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Drag Coefficient Sonification in Luge Using a Wind Tunnel

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Abstract. This paper describes a testing environment for luge that provides real time audio feedback to the athletes and presents findings from initial testing. The hardware is based on a wind tunnel, upon which an additional force plate and mount for the sledge were integrated. Determining the resistive forces in luge is sophisticated, because many interfering signals exist, e.g. stabili-zation movements of the athlete. Results show that it is difficult to repro-duce the drag coefficient to the second decimal place from trial to trial. As a consequence the central goal of wind tunnel training should not be to deter-mine the absolute optimum posture, but to create a feeling for good and bad movements on the sledge.

Keywords: Luge, Feedback, Sonification, Drag Coefficient, Wind Tunnel

1. Introduction

Drag resistance is a crucial factor for performance in luge. Even marginal changes in the angles of hip, ankle or knees lead to different resistive forces, which cause an appreciable loss of velocity [1]. The importance of an individual optimal body position becomes clear, when considering that the difference between winning and finishing second is only a few hundredths of a second. In order to reach peak performance in international competitions, it is necessary to analyze the posture of athletes in luge in a systematic way. This could allow coaches to realize the best possible individual position on the sled and to give scientifically based feedback to the athlete.

The drag coefficient is mostly measured in a wind tunnel so that environmental condi-tions can be ignored. Wind tunnels also provide sufficiently precise equipment for making measurements of drag forces. Surprisingly few papers have dealt with wind tunnel training so far [2][3][4]. One reason for this might be that representatives of top level sports are not willing to share this knowledge with potential competitors.

To provide further insight into this field of training and to support the German National Youth Team we developed a testing environment, which provides real time visual and audio feedback to the athletes. This feature is based on the expectation that the coupling of movements to a sound signal (sonification) supports the process of motor learning [5]. The present paper focuses on technological aspects of the environment, discusses general issues of drag resistance measurement and presents findings from initial testing.

2. Hardware Environment

For determining the drag coefficient we developed hardware and software components based on the wind tunnel of Technology University in Darmstadt (Germany). This wind tunnel is a traditional low velocity wind tunnel (up to 180 mph), in which the objects under study are located in a closed measurement chamber so that wind velocity is nearly uniform throughout the chamber totally separated from the environment. Below the measurement chamber there is a weighing scale, which is friction locked to the object under study. A fundamental problem of the wind tunnel for athlete training is that the weight scale was constructed for the measurement of heavy objects like cars or models of airplanes. It has a dead load of many tons and because of its inertia the measured forces have a delay of greater than five seconds. This is suitable for motionless objects, but it is not useful for giving real time feedback to moving objects.

Because of this it was necessary to integrate an additional force plate into the chamber and to construct a stable mount for the sledge (see fig. 1). First an aluminum pillar (top left) was connected to the steel construction built into the concrete floor. Upon this pillar we fixed an aluminum plate, which serves as the support for the force plate (top right). Because it is not possible to put the sled directly on the force plate (risk of damage, problems of fixation), an additional wood plate is attached to the force plate (bottom). This plate has several holes drilled into it for plastic belts to run through. This allows many different types of sleds to be fixed to the plate.

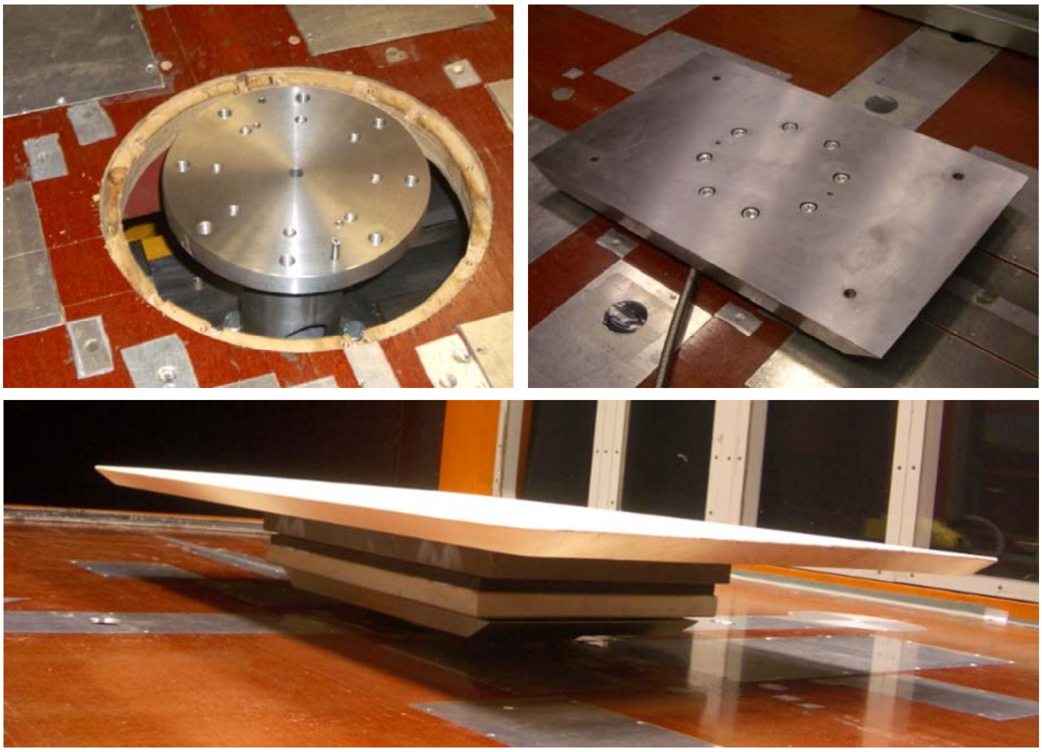

Fig. 1: Construction for the integration of a sledge into the wind tunnel.

3. Issues in determining drag coefficient

The drag coefficient c_d is typically defined as shown in equation 1, where F_d is the force component in the direction of the flow velocity, q is the dynamic pressure and A is the reference area.

$$c_d = \frac{F_d}{Aq} \tag{1}$$

When measuring these parameters it is indispensible to assure that the quality of measurement is sufficient to make reliable statements. Based on our experiences, we think that there are four important issues to be considered.

The first one is that athletes perform continuous balance adjustments to maintain their riding posture on the sledge. Fig. 2a and 2b show the curves of two athletes being instructed to lie on the sledge, in riding posture, for 10 seconds. Without the effect of air resistance, the adjustments of balance, along the longitudinal axis, in riding posture account for approximately10 N (athlete A, member of the national youth team) and 5 N (athlete B, international top level athlete). The amplitude of these peaks often increases during a test, when fatigue increases. During a real test run, these forces superimpose the force caused by the air pressure and make it difficult to relate a posture unanimously to a drag force.

The second problem is vibration of the testing environment. The left graph in fig. 3 shows the force signal generated when running the wind tunnel without an athlete on the sledge. In this condition a noise signal (amplitude of 25 N at 70 mph wind velocity) occurs, which is caused by vibrations of the chamber, the mount of the sledge and the ventilators movements. Although it is possible to reduce this noise e.g. by using a noise filter it is clear that these values also overlay the force signal from the athlete.

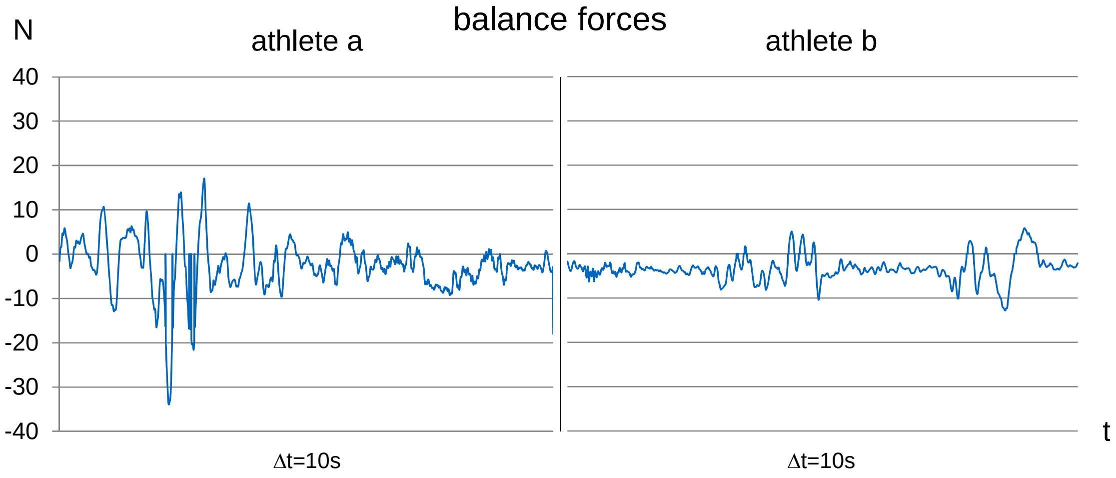

Fig. 2: Forces in the opposite direction of the air flow caused by balance adjustments. The results of a member of the national youth team are shown, graph b shows the results of an international top level driver, with less fluctuation (maybe because of his better physical constitution).

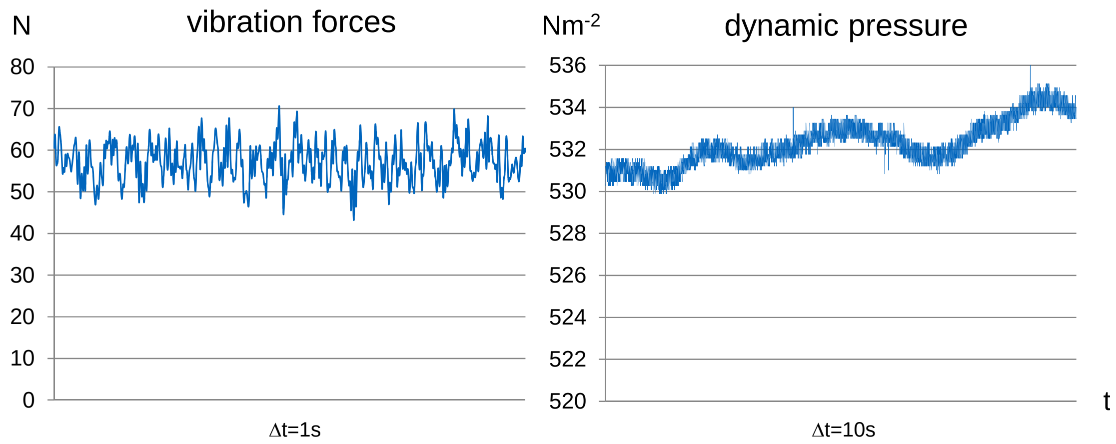

Fig. 3: Forces created by the vibration of the testing environment when running the wind tunnel (left). The sequence of air pressure during a time span of 10 seconds is shown.

The third issue is that the parallel feed of ventilators is not totally perfect. We tested this by running the wind tunnel with a constant ventilator speed and measuring the real air pressure existing in the chamber with an additional sensor located in the air flow. The resulting curve is shown in the right graph of fig. 3 and illustrates a maximum fluctuation of 0.5 Nm^{-2}. This would lead to a change of drag resistance of the nonmoving sledge-athlete-system of about 5 N at 70 mph.

Reason	*Size*
Fluctuation of air pressure	5 N
Vibrations of chamber & mount	25 N
Balance movements of athlete	10 N
Drift of force sensors	3 N
Changes in resistant forces caused by small athlete movements	1 N

Fig. 4: Dimensions of disturbances when measuring drag forces in a wind tunnel at a wind velocity of 70 mph.

The fourth issue is the drift of the integrated force plate. The range and speed of the drift depends on the temperature and properties of the piezo sensors inside the plate (in our case about 0.05 Ns^{-1}). When measuring forces for analyzing technique e.g. a golf sway or of a drop jump, this drift is not relevant, but in our case an error of 3 N per minute could lead to a misinterpretation of postures.

Fig. 4 summarizes the dimension of the disturbances discussed in the last paragraphs. Keeping in mind that a change of the posture (e.g. slight lifting the head or a minimal change of knee angle) lead to only to a change of approximately 1 N at 70 mph in our tests, it is clear that identifying this effect is not impossible but fault-prone.

To eliminate a part of the noise we used a few correction parameters when calculating the drag coefficient. As shown in equation 2 we measure the resistant force and the dynamic pressure at 500 Hz and calculate the moving average over the previous 1.0 s.

$$c_d(t) = \frac{1}{500} * \sum_{x=t-500}^{t} \frac{F(x) + w*(x - t_0)}{A*q(x-r)} \quad where \quad r = \frac{s}{\sqrt{2\frac{q}{\rho}}} \tag{2}$$

The variable w refers to the force plate's baseline drift, which we determined before the test. The variable r models the time delay between measuring the dynamic pressure of the air and the time it reaches the sledge (because the sensor is located $s=6$ meters away from the sledge, ρ is the density of air). The value for the reference area A was an approximation which was defined as the maximum cross-sectional surface area of the athlete in the transverse plane. A was estimated before the test and set to a constant value for all training sessions for each athlete.

4. Software Environment

Based on this, software for data collection, processing, visualization and sonification was developed (see screenshot in fig. 5). The controls in the upper left area (a) allow changing the input signal (force plate, recorded data file, simulated force signal). Other controls can be used to set the force plate's drift and its offset. The upper right part (b) visualizes the three components of the force vector and current drag coefficient in the progress bars. The controls next to the bars allow adjusting the range and sensitivity of the display. It is also possible to set trigger signals to mark timestamps in the data (c).

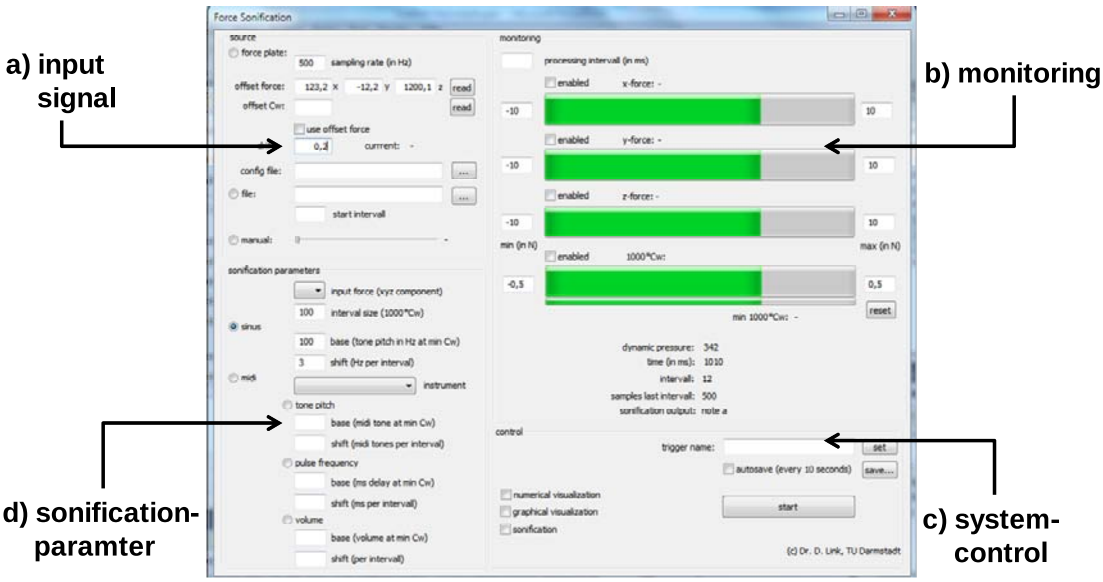

Fig. 5: Screenshot of the developed software. Main features are measurement, storage, monitoring and sonification of the drag coefficient.

To show the quality of different body postures to the athlete, the software provides visual and acoustic feedback. The visual feedback is given by two progress bars displayed on a second monitor located above the glass ceiling of the chamber. The first bar shows the current drag coefficient, whereas the second bar displays the best (lowest) value in a specified time range.

The second possibility is to present the drag coefficient as a sound signal. The sonification algorithm uses two steps. First, it transforms the difference between the current drag coefficient $c_d(t)$ and its baseline value ($c_{d\_baseline}$, determined at the beginning of the test) to discrete values (*IntervalID*) (see Equation 3). The parameters *NumberOfIntervals* and *SizeOfIntervals* are used to control the range and sensitivity of the transformation. Values outside the interval [0, *NumberOfIntervals*] are dropped. The intention behind this is to make sure that only changes of at least *SizeOfIntervals* have an influence on the generated sound.

$$IntervalID(t) = \frac{1}{2} * NumberOfIntervals - \mathrm{int}\left(\frac{c_{d\_baseline} - c_d(t)}{SizeOfIntervals}\right) \quad (3)$$

In the second step, the algorithm converts the *IntervalID* into the graphical (bar size, similar to fig. 1) or the auditory feedback. The user can select between three different types of sounds (sinus tone, pulse tone, midi-instrument), in which the modulation parameter (frequency, pulse duration, midi tone) is changed according to *IntervalID*. When playing a sinus tone its frequency is calculated based on a base frequency (tone played in first interval), and the change of the frequency per interval (see Equation 4). When playing a midi-tone) the *IntervalID* is transformed to a specific note.

$$Frequency(t) = BaseFrequency + IntervalID(t) * ChangePerInterval \quad (4)$$

The challenge for the user is to choose the sensitivity in such a way that one athlete is able to recognize differences in the discrete values mentioned in yet the tonal range covered is appropriate for the human auditory system in which the athlete one the one side can notice the differences clearly and on the other side a sufficient range is covered. Suitable values from previous tests were within an interval size of 0.005 c_d with 100 intervals. These settings fit to a base frequency of 100 Hz and a change of 10 Hz in each interval. For the playback of the sound we used a commercially available Bluetooth headset, which was integrated inside the helmet.

5. Results

We tested the environment with seven athletes from the German National Youth Luge Team located in Winterberg (North Rhine-Westphalia). With every athlete we performed three tests, where they were instructed to find their best position on the sledge, while listening to the generated sound. Variables of interest were: neck flexion, knee flexion, elevation of the shoulders, hip position (anteroposterior) and ankle plantarflexion as well as internal external rotation. Fig. 6 shows the lowest drag coefficient reached in each trial.

Trial	*Athlete A*	*Athlete B*	*Athlete C*	*Athlete D*	*Athlete E*
1	0,301	0,269	0,278	0,321	0,272
2	0,311	0,273	0,288	0,322	0,280
3	0,321	0,251	0,300	0,325	0,284

Fig. 6: Screenshot of the developed software. Main features are measurement, storage, monitoring and sonification of the drag coefficient.

A first trivial finding is that the drag coefficient differs from athlete to athlete. This is clear because of their different physique and their mass customized sledge. It is remarkable that the most successful athlete (B) not only has the best drag coefficient but also generates the lowest resistive forces. In our sample the female athletes (a, b, c) show a better drag coefficient, maybe because of a more shapely silhouette. Most of the athletes resistive forces became higher from trial to trial (except for athlete B). The athletes traced this back to their increasing fatigue, when lying for about 60 seconds in a sustained position on the sledge in each trial. The table also shows that the value of drag coefficient was not reproducible up to the second decimal place, because of the inter-test variability of the athlete’s posture. No athlete was able to capture exactly the same position again after standing up from the sledge.

Fig. 7 shows a typical run of the difference between the drag coefficient and its baseline value over a time period of 30 seconds (see fig. 5a; fig. 5b shows a magnification). With the aid of the sonified audio feedback the athlete made many postural adjustments throughout a single trial to reduce the amount of drag. During the trial the athlete tries different positions of ankle plantarflexion and internal external rotation, which lead to a change of drag of about .003 c_d points. We synchronized the measurement with a video recording and took two screenshots at the time points marked with the green and the red bar. Fig. 5c shows an overlay of the two corresponding postures. The one with increased ankle plantarflexion leads to a 0.014 lower drag coefficient, which corresponds to a drag force of 2 N at 70 mph.

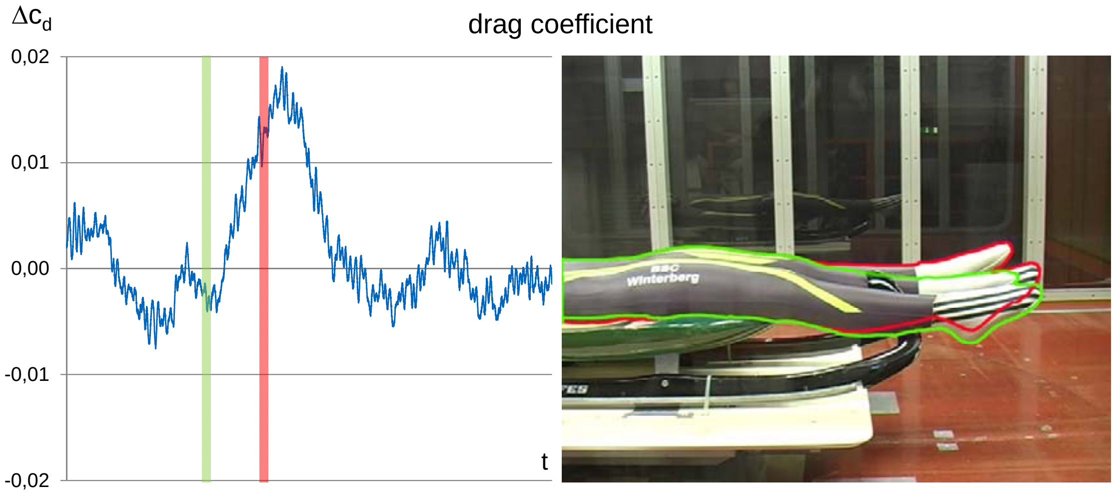

Fig. 7: Overlay of two typical riding postures. The drag coefficient of the posture with the green silhouette is Δc_d=.014 lower than the red silhouette.

6. Conclusion

This paper has shown technical and practical issues of determining of drag coefficient in luge. It turned out that it is difficult measuring resistant forces of a living object. It became clear that it is nearly impossible to reproduce the value of drag coefficient up to the second decimal place, because of the inter-test variability of the athlete's posture. It is the postural adjustments within the test which are most important. Accordingly, the athlete does not necessarily learn the optimal posture. Rather he learns to adapt his posture using various forms of feedback. Therefore, the central goal of wind tunnel training should not be to determine the optimum posture, but to create a feeling for good and bad movements on the sledge. With this in mind the developed environment surely provides a good means to enhance performance, especially for young athletes.

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