DEVELOPMENT OF AN AERODYNAMICS SIMULATION FRAMEWORK FOR SKI-JUMPING

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This study constructed a simulation framework for predicting unsteady aerodynamic characteristics in ski jumping competition. We focused on the time period from takeoffs to the early flight phase in which transient characteristics are expected to greatly affect the distance traveled. For the purpose of applying the developed framework to actual competition, the posture change was reconstructed from the sagittal plane obtained from the video image and simulation was performed. Moreover, in order to examine the validity of the result, it was compared with the simulation result obtained from the three-dimensional motion measured by the motion capture at the same time. In fluid simulation, we developed a finite volume method based on a hierarchical Cartesian grid for the purpose of reproducing complicated posture changes and obtaining results at high speed. The lift-drag ratio and flow structures obtained by both methods qualitatively agreed well.

KEYWORDS: Ski-jump, takeoff, fluid simulation.

INTRODUCTION: Take-off motion is the most important and difficult aspect of ski jumping. The definition of the take-off motion is from the start of the extension motion of the jumper until the jumper passes through the cante (the end of the runway rail). The objective of this motion is to extend the body to raise the center of gravity and to acquire a forward angular momentum around the center of gravity. In order to shift from the approaching posture to the flight posture, a jumper rapidly extends the body in a short time of 0.25 to 0.30 seconds. Since success or failure of this operation determines the flight posture, it is regarded as the most important phase in the coaching process. It is said that it is impossible to recover mistakes in the take-off motion during the flight phase. However, few studies have reported aerodynamic findings from the take-off motion of ski-jumping. This is because it is difficult to grasp unsteady characteristics associated with the rapid posture change. Therefore, in this study, we develop an aerodynamics simulation framework to understand the unsteady aerodynamic force acting on the jumper during the take-off motion and the dynamics of flow structures around the jumper.
Our final goal is to conduct an aerodynamics simulation which reproduces a real posture change of the jumper during the take-off motion based on the 2D video image taken from a fixed point camera of the ski-jump field. In order to do this, it is necessary to validate whether the aerodynamic characteristics obtained from a simulation using the jumper's motion based on the 2D video image are equivalent to using the actual 3D motion of the jumper. Thus, in this study, we compare the results of the simulation using 3D motion data taken from the motion capture system and the one using 2D motion generated by projecting the 3D motion onto a 2D plane.

METHODS: The procedure for simulations is shown in Figure 1. To obtain simulation results and provide feedback to jumpers in competition or practice in a short time, the framework needs to be able to take into account the jumper's specific posture and motions, and it is necessary to reduce the mental burden and physical load on the jumpers as much as possible during the motion capture process.

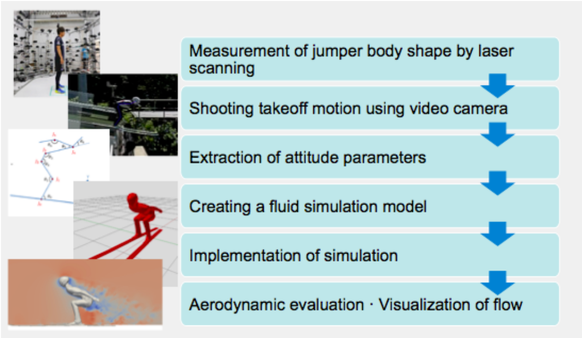

Figure 1: Overview of the framework developed in this study

An optical motion capture system (MAC3D, Motion Analysis Corp., Santa Rosa, California, 12 infrared cameras, sampling Freq. 200Hz) was used for the kinematic measurements. Thirty-five reflective markers (12.5 mm diameter) were attached to the participant. Following data measurement, the jumper's motion and reaction force acting on the slope data were further analyzed using motion analysis software (Visual3D, C-Motion, Inc.) as shown in Figure 2.
Then, time histories of 3D joint angles (ankle, knee, hip, shoulder, elbow, neck joints) were calculated. The participant (23 years old, 175.7 cm, 65.4 kg) glided through the slope installed in the laboratory and performed simulated take-off. After that, the joint angles of the 2D model were obtained by using extension / flexion components of the 3D joint angles.
Figure 3 shows the 2D model and 3D model used in the simulation. The model was developed using the laser scanned data of the jumper in standing posture and the 3D joint angles were imposed on the model.

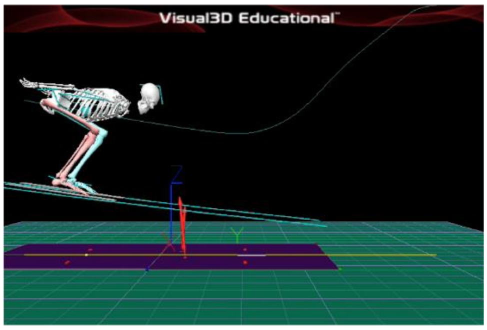

Figure 2: Snapshot of analysed motion with the motion analysis software

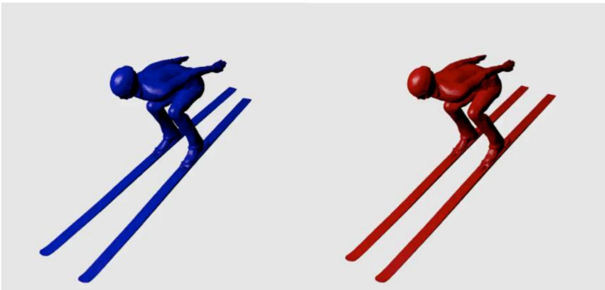

Figure 3: Reproduced jumper models (left: 3D model using 3D joint angle obtained by the motion capture system, right: 2D model assuming that 2D video is used to obtain motion data).

In the aerodynamics simulations, incompressible Navier-Stokes equations were solved as the governing equations.

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \nu \frac{\partial}{\partial x_j}\frac{\partial u_i}{\partial x_j} + f_i$$

Here, u_i is the velocity component for the x_i direction of the velocity vector, t, p and ρ are the time, pressure and the density (constant), respectively. ν is the dynamic viscosity coefficient (constant), and f_i is an external force term for the Immersed Boundary Method. Hierarchical orthogonal grid was combined with Immersed Boundary Method in this simulation. Although this method has limitations in accuracy, it can be applied to complicated moving boundary problems. In addition, it has an advantage in the efficiency of parallel computation. In our numerical method, deformation and movement of an object were represented by treating the object surface as a set of Lagrange particles and giving momentum to each particle. Figure 4 shows the numerical domain, boundary conditions and distribution of grid (cube) around the jumper. Each cube shown in the figure contains 4,096 numerical elements (16 elements for each direction).

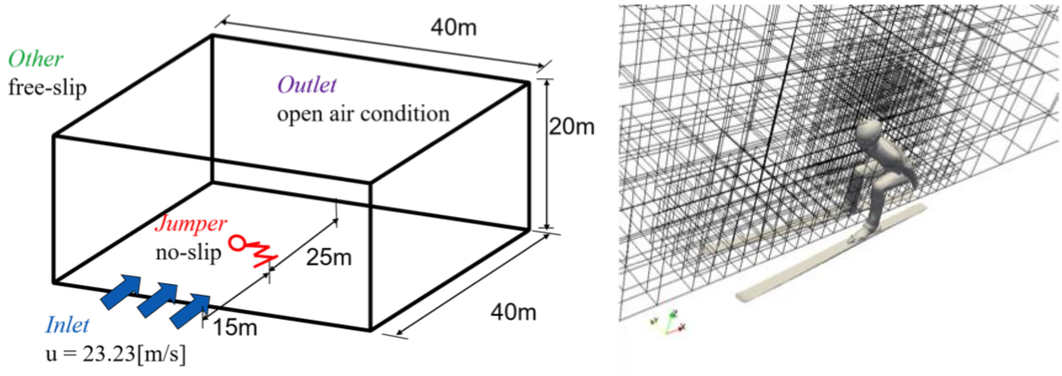

Figure 4: Dimension of numerical domain, boundary conditions (left) and distribution of numerical elements around the jumper (right)

RESULTS: Figures 5 to 7 show the pressure distributions in the sagittal plane of the jumper. In these figures, the left shows the 3D model and the right shows the 2D model.

Figure 5: Pressure distribution in the sagittal plane of the jumper at 0.1 s

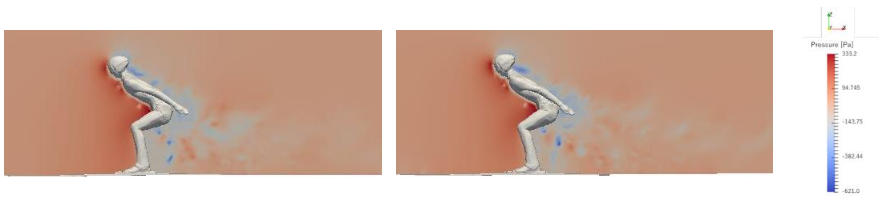

Figure 6: Pressure distribution in the sagittal plane of the jumper at 0.4 s

Figure 7: Pressure distribution in the sagittal plane of the jumper at 0.5 s

By comparing the results of the 2D model with that of the 3D model, although there are small differences in the pattern and value of the negative pressure region, the dominant flow structures such as the vortex structure and the separation point behind the jumper are very similar.

Next, the L/D (aerodynamic lift divided by aerodynamic drag) of both models were compared. Figure 8 shows the time history of the L/D. The L/D falls around 0.48 seconds. This is because the lift force decreases due to the expansion of wake area as the attack of angle of upper body increases. This tendency is the same for both models.

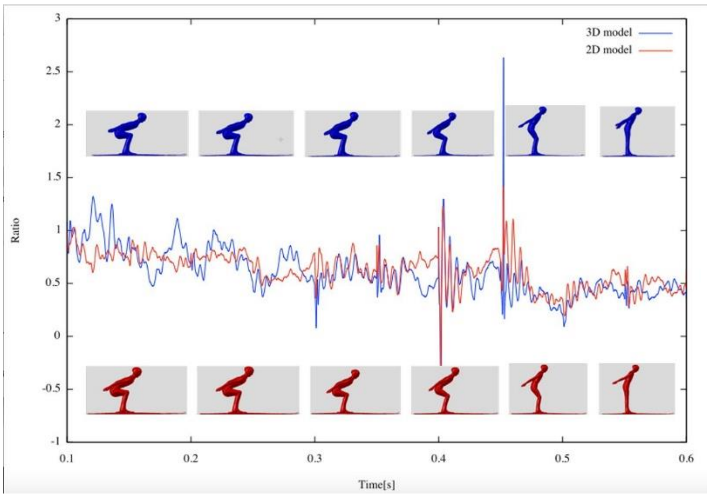

Figure 8: Time history of lift-drag ratio

CONCLUSION: In this study, for the purpose of developing a framework for aerodynamics simulation for ski-jumping which can be used in competition, we evaluated the accuracy of using 2D motion data obtained from 2D video image for the posture change in the simulation. From the viewpoint of pressure distribution, wake structures and lift-drag ratio, the major characteristics are very similar although there are small differences. Accordingly, we concluded that it is reasonable to use a 2D model for aerodynamics simulation of the take-off motion of ski-jumping.

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