Automated Aerodynamic Optimization of the Position and Posture of a Bobsleigh Crew

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Abstract

CFD-simulations were conducted to simulate the flowfield around a bobsleigh. A simplified crew model of the pilot and the brakeman of a 2-man bobsleigh was generated. The model was used to perform the fully automated optimization of the crew posture and position. Furthermore, a genetic optimization algorithm from the software package DAKOTA was used in order to search for the optimum crew position and posture. The considerable effect of the crew position and posture on the aerodynamic drag was verified and an optimum crew posture and position was found that deviates from a maximum ducking posture of the brakeman.

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1. Introduction

Previous investigations by Motallebi et al. [1], Dabnichki et al. [2] and Winkler et al. [3] have shown that there is a considerable dependence of the aerodynamic drag on the brakeman's posture and position. While the position of the pilot is practically fixed by the set up of the steering mechanism and by the cowling dimensions, there are several degrees of freedom for the brakeman. Numerical simulations and wind tunnel tests with a simplified crew representation in [3] indicated that the maximum ducking of the brakeman will not result in a minimized aerodynamic drag.

In the aerodynamic development process there are in principal three ways for analyzing the flowfield and its effect on the body of interest. Experiments under operating conditions pose the problem of properly separating the different physical effects on the bobsleigh performance. Full-scale wind tunnel tests can be very efficient in order to analyze the crew posture. However, the tests require a proper and sufficiently large wind tunnel and qualified personnel that prepares, conducts and interprets the experimental results. Sub-scale wind tunnel tests require

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sophisticated sub-scale models of the bobsleigh and the crew that allow the relevant shape variations. Experimental parameter studies require the frequent interaction of the developer with the sub-scale model.

An approach to avoid these disadvantages is to conduct fully automated computational studies of the bobsleigh crew. First, the automation releases the developer from the frequent routine interactions with the sub-scale model. Second, once a proper computational model of the crew is set up, it can easily be adapted to the biometrics of different crew members. In order to demonstrate the potential of this approach, the automated aerodynamic shape development (AASD) environment introduced by Winkler et al. [4] has been applied to the aerodynamic optimization of a generic bobsleigh crew. Therefore, a shape model was created based on typical human biometric features. CFD-Simulations were performed in order to analyze the flowfield around each shape version and an optimization algorithm was used in order to search for the optimum crew posture and position.

2. CFD-Simulations

The flow domain around the bobsleigh is shown in Figure 1 on the left. An unstructured mesh was used. It consisted of about 4,5 Mio. elements and the boundary layers on the bobsleigh were resolved with 10 elements normal to the wall. The freestream was assumed to be parallel to the bobsleigh center axis thus the whole geometry was cut in half saving 50% of the computing time. A typical mesh can be seen in Figure 1 on the right.

![Flow domain and mesh](image)

Fig. 1. (a) Flow domain and (b) typical mesh for the CFD simulations.

The flowfield around the bobsleigh was simulated using the CFD-simulation code ANSYS CFX. The flow was assumed to be steady, incompressible, viscous and turbulent. The Reynolds-Averaged Navier Stokes (RANS) approach was applied and the SST turbulence model formulated by Menter [5] was used. The flow was simulated using a 75% blend factor for the spatial approximation of the convective fluxes in order to assure the reliable convergence of the CFD simulation. The aerodynamic boundary conditions are shown in Table 1. The simulations were preformed at an ambient temperature of \( T_\infty = 0 \)°C and an ambient pressure of \( p_\infty = 1 \) atm. With this setup the simulation took about 36 CPU hours in average for one shape version.

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Boundary Condition</th>
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<th>Boundary Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>IN</td>
<td>inlet flow velocity ( V_\infty = 36.11 ) m/s</td>
<td>EDGE</td>
<td>free-slip wall</td>
</tr>
<tr>
<td>OUT</td>
<td>outlet pressure difference ( \Delta p = p_{\text{OUT}} - p_\infty = 0 )</td>
<td>SYM</td>
<td>symmetry</td>
</tr>
<tr>
<td>FLOOR</td>
<td>no-slip wall, ( V_{\text{FLOOR}} = 36.11 ) m/s</td>
<td>BOB</td>
<td>no-slip wall</td>
</tr>
<tr>
<td>TOP</td>
<td>free-slip wall</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3. Crew Model and Parameterization

A typical position and posture of a generic crew is shown in Figure 2 (top). The brakeman must take its position and posture in the space behind the pilot that is confined by the pilot as well as the side walls, the floor and the rear end of the bobsleigh. Therefore the brakeman can change his posture by bending or stretching his spine and he can move back and forth in order to change his x-location.

In order to reduce the geometric complexity of the crew and the bobsleigh interior a simplified crew model was created and is shown in Figure 2 (bottom). Several model parameters are defined there. The lower part of the crew including the legs was cut off and replaced by a horizontal cut plane. The modeling of the bodies was based on biomechanical properties of the spine and the arms [6]. The crucial biomechanical parameters can be seen in Figure 3. The spine was simulated connecting the lumbar spine joint, the thoracic spine joint, the cervical spine joint and the spine-skull connection by splines. The posture could be changed by adjusting the joint angles $\varphi_L$, $\varphi_T$ and $\varphi_C$. An upright sitting posture is defined by setting all three spine angles to zero. Two other exemplary brakeman postures are sketched in Figure 2 (bottom).

The arms were simulated by the shoulder joint and the elbow joint which were connected by straight lines representing the upper arm and the forearm. The body dimensions were taken from the biometric database of the CAD-software CATIA V5. The pilot was represented by the dimensions of an athletic male of 186 cm body height and the brakeman by the dimensions of an athletic male of 198 cm body height.

![Fig. 2. (a) Typical position and posture of a generic crew (top) and the crew model with different brakeman postures (bottom); (b) Crucial parameters of the biomechanical crew model.](image)

4. Optimization Process

The optimization process had to be implemented into the AASD environment [4] using a standardized formulation. Therefore three steps were necessary. First, the objective function that needed to be optimized had to be chosen. Second, the relevant design variables had to be deduced from the parametric shape model, based on preliminary flow investigations and on aerodynamic expertise. Third, the constraints of the design variables had to be determined.

The aerodynamic force that is relevant for the bobsleigh performance is the aerodynamic drag. Therefore, the objective function that needs to be minimized is the aerodynamic drag area $C_D A$, defined in equation (1), where $D$ denotes the aerodynamic drag and $q_{\infty}$ the free stream stagnation pressure.

$$C_D \cdot A = \frac{D}{q_{\infty}}$$  \hspace{1cm} (1)
Previous investigations have shown that the brakeman’s posture has a considerable effect on the aerodynamic drag [1] [2] [3]. That is why the joint angles $\varphi_L$, $\varphi_T$ and $\varphi_C$ of the brakeman’s spine were chosen as design variables. The x-location of the brakeman $x_{BM}$ affects how much the brakeman may flex its spine before colliding with the pilot. Hence the x-location of the brakeman was chosen as a design variable.

Two extreme arm postures were compared at which the spine angles and the x-location were fixed. The values were deduced from the investigations in [3]. The two arm postures are depicted in Figure 4. In the first case on the left, the arms are bent and the holding of the brakeman on the bobsleigh frame is simulated. This is the conventional arm posture in current bobsleighbing. In the second case on the right, the arms are stretched along the cowling edge in order to simulate the holding of the brakeman on the side walls. Bent arms led to a drag area of $C_D'A = 0.0596m^2$, stretched arms to a drag area of $C_D'A = 0.0609m^2$. Consequently, it was decided to keep the conventional arm posture and to abandon the arm joint angles as design variables. That means that the optimization problem was formulated in terms of the design variables $\varphi_L$, $\varphi_T$, $\varphi_C$ and $x_{BM}$.

![Fig. 3. Arm postures of the brakeman.](image)

The domains of definition of the design variables and the constraints of the optimization problem were deduced from the biomechanical properties of the spine described by Kapandji [6], from the dimensions of the bobsleigh shape and from aerodynamic expertise. First of all it is noted that current bobsleigs are designed so that the brakeman can only bend forward in order to take a save position. Hence the lower bounds of the lumbar spine angle and the thoracic spine angle were set to zero degree. The remaining bounds of the joint angles were taken from [6]. The bounds for $x_{BM}$ were dictated from the location of the bobsleigh’s rear end and from the requirement that the head of the brakeman must not collide with the pilot’s head or body. In addition, a safety margin of 50 mm between the two helmets was specified.

The design variables were not independent from each other which led to a set of linear and non-linear constraints. It was concluded from the bobsleighb dimensions and from biomechanical properties [6] that the sum of the lumbar spine angle and of the thoracic spine angle may not exceed 95°. From aerodynamic reasons the brakeman’s helmet should be in the wake of the pilot. Hence the maximum z-coordinate of the brakeman’s body $z_{BM,max}$ must not exceed the maximum z-coordinate of the pilot $z_{P,max}$. Both the maximum z-coordinate of the brakeman $z_{BM,max}$ and the minimum x-coordinate of the brakeman’s body $x_{BM,min}$ depend on the spine joint angles. Consequently, the function for determining the maximum z-coordinate $z_{BM,max} = f(\varphi_L, \varphi_T, \varphi_C)$ and the function for calculating the minimum x-coordinate $x_{BM,min} = f(\varphi_L, \varphi_T, \varphi_C)$ are non-linear. To sum up, the standard formulation of the crew optimization is given by the sets of equations (2) and (3).

**Objective function and constraints:**

\[
\begin{align*}
\text{Minimize} & \quad C_D \cdot A \cdot f_{\varphi_L, \varphi_T, \varphi_C, x_{BM}} \\
\varphi_L + \varphi_T & \leq 95^\circ \leq 0^\circ \tag{2} \\
0^\circ & \leq \varphi_T \leq 45^\circ \tag{3} \\
-50mm & \leq x_{BM} \leq 50mm & \quad & 2600 \text{ mm} \leq x_{BM} \leq 2800 \text{ mm}
\end{align*}
\]

The AASD environment [4] provides a fully automated iteration loop for the shape optimization of a given aerodynamic optimization task. The starting point is the open source software DAKOTA [7] that provides a set of different optimization algorithms. The chosen optimization algorithm determined a set of design variable values, that means a design point, and passed the design point to a CAD software. The design point was translated into a
shape version of the bobsleigh which was passed to a mesh generator where the flow domain was automatically meshed. The mesh was forwarded to the CFD simulation code. The simulated flow field was automatically analyzed in order to gain the value of the objective function. This value was forwarded to the optimization algorithm which determined the next design point.

Initially, it was unknown if the objective function \( C_{D'}A = f(\varphi_L, \varphi_P, \varphi_C, x_{8M}) \) is providing more than one minimum. Therefore a genetic optimization algorithm was applied in order to search for the global minimum. The genetic algorithm simulates biological evolution that means it is based on the principals of reproduction and selection. For this purpose, the following set up was chosen. The number of design points in one population was \( N_{pop} = 12 \), the number of cross-over operations per new population was \( N_{cross} = 10 \), the number of mutations per design point was \( N_{mut} = 5 \). The crossing and mutating were performed on binary encoded design variables. The chosen algorithm supports the handling of non-linear constraints by the use of penalty functions. For that purpose, every constraint violation was penalized with a constant drag area value and feasible design points were always preferred to infeasible design points during the selection phases.

5. Optimization Results

As benchmark a fully ducked brakeman’s posture was chosen which corresponds to a completely omitted brakeman. The bobsleigh without brakeman has a drag area of \( C_{D'}A = 0.0637 \text{ m}^2 \).

In Figure 5 the drag areas of the first 76 design points are shown. Only the feasible design points are included. The benchmark is indicated as a horizontal line. The following characteristics become obvious. It is apparent that a maximum ducking will not result in a minimum drag. The drag area tends to decrease with increasing design point number, showing the searching for the optimum within the design space. There are large differences in the drag area between several neighboring design points, indicating the exploration of the design space. At low design point numbers, the infeasible design points outnumber the feasible ones. That means that many design points are first created that violate the constraints of the optimization task. This behavior changes with increasing design point number, showing a learning effect of the algorithm concerning the locations of the design space boundaries. The lowest drag area of \( C_{D'}A = 0.0595 \text{ m}^2 \) results from design point 61. It falls slightly below the drag area of \( C_{D'}A = 0.0596 \text{ m}^2 \) of the arm parameter study mentioned above.

![Fig. 4. (a) Drag area of the evaluated feasible design points, (b) Pressure distribution on the rear side of the pilot at y = 0](image)

The effect of a proper positioned brakeman on the flowfield is pointed out in the Figures 6, 7 and 8. In Figure 6 the pressure distribution on the rear side of the pilot is depicted in terms of the pressure coefficient which is defined by the local pressure \( p \), the ambient pressure \( p_a \), and the stagnation pressure \( q_{\infty} \):

\[
C_p = \frac{p - p_a}{q_{\infty}}
\]  

(4)
The picture shows the line on the surface where the pressure coefficient is taken. The graph shows the pressure coefficient variation dependent on the z-coordinate of the benchmark case and of the design point 61. It is apparent that the presence of the brakeman reduces the suction on the rear side of the pilot while the suction on the helmet is nearly constant.

Previous investigations of the flowfield [3] showed that the flow over the cowling edge causes a delta-wing vortex evolving from the edge. The vortex shows high rotational velocities and consequently low pressures. Therefore it is a considerable source of pressure drag. This finding is verified in Figure 7 for the benchmark case and for the design point 61. The y-z-component of the flow velocity and the pressure distribution in a y-z-plane at $x = 2500 \text{ mm}$ are shown. The vortex center is marked by a white cross. In Figure 8 the same flow variables are depicted in a y-z-plane at $x = 3400 \text{ mm}$. It reveals another delta-wing vortex which counter-rotates compared to the vortex of Figure 7. When comparing the pictures within the Figures 7 and 8, it can be seen that the presence of the brakeman alters the location and the strength of the vortices. The vortex centers are moved outward and the negative pressure decreases.

6. Summary and Outlook

The application of the AASD environment to the fully automated optimization of the posture and position of the crew of a 2-man bobsleigh has been demonstrated. The optimization process revealed a) that the current arm posture of the brakeman is superior to a holding grip near the cowling rim and b) that a maximum ducking of the brakeman does not result in the minimum aerodynamic drag. In contrast, the appropriate posture and position of the brakeman can decrease the drag considerably.

The optimization was based on a simplified crew model which can be easily adjusted to various biometrics of the crew. Considering the presented results and the set up of a 4-man bobsleigh, there appears to be even more potential for drag reduction when optimizing the position and posture of a 4-man bobsleigh. With a given 4-man bobsleigh shape model, the presented approach could rather easily be adapted to this task.

References


