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Non-deterministic Shape Optimisation of Wind Cowls by applying Simulated Annealing and Fast Fluid Dynamics

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Abstract

In this study a Java tool is developed and applied in order to optimise the geometry of rotating wind cowls in terms of ventilation performance. Fast Fluid Dynamics is adapted and coupled with the optimisation method of Simulated Annealing – an algorithm able to solve complex problems. The practical application of this research is to explore the integration of numerical fluid simulation with optimisation algorithms for shape finding.
Since the performance of a wind cowl is influenced by its exposure to the wind – a highly dynamic force – an efficient evaluation and optimisation tool is needed. Hence, the application of Simulated Annealing and Fast Fluid Dynamics seem justified.
The main contribution of this work is to integrate performance evaluation and design processes. It is shown that a computationally enhanced design strategy can lead to more efficient and higher performing solutions.

Keywords: Simulated Annealing, Fast Fluid Dynamics, Optimisation, Wind Cowl

1 Introduction

Cutting down energy consumption and carbon emissions is a widely accepted necessity. Unfavourable ecological, economic and social impacts of our current energy and resource intense society demand a different approach to energy management (Stern, 2006). Since the built environment is a major consumer of energy and resource, a thorough planning is required to minimize the external effects – climate change, destruction of biodiversity, air pollution, etc. (Ibid.). Often, most of the total lifetime energy is consumed as a consequence of the operation of the building (MacKay, 2009). Breaking it further down, it is found that – depending on the building function – heating and cooling accounts for around 50% of operating energy consumption (CIBSE Guide F, 2004). An important aspect is the loss of conditioned air through the fabric and via ventilation (Ibid.).

A passive technical solution for providing natural ventilation in buildings is given with wind cowls. At the same time ventilation heat losses can be reduced by integrating heat recovery (HR) into these devices – such as realized with the BedZed project in London (Figure **1**). Wind cowls are roof mounted top-down ventilation systems, similar to windcatchers (Khan et al, 2008). The difference is that wind cowls have the ability to autonomously rotate with changing wind directions, so the air inlet always faces the windward- and the air outlet always the leeward side. Therefore, airflow directions within the ducts are constant – making the integration of HR possible. In contrast, windcatchers are static and airflow directions within the ducts change with the incident wind direction.

As an aerodynamic device, the shape of a wind cowl is an important factor in influencing its ventilation performance. The positive pressure on the air inlets have to be maximized to increase the airflow in. The negative pressure on the air outlets have to be maximized to

increase the suction effect and drawing air out of the building. Furthermore, the cowl shape has to contain geometric elements, which enables the ability to rotate with changing wind directions (Ibid.). Consequently, a careful shape definition is crucial for such a device to fulfil its purpose.

In this paper a performance based approach is presented on how to design such shapes. Here, computational and statistical methods play a crucial role. The developed design methodology is characterized by an integrated reciprocity between performance evaluation and shape definition. The performance evaluation is conducted by an airflow prediction model, similar to Computational Fluid Dynamics (CFD), but faster. The shape definition is carried out by a stochastic optimisation algorithm.

The planner is hereby not defining concrete shapes of a wind cowl. Rather more, he designs the process on how shapes are generated. In this process thousands of different shapes are evaluated for their performance. In doing so the final shape is open-end (non-deterministic). The interest of the application of such a methodology is finding the optimal shape for a wind cowl without the influence of personal liking for certain shapes.

Figure 1. BedZed Wind Cowls
Source: (Wikipedia, 2012)

2 Theoretical Background

2.1 Optimisation Algorithm

As optimisation algorithm Simulated Annealing (SA) is adapted (Kirkpatrick et al, 1983), which has its analogy from the controlled cooling process of liquid solids in metallurgy – called “annealing”. Here, the atomic structure of metal has the chance to rearrange to form a crystalline and more rigid configuration. The optimisation algorithm exploits this principle. In doing so, thousands of different configurations of wind cowl shapes are tested during the course of the optimisation process.

The applicability of SA in non-deterministic shape optimisation is proven e.g. in Sonmez, 2007 and in Shea et al, 1997. In the first study the shape of hooks is optimised according to different stress loads. Starting with a random shape, the algorithm was able to identify the optimal hook shape. In the latter study, the framework of geodesic domes was optimised. Again, SA was able to identify optimal configurations even though starting with random starting point.

2.2 Airflow prediction

To assess the performance of wind cowl shapes spatial quantitative information of airflow is required, such as given with Computational Fluid Dynamics (CFD). However, CFD simulations require considerable amount of computing time (Chen, 2009). Using a CFD as evaluation model with SA – where thousands of shapes are tested – would therefore cause long computing time in the magnitude of weeks. Thus, a quick evaluation model is required. Fast Fluid Dynamics (FFD) offers spatial quantitative information like a CFD but is around 50 times faster than a CFD (Zuo et al, 2009), albeit on the cost of less accuracy (Zuo et al,

2007). Therefore, FFD is used as airflow prediction model in this work and coupled with the optimisation method of SA.

3 Methodology

To carry out the optimisation process of the wind cowl shape a custom Java tool is developed using Eclipse and Processing as programming environments. It includes an output window to visualize the cowl configurations and the velocity vectors of the FFD. It also has a Graphical User Interface (GUI) for various control and display choices (Figure **2**). After starting the optimisation process the tool is running for 3 to 6 days depending on the settings. At completion, comma-separated values (.csv) files are exported to the hard-drive containing information about the course of the optimisation. Also, geometrical information of the final optimised shape is exported.

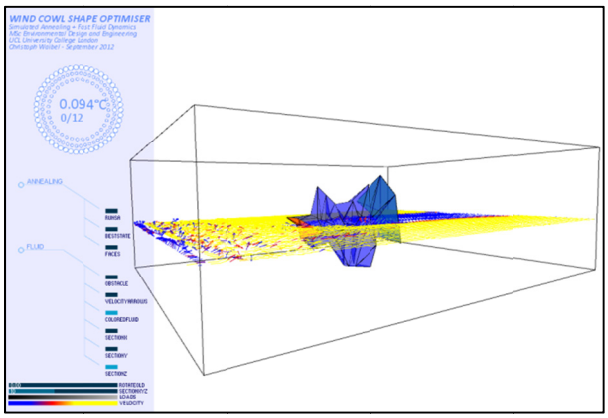

Figure 2. Wind Cowl Optimisation Tool

The optimisation tool consists of four main methodological elements: a) the parametric model of the wind cowl shape, b) the SA optimisation algorithm, c) the FFD evaluation model and d) the objectives of the optimisation. These are introduced in the following. Due to space limitations of a paper this section will avoid equations. Thorough explanations on each topic can be found in Waibel, 2012.

3.1 Parametric Model

The developed parametric model includes only the most fundamental elements of a typical wind cowl. They are chosen to be the air inlet – where air is drawn into the building, the air outlet – where air is drawn out, and a rotation axis acting at the same time as constructive attachment of the cowl to the building. The model is composed by an array of circles, where each circle is divided into equal segments. Each segment is populated with a control point. The resulting point-cloud is used to define the hull of the cowl (blue faces in Figure **2**). One end of the hull defines the air inlet, the other side the air outlet. The control points are the variables whose parameters (position in space) are subject to be optimised by the SA algorithm.

3.2 Simulated Annealing

In SA some terms derive from the real annealing process of liquid metal; The quality or performance of a cowl configuration is termed "energy" (E). When speaking of "temperature" (T) a control parameter of the algorithm is meant, not the real environmental temperature. The SA algorithm consists of an acceptance rule and a cooling schedule. They imply settings which have to be chosen carefully in order to achieve an efficient optimisation algorithm. During the course of the algorithm the temperature is reduced. At lower temperatures the acceptance probability for worse configurations to be accepted is also lower.

This principle is the main statistical logic of SA and enables the algorithm to escape from local optima. A thorough description of SA can be found in Kirkpatrick et al, 1983.

3.3 Fast Fluid Dynamics

FFD was originally developed by Stam, 1999. For this tool a 3D-implementation by Ash, 2006 is adapted and extended. The FFD solves the Navier-Stokes equations for incompressible fluids, assuming laminar flow. The lack of a turbulence model is seen as a significant limitation, especially for modelling the performance of wind cowls (Pfeiffer et al, 2008). This issue should be tackled in further research. Still, the adapted FFD is found to be the only reasonable airflow simulation model suitable for a shape optimisation with SA.

3.4 Objectives

The SA optimisation algorithm requires objective functions, which quantify the performance (energy) of a cowl configuration. Three objective functions are considered here: The first quantifies the amount of air being caught by the air inlet. The second quantifies the amount of air being drawn out by the air outlet. The third function measures the ability of a cowl to rotate. The values for calculating the functions are obtained by the FFD simulation. Per configuration two wind simulations are tested. In the first the wind faces the air inlet to evaluate the ventilation performance. In the second simulation the wind hits one side of the cowl to test the rotation ability.

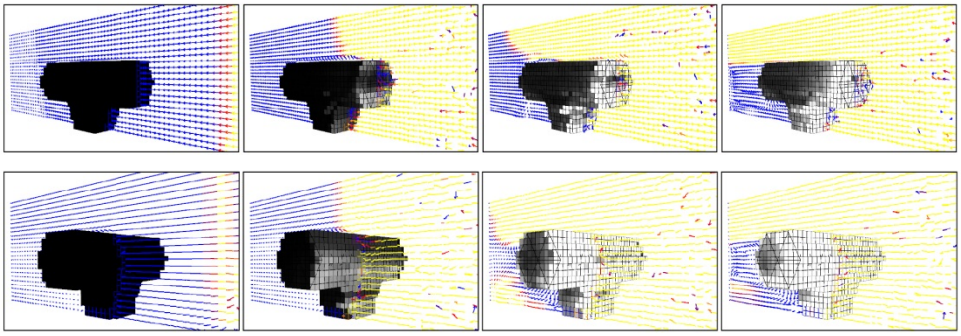

Figure 3. Testing wind cowl performance
Top: testing wind pressure at air inlet and air outlet
Bottom: testing rotation ability, when wind hits flank of cowl

4 Results and Discussion

The optimisation tool is starting with a uniformly shaped cowl (Figure 4, left). Different runs were executed and the optimised shape always showed similar geometrical characteristics (Figure 4, right).

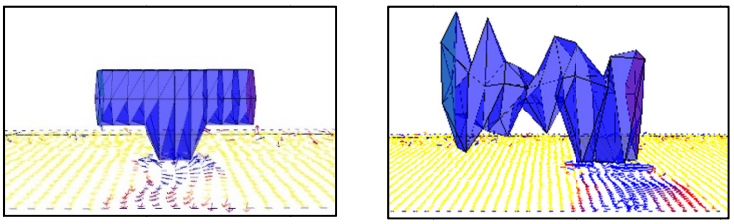

Figure 4. Initial and optimised wind cowl shape; Side Elevation

It can be seen, that the rotation axis/attachment to the building is moved to the right end of the cowl. This makes sense, as the drag force will now cause the cowl to align its air inlet into the windward direction, when the wind hits the side. If the rotation axis was on the left end, the air outlet would wrongly align into the windward direction. Furthermore it can be observed that the air in- and outlets are significantly larger than in the initial shape. This also

is logical as larger openings increase the airflow in and out. However the lack of a turbulence model is most probably causing wrong results for the negative pressure at the air outlet.

In Figure 5 all tested cowl configurations are shown in light blue circles indicating their respective energy on the ordinate. The dark blue circles show accepted configurations. The red surface shows the temperature of the SA algorithm. Around 2600 configurations have been tested. It can be seen, that in the beginning of the optimisation process the energy increases steeply and many configurations are accepted. With decreasing temperature less configurations are accepted and the energy curve converges to around 8 (normalized, non-dimensional value). The graph shows a typical SA optimisation process and it can therefore be concluded, that the tool is successful in improving the shape of wind cowls.

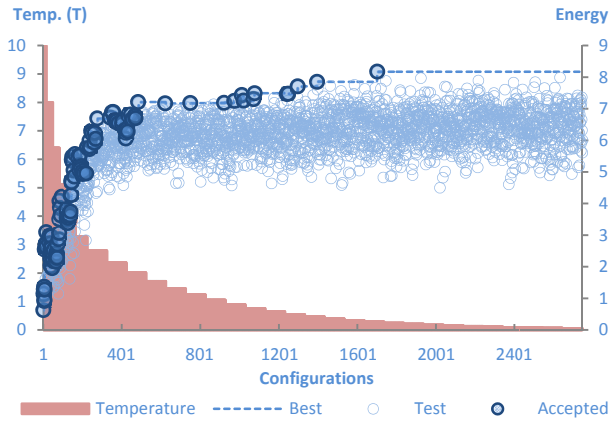

Figure 5. Scatterplot of Total Energy of Samples

One limitation however is that the objective functions were defined based on simplified assumptions. Nevertheless, the resulting shapes may represent the aims of real world decision makers. The findings of these case studies are to be considered as a first step towards developing performance based design techniques.

Much more work is required in order to make the algorithm run more efficient. The major challenge is to couple SA with the fluid simulation method of FFD. Also, the validation of the FFD is still not very well explored. Especially the lack of a turbulence model is a great disadvantage for simulating cowl performance (Pfeiffer et al, 2008).

Overall, the results indicate, that the approach taken in this research seems to have good potentials for modern energy efficient architectural and engineering designs. A further advantage is that it stimulates collaboration among the different disciplines, including building physicists, structural and mechanical engineers, computer scientists and architects.

5 Conclusion

This study presented an alternative design methodology for architectural engineering of rotating wind cowls. Here, computational methods play a crucial role to integrate building performance simulation directly with the shape definition.

The study confirmed the feasibility of the methodology developed in this research. By setting up a parametric model, incorporating simulation of physics, defining quantitative objectives and applying an optimisation algorithm high performing wind cowl shapes can be generated, which can provide a complementary tool to manually made designs.

The interdisciplinary nature of this work enforces a tight collaboration of specialists from various fields. This methodology requires the expertise of all professions coevally. Because

this study was conducted by a single person, it can be seen as an outlook on how design in the built environment can be approached alternatively.

For a real application it is suggested to bring together a team of experts from different fields: Building Physicists, Structural and Mechanical Engineers, Computer Scientists, Architects and other relevant. By applying the design methodology outlined in this paper, a participatory and integrated design process can be achieved which is expected to bring about better solutions in engineering and architecture.

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