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Original paper

Force acting on the jumper during the transition in the ski jump

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Abstract

The purpose of this study is to reveal the forces in the transitional area by using a compact accelerometer into which a gyroscope is incorporated. In this paper we defined the transitional area by time (0.5 sec before take-off to 1.5 sec after). Four jumpers jumped wearing a small accelerometer, which is designed to record the three dimensional forces and angular velocities on three axes. The accelerometer was made by Microstone Co. Ltd. Japan. The data was taken digitally with 200 Hz sampling frequency. The data on the local coordinate system are translated into the global coordinate system in accordance with the angle of the gyroscope. The data in the local coordinate system had to be converted into the corresponding value in global coordinate system by using Eular's rotation matrix. FFT analysis in the force data is done by using 128 points data set eight times, using Hanning window. Each adjacent period overlaps 87.5% (A to H). We came to the following conclusions:

1. The vibration of the skis results in the large amplitude of both the drag and lift forces.
2. The aerodynamic forces are large during the initial aerial phase. However those forces decrease and converge exponentially to a small value.

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Key words: ski jumping, transition area, force, FFT analysis,

Introduction

The purpose of this study is to reveal the influence of forces in the transitional area. The transitional area includes the motion on the take-off platform and the motion in the aerial phase. During this transitional area, mechanical forces change drastically. In ski jumping, when the jumper performs his ski-jumping, the mechanical forces affect the body and skis. The two external forces are the aerodynamic force and gravity (Tani & Iuchi, 1971). The aerodynamic force influences the jumper's muscular action. On the other hand, the body's moment force is mainly determined during take-off (Sasaki et al., 1997). Both moment forces must be taken into consideration when trying to maximize the effect of the aerodynamic forces especially during the initial flight (Sasaki et al., 1997). While in the air, moment force, aerodynamic force and gravity act on the jumper (Tani & Iuchi, 1971). The lift force weakens the reaction force during the jump motion (Virmavirta et al., 2001). In the flight phase, aerodynamic force increases in proportion to jumper's velocity (Hubbard et al., 1989, and Virmavirta et al., 2005). On the platform, the moment force is produced mainly by jump motion (Sasaki et al., 1997). Previous studies suggest that both take-off action and aerodynamic force are associated with take-off techniques (Hubbard et al., 1989 and Virmavirta et al., 2005). It should be considered that the aerodynamic force develops a moment force on the jumper's body (Sasaki et al., 1997). The aerodynamic force depends on the breadth of the surface areas of both the body and the ski (Denoth et al., 1987, and Jin et al., 1995). Body

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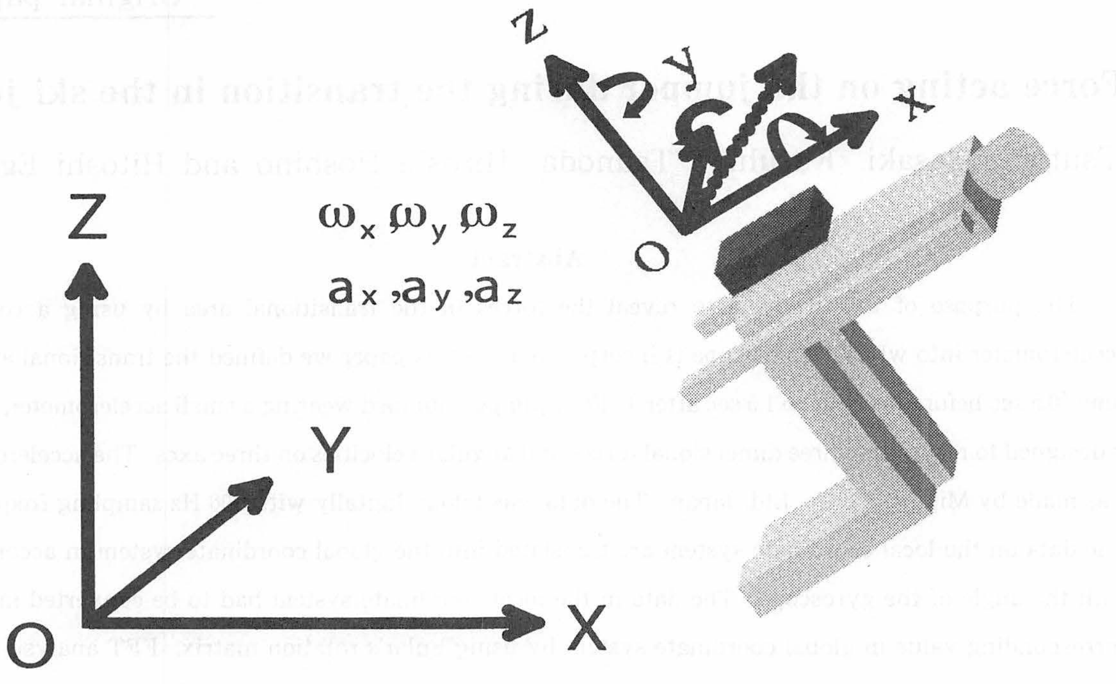

Fig. 1 The relationship between local (o-xyz) and global coordinate system (O-XYZ)

surface area becomes larger in getting closer to the end of the jump motion on the platform. Therefore, jumpers cannot ignore aerodynamic force in trying to maximize the effect of jump motion at the transition area (Sasaki et al., 2007). Especially in the aerial phase, only the gravity and aerodynamic force affect a jumper (Sasaki et al., 2001). It is important to know the behavior of these forces for better performance. We tried to prove our hypothesis regarding the influence of the mechanical quantity in any phase by using a compact accelerometer into which a gyroscope is incorporated.

Methodology

This study became possible thanks to the collaboration of four voluntary jumpers during their training camp at two normal hills from 2007 (Summer in Hakuba) to 2008 (Winter in Zao). Four jumpers jumped wearing a small accelerometer, which is designed to record the three dimensional forces and angular velocities on three axes. The accelerometer was made by Microstone Japan. The accelerometer was placed on the jumper's back between the lumbar bones (L2 and L4) and fixed by an elastic band. The data was taken digitally with 200 Hz sampling frequency and was saved into the bilt-in memory. The diagram in the coordinate systems and materials are indicated in Fig. 1. Three directions on the local coodinate system are defined in the parallel to each three axes. The x-axis is parallel to the longitudinal axis, y-axis is parallel to the transverse axis and z-axis is parallel to the sagittal axis. The displacement values were calculated by the second order integration of acceleration factors determined in the global coordinate system. The data were digitized with a frequency of 200 Hz. The frequency range of the acceleration data changes mainly at 10Hz. Additionally, the calibration of the three accelerometers were done on two conditions. In the first calibration, each sensor was placed parallel to the gravitational plane. Thus, the acceleration was indicative of gravitational acceleration (9.81m/s/s). In the second calibration, the accelerometer was placed perpendicular to the gravitational plane, then the acceleration indicated zero (0 m/s/s). The standard deviation (S.D.) in the mean acceleration during a three second test phase in each axis and each condition is 0.112 m/s/s , 0.105 m/s/s and 0.096 m/s/s in the x, y and z axis respectively. Here, it can be seen that each value of the (S.D.) was white noise. Those noise factors can be cancelled out by the integration calculation (Fig. 2).

The data in the local coordinate system had to be converted into the corresponding value in global coordinate system by using Eular's rotation matrix (Fig. 3). The data for conversion of coordinate systems were obtained using a gyroscope. FFT analysis in the force data is done by using 128 points data set eight times, using Hanning window. Each

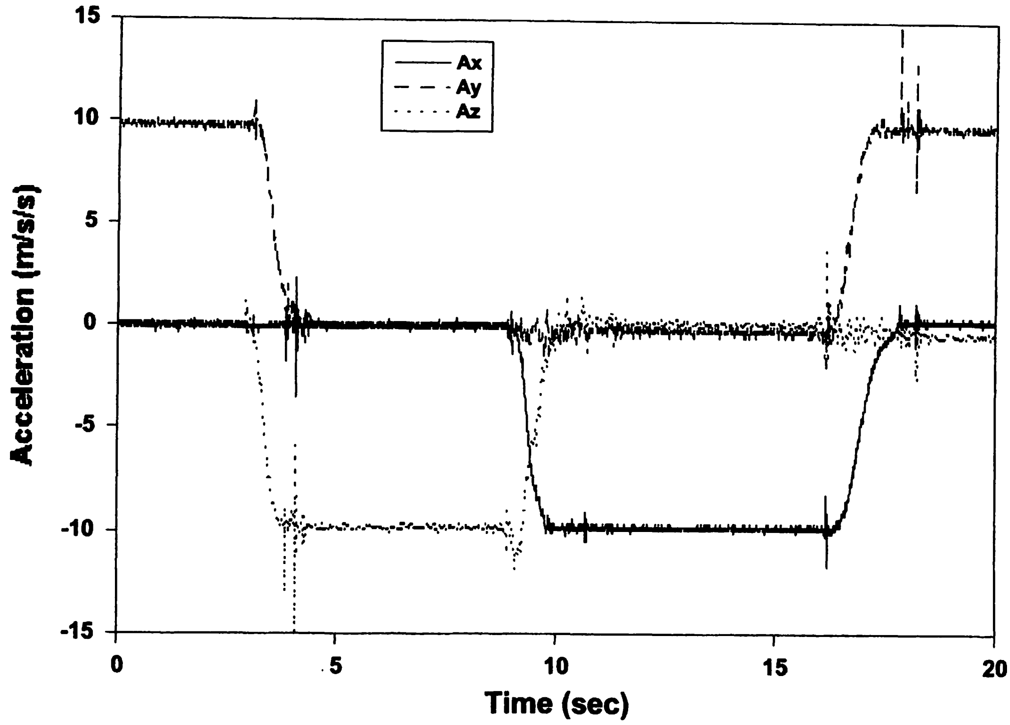

Fig. 2 A single calibration data set of three accelerometers. The accelerometer was rotated 90 degrees in the x-axis, 90 degrees in the y-axis and 90 degrees in the z-axis.

$$A_{X,Y,X} = R^{-1}_{\phi,\theta,\psi} \cdot a_{x,y,z}$$

$$\begin{bmatrix} A_X \\ A_Y \\ A_Z \end{bmatrix} = \begin{bmatrix} C\phi C\theta & S\phi C\theta & -S\theta \\ C\phi S\theta S\psi - S\phi C\psi & S\phi S\theta S\psi + C\phi C\psi & C\theta S\psi \\ C\phi S\theta C\psi + S\phi S\theta & S\phi S\theta C\psi - C\phi S\psi & C\theta C\psi \end{bmatrix} \bullet \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix}$$

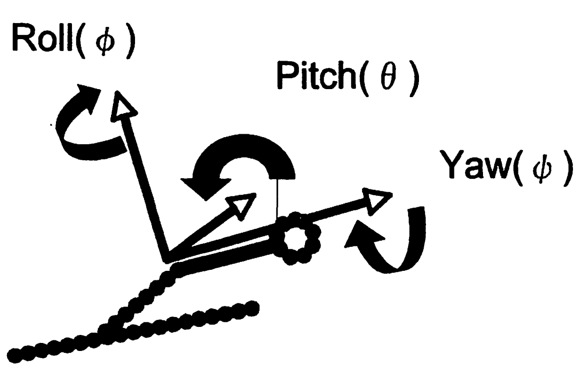

Fig. 3 Force data conversion onto the velocity vector using Eular's rotation matrix

adjacent period overlaps 87.5% (A to H).

Results

1. Two factors of forces in the initial aerial range

Fig. 4 indicates the change of a parallel force in the direction of the velocity vector in each jump motion. Forces of four jumpers are indicated by different line styles. These forces largely vary at the transition from the take-off platform to the initial aerial range. The data on global coordinate systems are converted onto the velocity vector. The force in the direction of the velocity vector includes multiple factors, such as the gravity, the reaction, the friction and the drag force. On the take-off platform, parallel forces are almost completely positive. These forces are the evidence that the jumpers moved

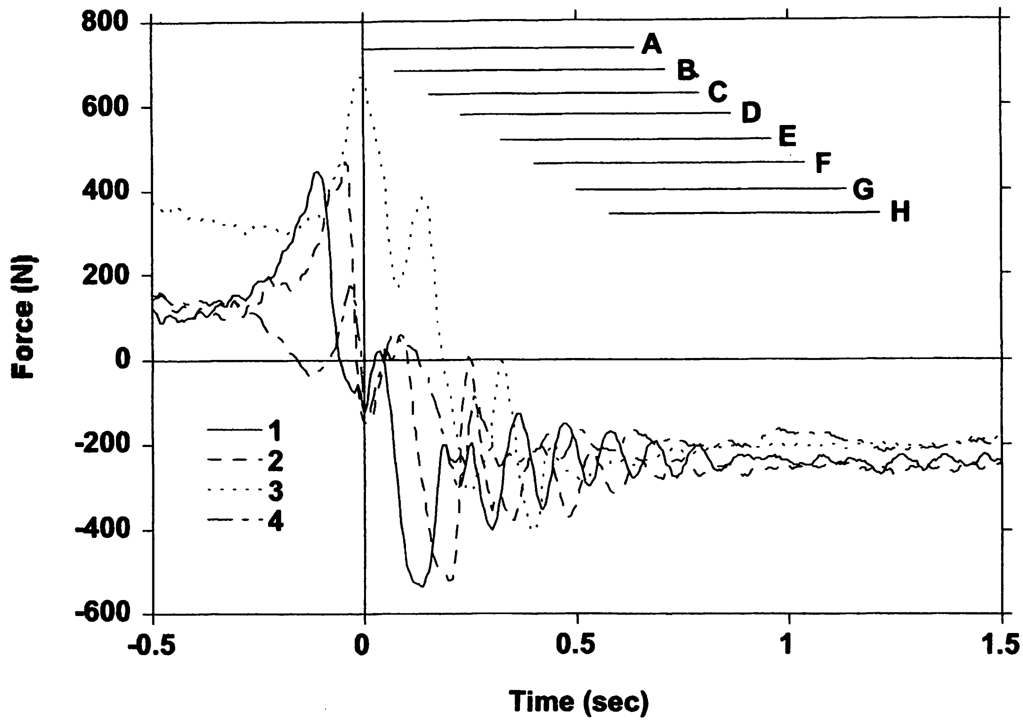

Fig. 4 Force in the direction of the velocity vector of four jumpers (1-4). A-H indicate the ranges used for FFT analysis.

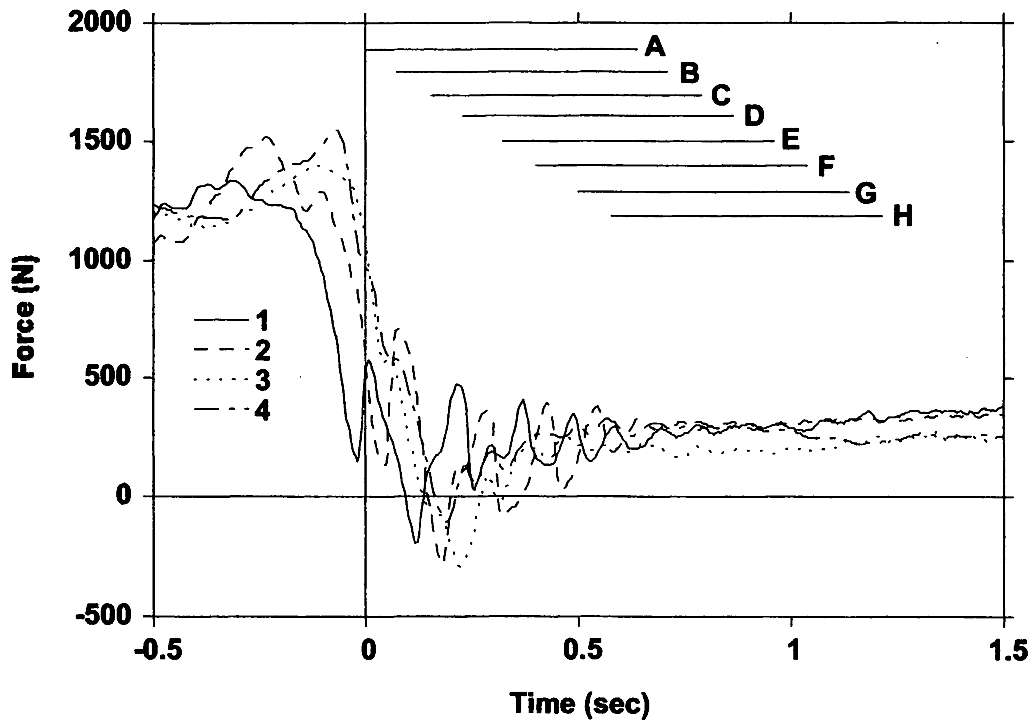

Fig. 5 Vertical forces to the velocity vector of four jumpers (1-4). A-H indicate the ranges used for FFT analysis.

forward. Various jump motions in each jumper cause the various force curves to be observed. Because the direction of the gravity is consistent, the drag force can be considered to be a sole variable in the transition. Amplitude of the drag force changes drastically in this initial aerial range. The amplitude converges around the value 200 N approximately in 0.5 seconds after the take-off.

Fig. 5 also indicates four examples of the force factors in the perpendicular direction to the velocity vector during the jump motion. On the take-off platform, forces include many forces, such as gravity force, reaction force with jump motion, and lift force. The summation of forces on the

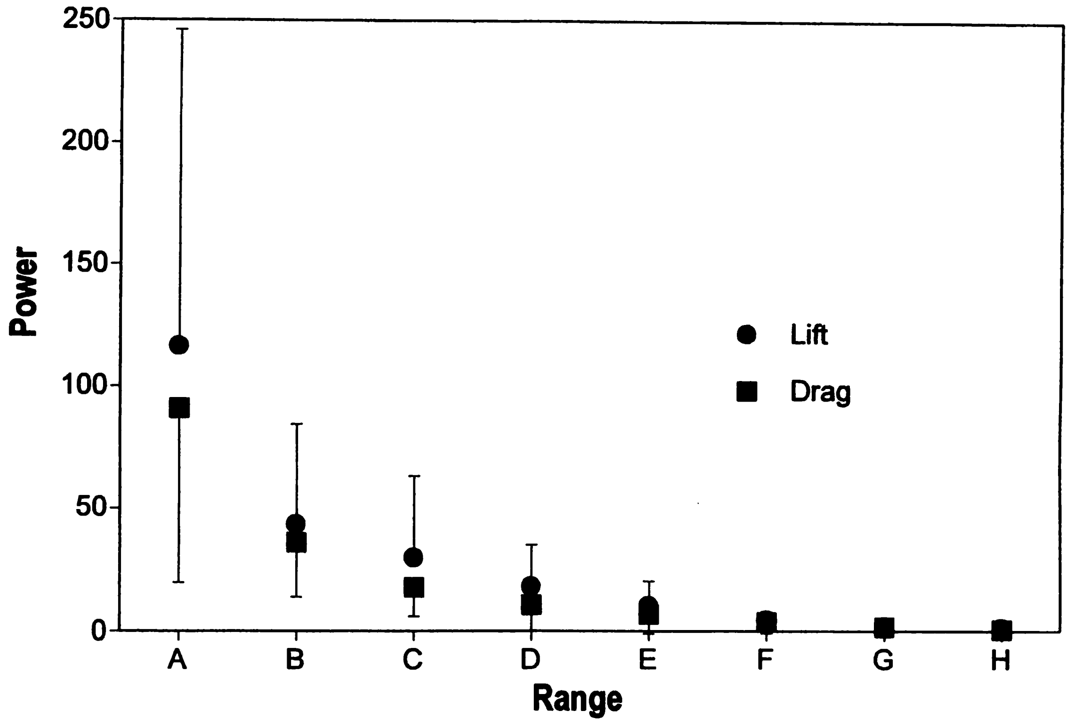

Fig. 6 The mean power spectrum of both parallel force and perpendiculor force to the velocity in each range (A to H)

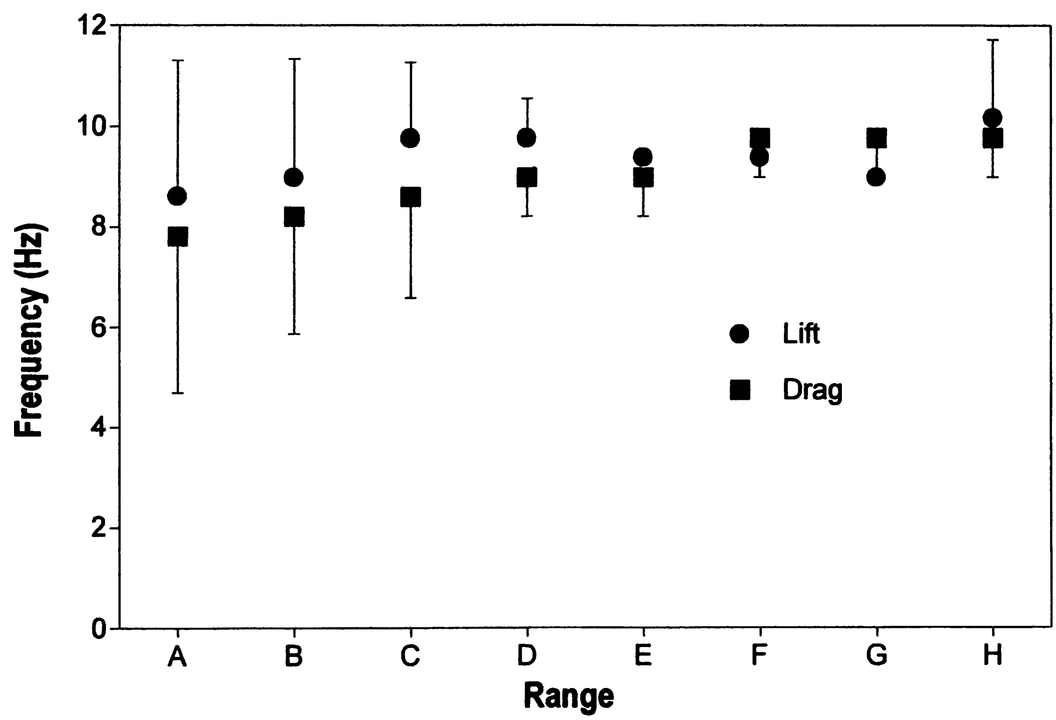

Fig. 7 The mean frequency of both the parallel and parpendisular forces to the velocity in each range (A to H)

platform is observed in the range from 1300 N to 1500 N. In the initial aerial range, forces rapidly vary with large amplitude. However, after 0.5 seconds, the amplitude converges to around 200 N.

2. FFT analyses in the aerial phase

The power spectrum and frequencies of drag force and lift force in each jump are indicated in Fig. 6 and Fig. 7. Fig. 6 indicates the mean power spectrum of both the forces in each of eight ranges. The dot marks indicate the power spectrum of the lift force. The power of the drag force is indicated by the square marks. The mean values of the power spectrum of both the drag force and lift force converge from 100 to 0 exponentially. The mean values of power spectrum for all the ranges indicate no significant difference between the drag force and lift force.

On the other hand, the frequency of both of the forces in each range stays between 8Hz and 10Hz (Fig. 7). The frequency at the peak in each range was also calculated. The dot marks indicate the frequency of the lift force. The frequency of the drag force is indicated by the square marks. Standard deviations in both mean forces is large in the ranges from A to C. However, the mean values of frequency in all the ranges indicate no significant difference. As for the power spectrum, there appears to no significant difference between the drag force and lift force.

Discussion

1. Two forces in the initial aerial phase

Drag force and lift force in the initial aerial range drastically vary and gravitational forces on skis should be taken into serious consideration to analyze total forces. By doing so, it is made possible for us to figure out what is happening in the transition. This study proves that the lift force and drag force are affected by skis' vibration of jumpers in the transition. The rapid change of amplitude right after the jump motion proves to be caused by the vortex which is produced behind jumpers. The influence of lift force and drag force remain active through out the aerial range. The lift force, drag force and gravity force remain active in the initial aerial range (Fig. 4 and Fig. 5). Therefore, these force data mainly represent the changes of the lift force or drag force in the aerial range, because values of the gravity force should remain consistent.

Amplitude of both lift force and drag force changes drastically in the initial aerial range (Fig. 4 and Fig. 5). Furthermore, the amplitude converges around 200 N approximately in 0.5 seconds after the take-off. Drag force and lift force act constantly on the jumpers even after the amplitude converge. The cause of the rapid change of the forces at the initial range of the transition has yet to be known. We hypothesize that two factors, ski vibration and vortex, are involved in the rapid change. The vibration of the skis seems to produce the large amplitude in the force. The vortex, which is produced by the air flow behind the jumper at the transition, seems to affect the frequency. In this study, drastic changes of the amplitude were observed consistently in the initial aerial range.

2. FFT analyses

The mean power spectrum of the lift force is slightly larger than that of the drag force. It is suspected that the large amplitude in the initial aerial range is due to the vibration of skis and the vortex (Fig. 6).

The mean frequency of both of the forces in four jumpers in each of the eight ranges is indicated in Fig. 7. The large power spectrum from the 100 to 50 in low frequency (8Hz) at the transition (A to C) indicates that some forces are produced by the upward motion of the jumpers. On the other hand, the power spectrum between D and H converges in low frequency (10Hz). It leads us to conclude that the oscillation of around 10Hz must be due to the influence of vortex. This result replicate our previous studies (Sasaki et al., 2007).

Both of the drag forcce and lift force remain in a narrow frequency band between 8Hz and 10Hz. the mean frequency of the lift force is slightly larger than that of the drag force. The standard deviation decreases sequentially.

It is suspected that the large amplitude is due to the vibration of skis while consitent frequency is due to the vortex.

Conclusions

We reached to the following conclusions:

1. The vibration of the skis causes in the large amplitude of both the drag force and lift force.
2. The aerodynamic forces are large in the initial aerial range. However, those forces decrease and converge exponentially to a small value.

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