of the transmitter, whereas the pressure distribution along the seal did not change significantly.

Fig. 4 **a** Velocity vectors (seal without transmitter). **b** Velocity vectors (seal with transmitter)



Wall shear stress

The simulation demonstrated that the transmitter generates areas of decreased wall shear stress on the seal’s back (Fig. 8).

Discussion

Hydrodynamics

The CFD simulation demonstrates that there are several ways in which the transmitter affects the hydrodynamics of the seal: velocity distribution, drag, lift, pitching moment, static pressure and wall shear stress change. Below, the effects of externally attached devices will be discussed.

The CFD simulation reveals that there is a change in flow velocity along the seal. The identified vortices and backflow around the transmitter may interfere with the seal’s whiskers and thus its search for prey.

The simulated drag coefficient varies between 0.08 and 0.1. The transmitter-induced drag increase of 12% corresponds with values found in the literature based on model studies for external devices on highly streamlined marine mammals and diving birds with back-mounted devices (0.07–0.14; Bannasch et al. 1994; Orthmann 2000; Stelle et al. 2000). The highest values for the static pressure could

Table 1 Results for drag coefficient, lift coefficient (Cl) and pitching moment coefficient (Cm) for a swimming seal with and without a transmitter at different swimming velocities (metre per second)

Swimming speed (ms^{-1})	1	2	3	4	5
Cd1 (with transmitter)	0.119	0.109	0.101	0.094	0.091
Cd2 (without transmitter)	0.108	0.098	0.090	0.083	0.080
Cd1–Cd2 (%)	0.011 (10.2%)	0.011 (11.2%)	0.011 (12.2%)	0.011 (13.3%)	0.011 (13.8%)
Cl1 (with transmitter)	0.016	0.016	0.019	0.019	0.018
Cl2 (without transmitter)	0.007	0.006	0.005	0.005	0.004
Cl1–Cl2 (%)	0.009 (128.6%)	0.010 (166.7%)	0.014 (280.0%)	0.014 (280.0%)	0.014 (350.0%)
Cm1 (with transmitter)	−0.0077	−0.0071	−0.0062	−0.0063	−0.0065
Cm2 (without transmitter)	−0.0093	−0.0098	−0.0101	−0.0102	−0.0103
Cm1–Cm2 (%)	0.0016 (17.2%)	0.0027 (27.6%)	0.0039 (38.6%)	0.0039 (38.2%)	0.0038 (36.9%)

be found at the frontal section of the transmitter. This pressure drag from the frontal region of the transmitter contributes to the increase in the total drag of 12%. The pressure drag of the transmitter may lead to lesions such as necrosis and inflammatory lesions in the tissues underneath the device.

Next to the increase in drag, two additional forces were identified by the CFD simulation. We found that the transmitter also creates a significant average increase in the coefficient of the lift force of 240%. While diving, the increase in lift creates an upward force. If sufficiently large, this may consequently affect diving depth and duration. It may take the animal a certain period of time to learn how to adjust to the extra energy expenditure and changes in hydrodynamics. The sudden increment of the lift force, which was revealed between a swimming speed of 2 and 3 ms^{-1}, requires the animal to deal with a changing lift factor. Furthermore, we found that there is a significant increase of 32% of the average transmitter-induced pitching moment coefficient. The animal is exposed to a force, which induces a momentum around its lateral axis. If sufficiently large, the seal may subsequently become hydrodynamically unstable. That means that, when the seal starts to pitch up, the angle of 'flow' attack increases. This further increases the lift force and the pitching moment, which further and even faster increases the angle of attack, and so forth. All the compensating activities will again lead to an increase in drag and energy expenditure.

The simulation demonstrated that the transmitter generates areas of decreased wall shear stress on the seal's back. Necropsy on a grey seal, which had been fitted with a transmitter and washed up dead on the Dutch coast, showed fouling on the satellite transmitter attached to the seal (SRRC marine mammal database 2006). Algae was found growing in the fur of the seal's back and around its neck. When compared to the areas of decreased wall shear stress in the model, it revealed that the areas match perfectly. The areas of high wall shear stress on top of the transmitter also correspond with areas where no fouling was present. It may therefore be concluded that fouling adheres to the seal in areas with low wall shear stress induced by the transmitter. There is a close relationship between the wall shear stress and the heat transfer from the seal's body to the surround-

Fig. 5 Drag coefficient for a swimming seal with and without a transmitter at different swimming velocities

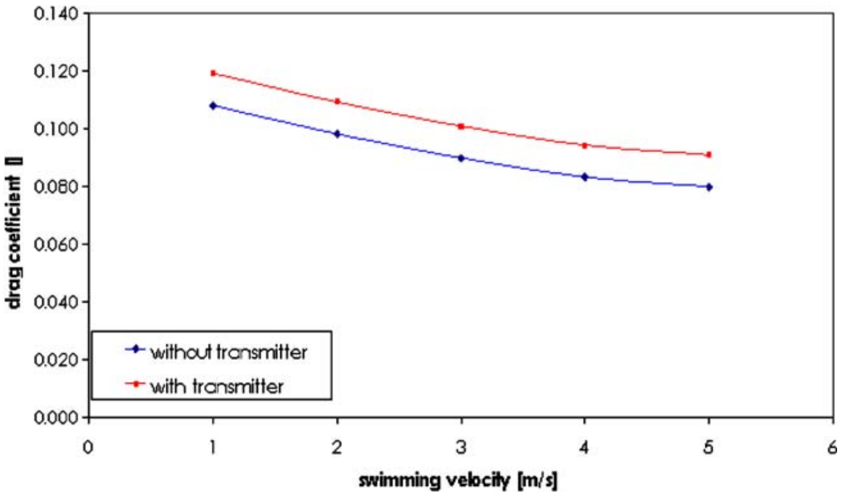
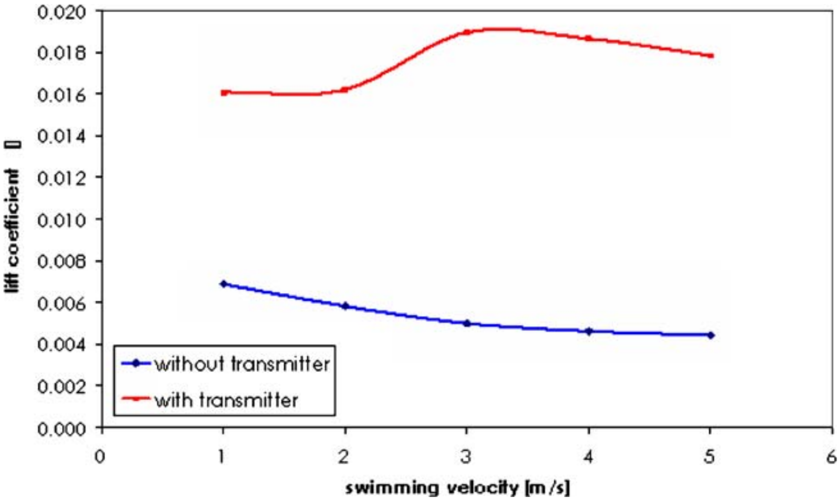


Fig. 6 Lift coefficient for a swimming seal with and without a transmitter at different swimming velocities



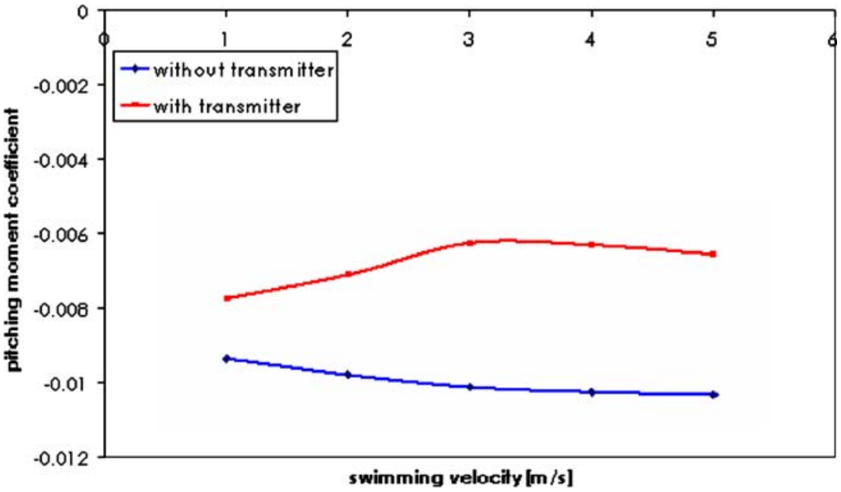
ing water. In areas of decreased wall shear stress, the heat transfer is lower. Therefore, the energy balance and body temperature regulation of the seal might be influenced by the transmitter. A disturbance in the warmth regulation and energy balance of the seal may have serious consequences for the animal, especially when its overall condition is poor.

Modelling with CFD demonstrates the significant impact of external devices on the hydrodynamics of seals. The altered hydrodynamics will inevitably have effects on the free-living behaviour of seals; however, it is difficult to quantify these effects. The performance of equipped seals has not yet been compared with that of unequipped seals. Potential impacts include, amongst other things, changes in maximum swimming velocity, time spent foraging, weight gain, reproductive success, etc. Eventually, the use of external devices may have serious consequences for the welfare of the individual animal. Further research is required to understand how altered hydrodynamics relates to the performance of free-living seals.

The effects of external devices are most likely to be severe when (1) animals are small, (2) devices are large, (3) animals are pursuit predators for which speed is important and (4) deployments are long. We expect that applying the same size transmitter on a smaller species, such as harbour seals, will induce more significant changes in hydrodynamics. The use of smaller instrumentation may reduce the deleterious effects of external devices. Due to advances in microelectronics, it is possible to produce smaller and lighter devices with improved hydrodynamic characteristics. It is essential to minimise drag by reducing the frontal area of the device and streamlining its shape. The development and use of short deployment devices should be considered, like those already applied for turtles (Houghton et al. 2002) and cetaceans (Aguilar Soto et al. 2008).

Next to effects on hydrodynamics, external devices may have other consequences. The procedure of attachment of the devices, which may involve stress during capturing, the use of anaesthetics or sedatives or the physical obstruction due to the device itself, may impede the individual animal's welfare. Furthermore, bio-fouling seems to be a problem in some of the tagged animals. In the aforementioned case, green algae, mussels and seaweed were observed within

Fig. 7 Pitching moment coefficient for a swimming seal with and without a transmitter at different swimming velocities



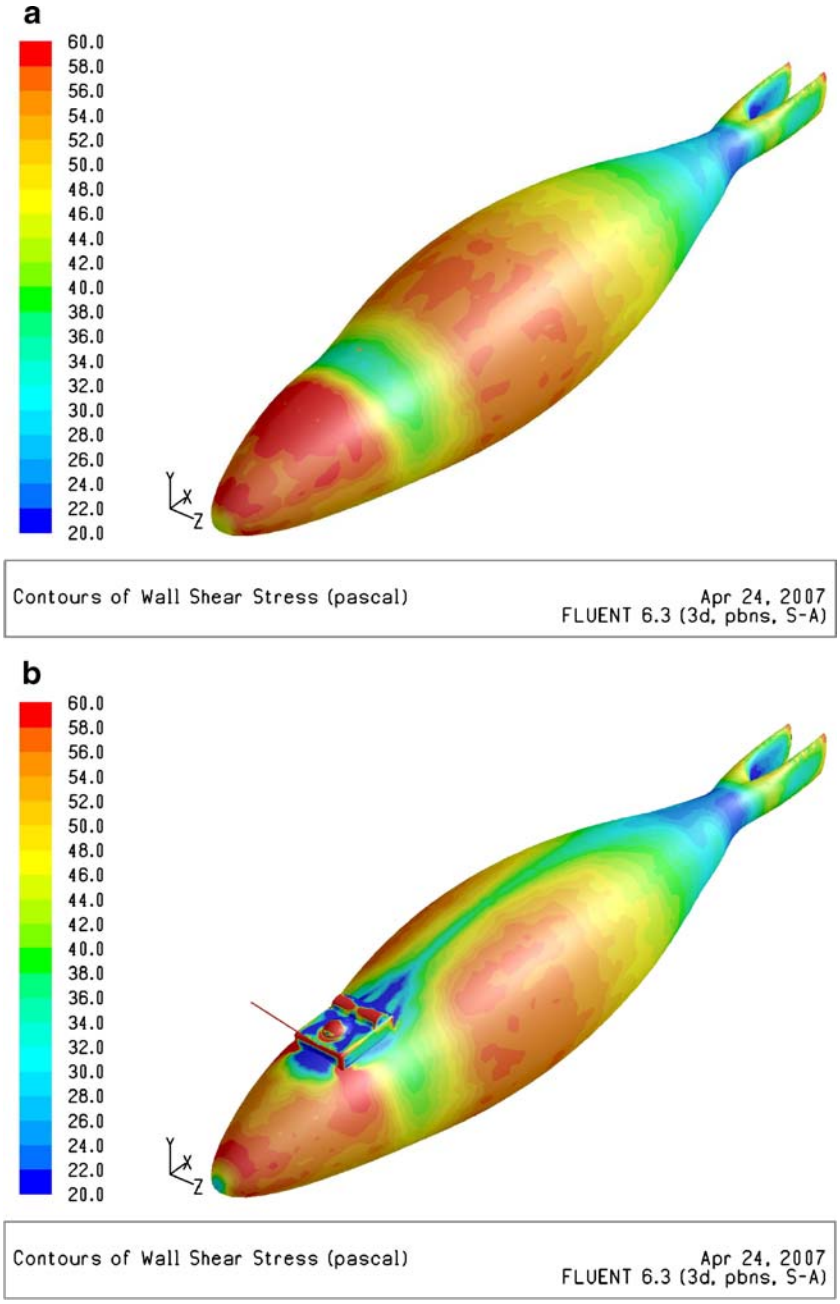


Fig. 8 **a** Wall shear stress (seal without transmitter). **b** Wall shear stress (seal with transmitter)

4 months after the attachment of the device (SRRC 2006). Fouling on transmitters has been described for tagged fish (Dicken et al. 2006; Thorstad et al. 2001) and marine turtles (Hays et al. 2007). Fouling increases the drag and decreases the swimming performance, but is seldom taken into account when estimating negative effects from devices on animals.

Biased results

The successive steps required to obtain telemetry data, from the sampling program to the final analyses of the data, have a subjective element. Predictions on population distribution are being increasingly based on telemetry studies, which focus on a few individual animals. Results are then extrapolated to the level of the population. Aarts et al. (2008) question the sampling error in telemetry-based population level inferences. They argue that sampling error in telemetry studies is usually large because, due to logistical constraints, only a small sample of animals are tagged and because sampling effort between tagged individuals is almost never balanced. The principle of telemetry studies implies that the tagged animals behave normally and that the instrumentation used does not alter the behaviour of the animals studied. However, various studies demonstrated that attaching or even implanting telemetry devices to animals have an impact on physiology or behaviour, and this can be significant (Bannasch et al. 1994; Croll et al. 1991; Culik and Wilson 1991; Ropert-Coudert et al. 2000; Whidden et al. 2007). These effects should not be neglected when analysing data retrieved from these devices; otherwise, the value of the information obtained from the devices will be poor. The subjective assessment that an animal is performing ‘normally’ is probably one of the weakest links in the chain of events from telemetry device designing, testing and implementation, to analysis and interpretation of results (Ropert-Coudert and Wilson 2004). Only 10% of marked animal studies published in major journals in 1995 mentioned that tag impact had been considered (Murray and Fuller 2000). Therefore, interpretations and extrapolations regarding ‘natural behaviour’ of animals in their ‘natural environment’, such as estimated population size, rates of survival, diving and foraging behaviour, should be made with great caution.

The simulation

In this study, we chose a model of a seal in the steady gliding position, with minimal fluid dynamical drag. The three-dimensional seal model used in this study was based on data of a grey seal. A ‘best case scenario’ was used, in which the transmitter is situated exactly in the middle of the seal’s back and is not rotated. We assume that in practice this is more difficult to achieve, resulting in somewhat more serious transmitter-induced effects on the animal. The model was based on a seal without complex details such as front flippers, eyes and whiskers. The absolute transmitter-induced changes in hydrodynamics may therefore be slightly different. The model can be improved by adding more details in future studies. It would also be useful to assess device impacts in relation to natural variation in hydrodynamics in seals, e.g. fat versus thin individuals. The additional effects of different levels of biofouling need to be investigated as well.

Conclusion

The tracking of marine mammals can provide useful information for conservation such as identifying important conservation areas. However, the ethical implications of device effects need to be balanced against the benefits for species conservation. We recommend that before using external devices on (streamlined) aquatic animals, the effects of the device should be calculated using CFD models. Since species and device characteristics will determine the severity of the impact of the devices, this should be done on a ‘case-by-case’ level. The calculated effects render it possible to determine the level of altered hydrodynamic forces. The calculated effects can be used to assess the impact on animal welfare and adjust the data collected from the transmitter. Improving the hydrodynamic design of external devices will benefit the research results while minimising the impact on the welfare of the individual animals.

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