Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia Engineering 34 (2012) 473 – 478

Procedia Engineering

www.elsevier.com/locate/procedia

9th Conference of the International Sports Engineering Association (ISEA)

Cross-country ski vibrations and possible mechanisms of their influence on the free gliding

Andrey Koptyug[a]*, Mikael Bäckström, Mats Tinnsten, Peter Carlsson

Mid Sweden University, Department of Engineering and Sustainable Development, Sports Technology Group, Akademigatan 1, SE-831 25, Östersund, Sweden

Accepted 05 March 2012

Abstract

Present paper describes the results of experimental studies on the self-induced and forced vibrations of loaded cross country skis and presents the discussion on the possible mechanisms causing such vibrations and the ways they can influence the friction between the ski running surface and the snow. Studied vibrations of gliding skis are most probably caused by the frictional effects. Mechanisms involved are similar to the ones causing the brake disc squeal or the violin string excitation by the bow. Major factors responsible for the development of these vibrations such as micro roughness of the surfaces, nonlinearities in the material properties, thermo-elastic instabilities and instabilities due to decreasing friction with increasing sliding velocity are also common for the case of gliding skis. The results of this study indicate that the ski vibration pattern both in amplitude and in frequency could influence the ski gliding properties. Though it seems quite feasible that the control of the cross country ski vibrations can improve the gliding performance, further systematic studies are needed to confirm it and to formulate the consecutive strategies of cross country ski design improvement.

Keywords: Skis; induced vibrations; gliding; field experiments; mechanisms

1. Introduction

Vibrations of alpine skis and snowboards and their effect upon the equipment and athlete performance [1, 2] and athlete health [3] are well recognized and intensely studied. The vibrations of cross country skis are much less pronounced, but their influence, especially upon the ski gliding, may be underestimated.

* Corresponding author. Tel.: +46-63-165941; fax: +46-63-165900.
E-mail address: Andrei.Koptioug@miun.se.

doi:10.1016/j.proeng.2012.04.081

Discussions with the athletes and ski technicians indicate that cross country ski vibrations to certain extent seem to be beneficial for the free gliding performance. Our field tests [4] and laboratory experiments also show that the vibrations of loaded cross country skis may have a significant effect on the gliding efficiency. Here we present some experimental results and a discussion on possible mechanisms of generation of such vibrations, and of their influence upon the free gliding efficiency.

2. Experimental results

Field measurements of the pressure between the skis and the surface of the ski track (measurement setup description can be found in [4]) clearly show a presence of the intense pressure oscillations (Fig 1).

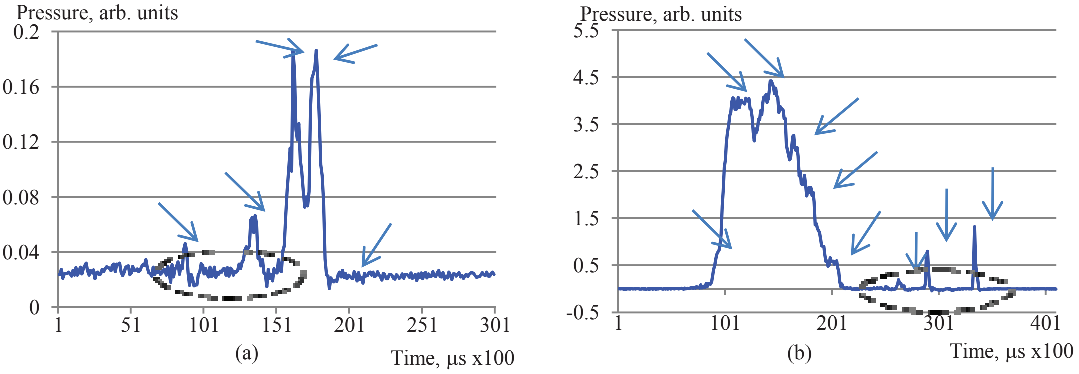

Fig. 1. Time dependence of the pressure between the skis and the snow; field experiments, descend #39, pair 105 [4] from the front of the right ski (a) and the rear of the same ski (b). Corresponding oscillations are marked by arrows and the incidents, when parts of the skis are losing contact with the snow are marked by dashed lines. Signal (b) is coming 100 ms after signal (a)

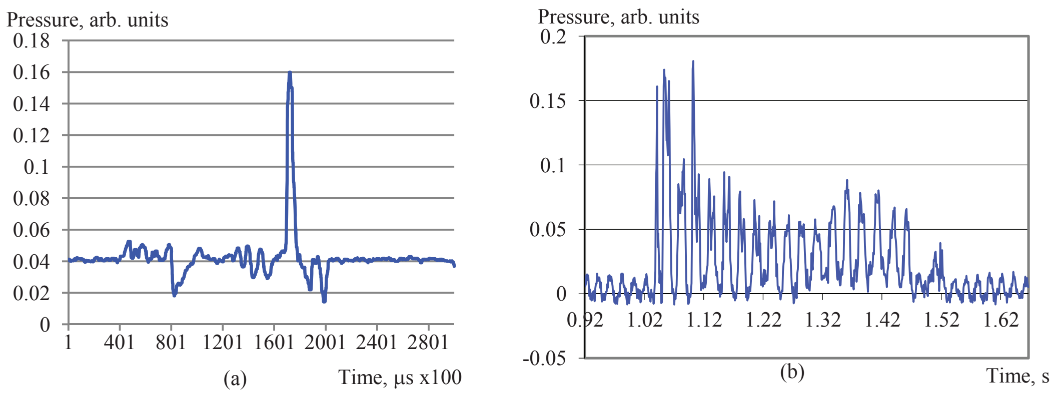

Fig. 2. (a) Time dependence of the pressure inside the snow under the ski track; descend #6, ski pair 112 [4], both front and rear signals are visible. (b) Pressure signals from the pressure sensor on the snow, when static skier is 'stamping' over the sensor

Ski vibrations are so intense that during the time, when a ski is passing over the pressure sensor its front and rear at least in some parts loose the contact with the snow (zero pressure value) and bounce back. Such behavior was detected for all tested pairs of skis and all glides, and strong vibrations were detected for both the front and the rear of the ski. Even during the short time when the ski front and rear are passing over the pressure sensors (tens of milliseconds) it was possible to detect up to 8 periods of oscillations allowing reasonable estimations for the corresponding resonance frequencies. For the example shown in Fig 1 the oscillation period averaged over both signals is $T \approx 2.8$ ms, and the corresponding resonance frequency is $F_{res} \approx 357$ Hz. Similar oscillation type signals were recorded with the pressure sensors placed in the snow two centimeters under the ski track surface (Fig 2a) indicating that ski vibrations are quite intense and there exists a coupled acoustic wave travelling inside the compacted snow in the ski track. Almost equal overall intensities of the signals from the tri-axis accelerometers, placed 2-3 cm under the surface of the ski track [4] indicate that the snow displacements caused by these waves are similar in intensity in all directions and the direction orthogonal to the snow surface does not dominate as it could be assumed, and so these waves are almost semi-spherical.

Simple technique was employed in attempts to determine the losses in the loaded ski resonance system caused by its interaction with the snow. Stationary skier was raising the front of the ski over the pressure sensor laying on the snow and stamping by it over the sensor (Fig 2b). From the train of decaying pressure peaks it is possible to determine the corresponding frequency of the excited resonance (about 40 Hz in the given example) and the characteristic oscillation decay time. For the common linear resonance systems the quality factor for the corresponding mode can be determined as the ratio of the energy saved in the system to the energy lost during the oscillation period, and thus can be estimated as the number of periods while the decaying resonance signal falls e (≈ 2.7) times. In the shown example such calculation yields the apparent quality factor value of about 8 - 10, which corresponds to the loss factor (reciprocal of the quality factor) of about 0.125 - 0.10.

Oscillation frequencies calculated from the pressure signals recorded for the same pair of skis during different descends on the same slope with similar glide rates were similar but not identical (for the ski pair 105 mentioned in Fig 1 this difference reached 50 Hz). These also differed from the resonance frequencies determined from the pressure sensors placed inside the snow. The pressure between the skis and the snow and the pressure inside the snow was recorded for the same pair of skis but for different descends. The quoted difference in the measured oscillation frequencies may be caused by the changes in the experimental conditions between the consecutive descends due to, for example, the changing skier posture. The difference in the posture leading to the varying center of gravity position is clearly showing in the field experiments through the difference in the loading of the left and right skis and between the front and the rear contact surfaces of the same ski (determined from the differences in the corresponding pressure and acceleration signal peaks and signal integrals [4]). It should be noted that the changes in the resonance frequency of the skis under varying load may be caused by a variety of factors such as the changes in the ski geometry, changes in the internal stress within the ski structure and changes in the average area of the ski contact with the snow.

For further experiments modifications were made into the laboratory setup described earlier [5] to allow for the studies of the forced vibrations of the loaded cross country skis. Fig 3 sketches the essentials of the additional components introduced into the existing setup. An absorbing mat was placed over the solid base to improve the acoustic insulation. Along with the static loading force sinusoidal excitation was produced by a pair of vibration generators (SF 21865.00 by Frederiksen). Both the static load and vibration excitation were applied to the ski center of gravity (marked on the sketch by a cross). Thin-film pressure sensors P_1 and P_2 were placed in the front and rear ski contact areas, and three-axis accelerometers A1 and A2 (LIS344 by STMicroelectronics) were placed on the upper ski surface above the pressure sensors. Additional pressure sensor (P_3) is introduced to control the static load and excitation intensity (all pressure sensors are FlexiForce A201 by Tekscan). In the described experiments vibrators were excited by the sine-wave signal with constant amplitude and varying frequency. The discussed results were measured for a single soft classic style ski (Hypersonic X3, 252 classic cold, by Madshus).

The chosen loaded ski has multiple resonances in the frequency range 12-500 Hz exhibiting unusual peculiarities. For example, at many response frequencies forced vibration signals are not sinusoidal and have in their spectrum harmonics at higher frequencies, which are not multiples of the excitation one. Forced vibration amplitude at some frequencies behaves in a quite unstable way; it "jumps" between lower and higher values at some frequencies. Also the measured "resonance curves" are significantly asymmetric and are strongly dependent on the excitation signal amplitude.

Fig 4 illustrates the difference in the measured frequency dependence of the acceleration signal (component normal to the ski surface) on the frequency (a) and excitation signal amplitude (b). For the shown resonance, when sweeping frequency up, the instability point (signal amplitude suddenly increases 5 times) is at about 52.4 Hz. When sweeping down, the instability point (signal amplitude suddenly drops 3 times) is at lower frequency of 51.6 Hz. When the excitation amplitude decreases 1.6 times the apparent position of the resonance (maximum on the curve) is shifted from 55 to 60 Hz.

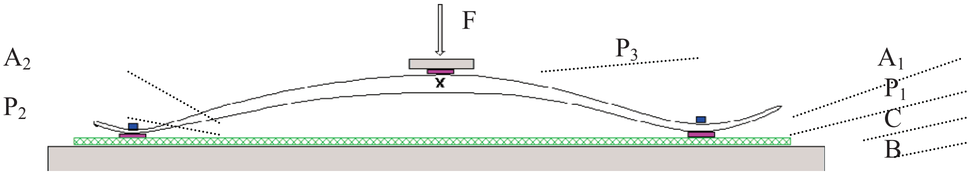

Fig. 3. Setup for the studies of the forced vibrations of the loaded cross-country skis. P_1, P_2, P_3- thin film pressure sensors; A_1, A_2 – accelerometers; F- static load and harmonic excitation; C- acoustic insulation, B- solid base

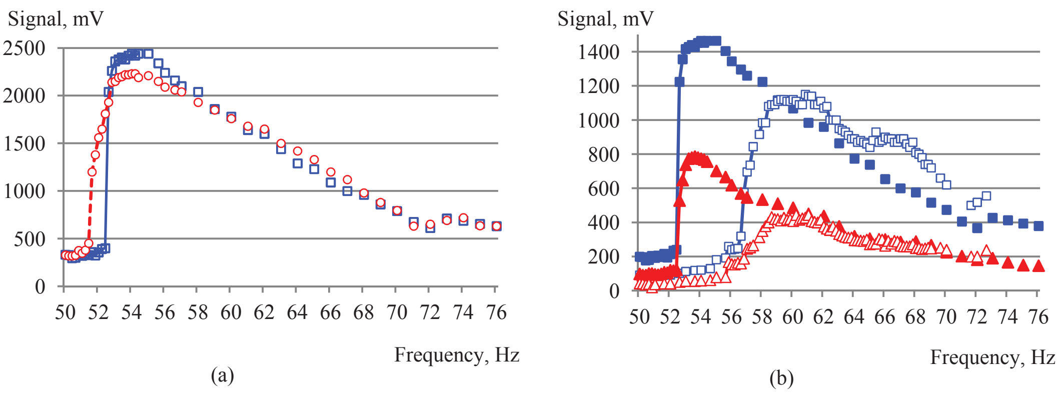

Fig. 4. Frequency dependence of the peak-to-peak magnitudes of the acceleration signal components normal to the ski surface.
(a) Front of the ski, frequency is swept up (squares, solid line) and down (circles, dotted line);
(b) Front of the ski (squares) and back of the ski (triangles), with different excitation amplitude. Solid squares and circles correspond to 60% higher excitation signal amplitude

Such peculiarities in the signal behavior are quite characteristic to a so-called parametric resonance [6]. These are excited in the systems with the parameters depending periodically on time, or on the oscillation amplitude. In such systems determination of the exact position of the natural resonance is complex, especially in case of forced oscillations. And the ways of determining losses from the resonance curves traditional for the common linear resonances may also be incorrect [6]. Also the frequency of the forced oscillations may be quite far from the one of the natural ("free") one because of the "frequency pulling" within a certain synchronization range. Thus the studies of the resonance modes for the free hanging cross country skis (in the way similar to the one described in [7]) should be complemented by the studies into the resonance behavior of the loaded skis, placed on the snow or the surface mimicking snow.

3. Influence of the vibrations on the free gliding performance

The influence of vibrations on the friction forces is widely studied in the technology and industry (see, for example, [8] and [9]). The intense self-generated vibrations are known, for example, to decrease the efficiency of the car brakes ("brake disc squeal", [9]). Studies of the discussions on the interactions involved indicate that the qualitative conclusion on the decreasing friction forces in presence of vibrations could also be valid in the case of ski gliding. Indeed, the decreasing average value of real area of contact, decreasing “effective” value of normal force and the stick-slip character of the motion, caused by the variations in the normal force in presence of vibrations are still valid in the case of vibrating skis.

Also the research results indicate that measured friction coefficient decreases with growing pressure both for the friction between the polymers and ice or snow [10-12]. This effect is generally attributed to the changes in the apparent area of contact between the surfaces when the pressure changes micro-geometry of actual contact points. Such effect could also shift the average of the friction forces in presence of vibrations towards the lower values.

The same time, experimental studies indicate that the friction coefficient between the moving bodies also depends on the sliding velocity and ambient temperature [10-12]. For the relatively low temperatures, when the frictional heat causes the presence of the melt water layer in the interface area, the friction coefficient decreases with increasing speed. Thus one can expect more pronounced effect of vibrations: reduced friction should increase the free gliding speed, which in turn should lead to decreasing friction coefficient and further increase in gliding speed. On the other hand, for the higher temperatures, when amount of water present in the interface zone dramatically increases, the drag forces considerably contribute to the overall friction and friction coefficient increases with increasing speed (mixed friction and hydrodynamic friction regimes).

4. Possible mechanisms of the generation of cross country ski vibrations

Experimental data are indicating that there are viable mechanisms for providing the initiation and continuous support of the ski oscillations during gliding. It is generally supposed that few different mechanisms lead to the development of instabilities during friction. These are geometric roughness of the surfaces, nonlinearities in the material properties (e.g. nonlinear contact stress), thermo-elastic instabilities and instabilities due to decreasing friction with increasing velocity [9]. Such mechanisms are capable of providing necessary positive feedback and the development of self-oscillations. For example, even in the idealized brake system model (ideal materials, constant friction coefficient, perfect geometry and constant normal load) the self- oscillations will be generated through the development of the regular changes in the contact area due to the surface deformations caused by the in-plane vibrations [9]. According to the existing body of research, all of the mentioned mechanisms are at least to some extent present for the gliding skis [9, 11-15]. Experiments with the solid specimens not only clearly show the development of the oscillations in the displacement of the sliding bodies [15], but that the stick-slip character of the motion in the case of non-lubricated [9] and lubricated friction [13] causes such vibrations to develop.

The same time, already existing models illustrate the complexity of the interactions involved. For example, the frequencies of self-oscillations are determined by both the parameters of the sliding body and the surface (in our case- skis and snow). Intense self-oscillations will be generated in the system only for certain conditions at certain sliding speeds. The development of the self-oscillations is often showing some threshold-style behavior (due to the existing instabilities [15]). The frequency of such oscillations depends not only on the parameters of the system, but also on the sliding speed. Also the mechanisms of generation of such oscillations are some different in cases of dry and wet friction. All of the above makes studying such oscillations quite a complex and tedious task.

5. Conclusions

There are multiple studies into the vibrations in the alpine skis and snowboards, where the intense vibrations are supposed to have predominantly negative effect upon the athlete's performance. On the other hand, existing experimental evidence indicate that in the cross country ski vibrations may play a positive role and improve gliding performance, especially at lower snow temperatures. The significant complexity of the system (complex vibration modes of the skis, their dependence on the loading, variable properties of the snow under changing ambient conditions, etc.) does not allow direct use of the vibration-friction models developed in the technology and industry for the studies of cross-country ski vibrations. The results of this study indicate that the ski vibrations could influence the ski gliding properties. Thus only through thorough and systematic experimental studies into the mechanisms of the induced vibrations of the cross country skis it would be possible to suggest the ways of the vibration control and, hopefully, in the ski design leading to the improvements in the ski gliding performance.

Our further work in this area will be aiming at the in-depth studies of the free and loaded ski vibrations both in the controlled laboratory environment and in the field.

Acknowledgement

We would like to thank Leonid Kuzmin for the help with the field experiments.

References

[1] Fuss FK, Cazzolato B, Shepherd A, Harding J. Vibration of snowboard decks. Procedia Engineering 2010; 2: 2863-7.
[2] Causey GK. Testing of vibration damping binding system used on alpine ski equipment. Master of Science Thesis (Mechanical Engineering), 1993, Case Western Reserve University, USA.
[3] Klous M, Muller E, Schwameder H. Knee joint loading in alpine skiing: a comparison between carved and skidded turns. In: Proc 12th Annual Congress of the ECSS, 2007, Jyväskylä, Finland.
[4] Koptyug A, Kuzmin L. Experimental field studies of the cross-country ski running surface interaction with snow. Procedia Engineering 2011; 13: 23-9.
[5] Bäckström M, Dahlen L, Tinnsten M. Essential ski characteristics for cross-country skis performance. In: Proceedings of 7th Conference of the International Sports Engineering Association (ISEA), 2008, Biarritz, p. 543-9.
[6] Butikov EI, Parametric Resonance in a linear oscillator at square-wave modulation. Eur J Phys 2005; 26: 157-74.
[7] Hosokawa K, Kawai S, Sakata T. Modeling of alpine skis considering individual constituent material properties. In: Alam F, Smith LV, Subic A, Fuss FK, Ujihashi S, editors. Proc. of The Impact of Technology on Sport III 2009; Melbourne, p. 75-9.
[8] Kumar VC, Hutchings IM. Reduction of sliding friction of metals by the application of longitudinal or transverse ultrasonic vibration. Tribology International 2004; 37: 833-40.
[9] Akay A. Acoustics of friction. J Acoust Soc Am 2002; 111: 1525-48.
[10] Bergh U. The influence of body mass in cross-country skiing. Medicine in Sports Science and Exercise 1987; 19: 324-31. [11] Kieyzig A-M. Microscopic ice friction. Doctoral Thesis, 2006, Technische Universität Berlin, Germany.
[12] Bäurle L. Sliding friction of polyethylene on snow and ice. Doctoral Thesis, 2006, ETH Zürich, Switzertland;
[13] Bushan B. Stick-slip induced noise generation in water-lubricated compliant rubber bearings. J Lubr Techn1980; 102: 201-12.
[14] Persson BNJ. Sliding Friction. 2d ed., Springer; 2000.
[15] Vingsbo O, Schon J. Self - induced and machine - induced specimen vibrations in fretting testing. In: Bayer G, editor. Mechanical stiffness and Vibration on Wear, 1995, Philadelphia, ASTM STP 1247, p. 9-21.