Reducing On-Snow Vibrations of Skis and Snowboards

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Skiers and snowboarders experience a speed limit. As the speed limit is approached, the ski or snowboard begins to lose contact with the snow surface and repetitive impacts cause vibration. Frequently, this vibration is severe enough to affect the rider's control and balance. The authors examine on-snow vibrations of skis and snowboards and show how they developed laboratory tests to correlate with field behavior. Proper simulation of the boot/binding interface proved to be an important condition for meaningful test results. For comparison of different layups and damping treatments, color map-type plots proved helpful. On hard snow, torsion characteristics of skis and snowboards were found to play a predominant role in rider control. This helps to explain why the performance-driven evolution of high-speed racing skis has moved toward high-torsion stiffness and viscoelastic inlays. The article concludes with an illustration of the effects of a viscoelastic stand-off damper on a ski.

The dynamic responses of skis and snowboards depend on snow conditions (surface irregularities and hardness), rider speeds, the boundary properties between the binding, boot, and rider and the physical ski or board characteristics. The forcing functions are the snow surface irregularities as they contact the ski and travel along the base. They may excite severe vibrations, particularly when a ski or snowboard is placed on its edge as in a high-speed turn on hard snow. In such a turn, the significant range of vibration appears to be 20-200 Hz, with emphasis on transverse modes such as torsion. As with tennis rackets, baseball bats and bicycles, the presence and actions of the user affect the frequencies, amplitudes and damping, rendering conventional laboratory fixturing and suspensions rather academic.

A fall by a skier or snowboarder usually results from a loss of control of skis or board. Control is jeopardized when vibrations reduce the effectiveness of edge contact with the snow – when the ski or board no longer follows the anticipated path or arc. This often takes place when the rider goes too fast or hits a rough or icy patch of snow. In this manner, the dynamic behaviors of skis and snowboards excited by snow surface conditions impose a "speed limit." Exceeding that limit may result in unexpected responses, making control difficult. But each skier and ski (boarder and snowboard) defines his own personal speed limit that depends on the equipment, snow conditions and skill level.

Ski and snowboard vibration is a much lower hazard on soft snow, which provides smaller excitation forces and substantial damping. For the casual recreational user who avoids the speed limit, vibration and damping may not be an important issue. In fact, some enthusiasts claim that gliding on soft snow is enhanced by 'lively' or vibratory skis and that over-damped skis and snowboards feel dead and heavy.

On the other hand, skis used in high-speed competitive events (like the Downhill or Super G) are long and substantial with a laminate metal/fiberglass/wood construction that yields high torsion stiffness. They are chosen primarily for good glide and stability at high speeds on hard snow. Their stability or quietness is due to long length, high mass and stiffness and high damping (particularly in the 90-120 Hz frequency range).

Today's recreational skiers have indicated a preference for shorter skis with more shape (sidecut) to the edge. This combination permits turning with significantly less effort, shortening the learning cycle and contributing to the popularity of the sport. However, short skis and snowboards tend to be less stable than long ones. If the greater agility of shorter skis must be combined with stable performance on icy snow at high speed, then more damping is required. How to achieve this damping without adding weight and bending stiffness is an important challenge for manufacturers.

Figure 1. Preparing the recorder.

Figure 2. Ski testing.

Early Measuring Attempts in the Laboratory

Gliding and vibration studies have been carried out by private ski companies but with results largely unpublished. Downhill racing skis have received particular attention by manufacturers such as Atomic, Fischer, K2, and Rossignol.

An early laboratory test of ski vibration still exists as an ISO Standard (ISO Document No. 6267). It clamps a ski as a cantilever beam and measures the logarithmic decay of the first bending mode. Results are difficult to reproduce (due to clamping variations) and seem to have little relevance to on-snow behavior. Soft suspended laboratory test setups (using rubber bands or surgical tubing) are easier to reproduce but the results still have relevance

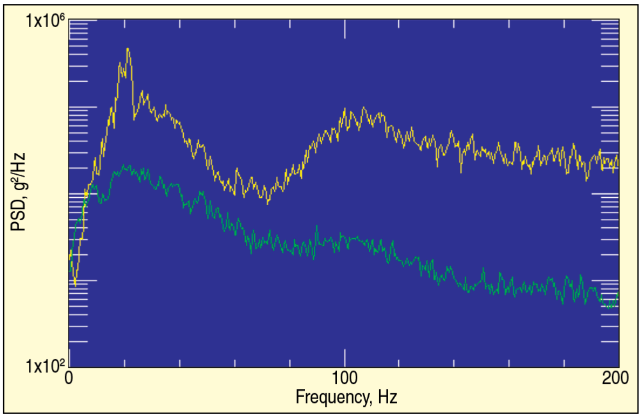


Figure 3. Vibration spectra on hard and soft snow.

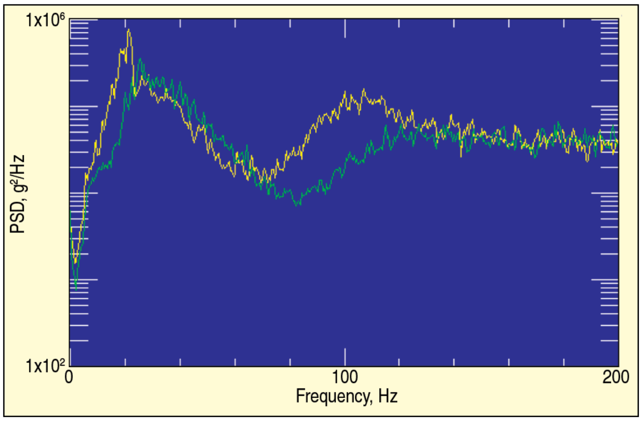


Figure 4. Vibration spectra of different ski constructions.

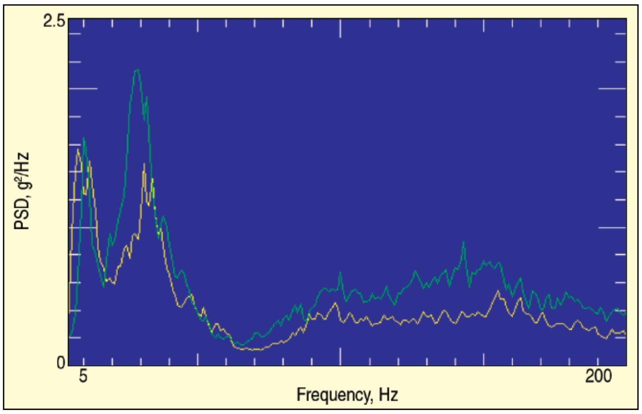


Figure 5. Vibration spectra from front and rear of snowboard.

problems.[1]

In 1972, Pizialli and Mote[2] clamped the middle of a ski to a laboratory shaker and recorded five aft-body bending modes below 100 Hz (9.7, 13.5, 39.7, 54.0 and 76.4 Hz). In such laboratory tests, the bending modes of fiberglass skis typically show higher material damping than those of metal/fiberglass skis. This contrasts with frequent on-snow reports in which racers and experienced skiers deem laminated metal/fiberglass/wood skis to be quieter and more stable than fiberglass/wood skis at high speed. This paradox made the authors turn to a real ski hill to map actual operating modes of skis and snowboards.

On-Snow Vibration Studies

Gardiner, Glenne and Mason[3] instrumented a ski forebody with 12 strain gages and found a significant torsion mode of 85 Hz and a side-flex mode of 53-55 Hz when skiing on hard snow. Pizalli and Mote[4] also went skiing with strain gages and found dominant bending frequencies of 16-24 Hz but were limited to measuring frequencies below 80 Hz. Davignon[5] attached accelerometers at a ski's tip and tail and found them to vibrate separately, with tail vibrations considerably smaller than tip ones.

Measured performance is consistent with the usual reports from ski racers that laminated metal/glass skis are more stable and quiet than regular fiberglass skis.

In 1995, the authors began a series of on-snow measurements using two or more accelerometers mounted in the shovel (the curved front end) of different skis and snowboards. By adding and subtracting responses from each edge, we isolated bending and torsion characteristics. Early results were published in 1999.[6] Figures 1 and 2 show skis instrumented with accelerometers being tested at Mt. Hood, Oregon. Note the small DAT recorder (Figure 1) carried by the skier to record data.

Figures 3 through 5 depict some important field observations. Figure 3 contrasts acceleration power spectral densities for a ski (K2 SLC) traveling on soft (green trace) and hard (yellow trace) snow. Both spectra peak at around 20 Hz, which appears to be the main bending mode excited in the ski forebody. The peaks are quite rounded, probably due to shifting natural frequencies as the ski sees changing boundary conditions against the snow. In particular, the responses on hard snow are about one order of magnitude higher than those from soft snow, and the torsion mode around 90-120 Hz is virtually absent on soft snow.

Figure 4 shows acceleration power spectral densities recorded during a series of turns for a fiberglass/wood ski (yellow trace, K2 SLC, 204 cm long) and a laminated metal/fiberglass/wood ski (green trace, K2 GS Race, 204 cm long). The main difference exists from 70 to 120 Hz, where the accelerations of the laminated metal/glass/wood ski are considerably smaller. This frequency range consisted mainly of torsion and mixed bending/torsion modes. The K2 GS Race ski is considerably stiffer in torsion than the K2 SLC – this important property raises the basic torsion mode and couples it with the fourth bending mode at around 100 Hz. Figures 3 and 4 seem to say that for skis:

- The dominant bending vibration of the ski forebody on snow is around 20 Hz.
- Vibrations are greatly amplified by hard snow conditions.
- On hard snow, torsion and mixed vibration in the range 70-120 Hz becomes critical to performance.

Figure 5 compares the acceleration power spectral density of the fore (green) and aft (yellow) ends of a snowboard (K2 El Dorado, 158 cm long). The dominant bending frequency is around 10 Hz. However, the bending accelerations are overshadowed by torsion and mixed torsion/bending behavior between 20 and 40 Hz. In general, these field measurements convinced the authors that a laboratory setup to test skis and snowboards must include the boot and binding and the inertia of a user to yield the dominant bending and torsion modes observed on snow.

Laboratory Tests

Today, the manufacturing of skis and snowboards involves considerable trial and error. Much of the trial occurs on the mountain, where prototypes are evaluated. While the evaluators are expert skiers, their judgments may be vague and inconsistent. A more efficient method of prescreening the prototypes would be an objective laboratory test that would reveal characteristics by assigning simple figures of merit. The value of this laboratory test would depend on how closely the figure of merit conformed to the consensus opinions of the experts on the hill.

With this goal in mind, the authors devised a number of laboratory tests. Most of the laboratory tests had the ski mounted to a binding attached to a boot. The boot was buckled to a dummy rubber foot, which was then attached to a rigid fixture.

Early tests focused on bending mode damping and its nonlinear relationship to amplitude. When the authors became convinced from the field testing that the torsion mode was the key to ski performance, a test was devised where a random force was applied to the ski under the boot, and frequency response functions (FRFs) were measured between there and a matrix of accelerometers mounted

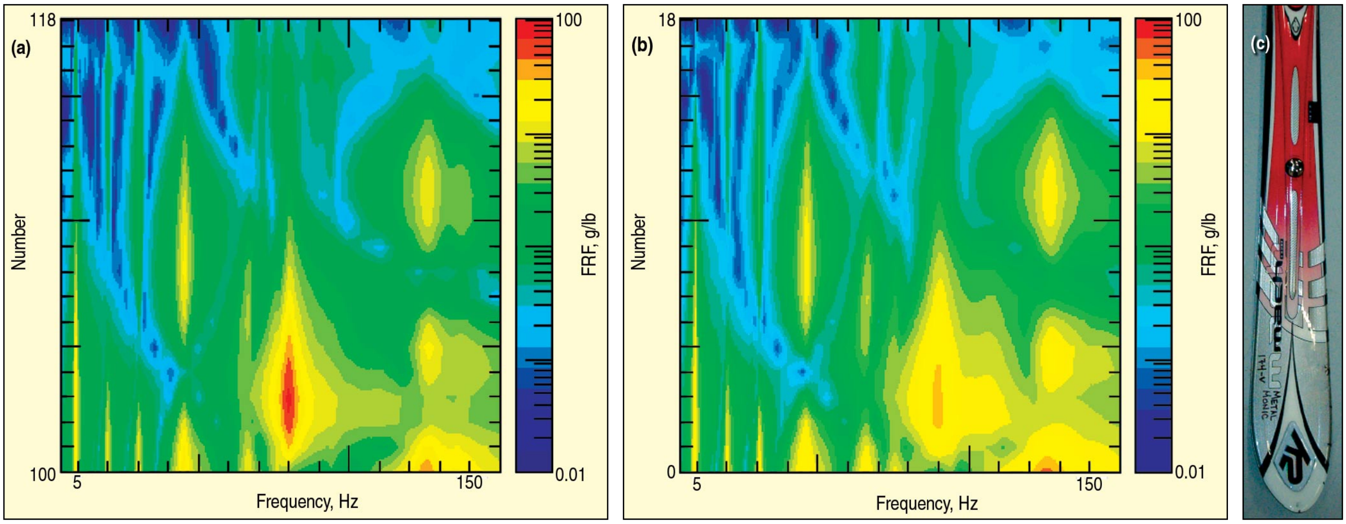
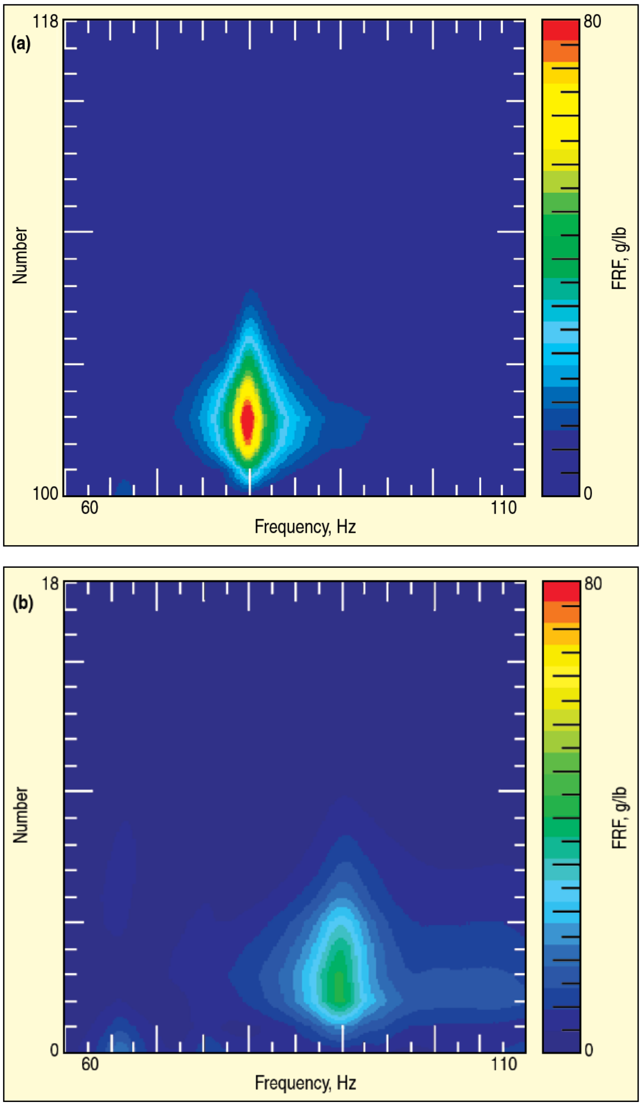


Figure 6. Accelerance maps comparing different ski constructions. Ordinary ski is on left; a racing ski containing aluminum on right. Photo of ski on far right shows location of measurement along Y axis.



Figures 7. Comparison of ski constructions highlighting difference in torsion mode response around 80-90 Hz with linear color scale.

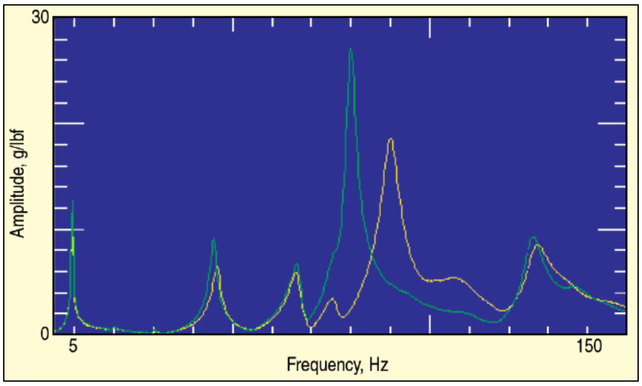


Figure 8. Comparison of different ski constructions. Driving-point FRFs at the forward contact point.

near the shovel on both ski edges. In this laboratory setup, the total force applied to the ski also included a compressive static preload to account for the weight of the skier. The FRFs were summed together, and the area under the magnitude curve was integrated over a frequency range that included the torsion mode. This figure of merit correlated reasonably well with the opinions of the ski testers and was used for a number of years. A similar technique has been used to compare golf clubs.[7] Modal analysis was also performed on skis and snowboards using a boot/binding attachment and as many as 32 accelerometers. In this manner, vibration modes could be identified under relatively realistic boundary conditions.

More recently, a compliance map technique was used to give a more panoramic comparison of ski and snowboard dynamic properties.[6] This technique combines frequency response spectra with a physical dimension to show the spatial distribution of structural dynamics characteristics. Color spectrogram plots normally use color to indicate vibration amplitude, where the X dimension is frequency and the Y dimension is time. The compliance map technique replaces time with distance. In the case of a ski, frequency response functions are measured at a series of points along one edge of the ski. The Y axis scale then becomes a position along the edge. The color shows how dynamically active or inert each location is at each frequency. The spectral amplitude can be scaled for displacement, velocity or acceleration. For logarithmic displacement scaling, the colors represent compliance in one direction and its reciprocal, dynamic stiffness in the other. For logarithmic acceleration scaling, the colors represent accelerance in one direction and its reciprocal, dynamic mass, in the other. For the maps here, acceleration scaling was chosen to best enhance the appearance at the most important frequencies. The units of the color scale are in g of acceleration response per lb of input force.

Racing skis have been found to perform better under high-speed conditions if they have thin layers of high-strength aluminum in the lay-up. Figure 6 shows accelerance maps comparing the forebodies of a consumer ski made with layers of wood and fiberglass (Figure 6a) with a laminated racing ski containing wood, fiberglass and aluminum (Figure 6b). The skis were attached to the cantilever boot through a binding. Drive point FRFs were obtained with an instrumented hammer measured along the edge of the ski

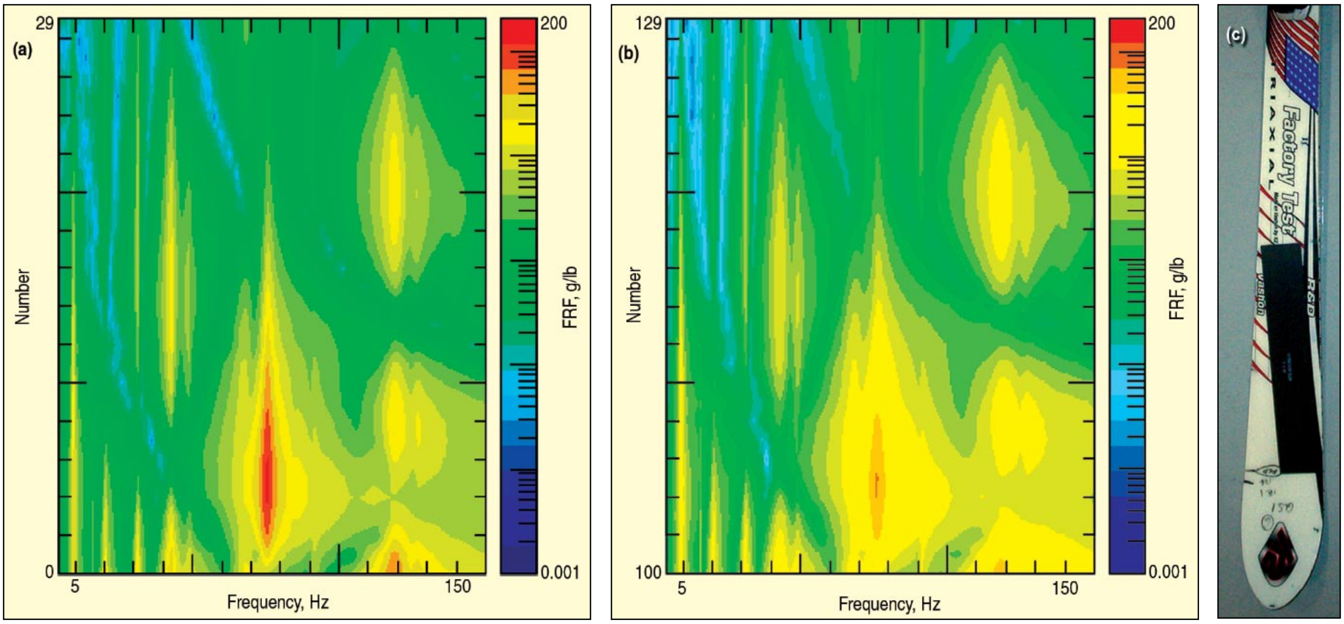


Figure 9. Accelerance maps of fiberglass/wood ski before and after installation of a DTI viscoelastic standoff damper. Ski with applied damper is on right.

from the boot binding to the ski tip. A photo of one of the skis, Figure 6c, is shown at the right, oriented with the Y axis of the color map, representing position along the ski edge. The red areas are dynamically active (high accelerance) and the blue areas are dynamically inert.

At first glance, the two color maps appear similar. The modes are identified by regions of maximum accelerance (yellow and red) that line up vertically at a specific frequency along the X axis. The mode shapes are identified by counting the nodes (blue or green) along the same vertical line. The primary difference between Figures 6 and 7 is the torsion mode at about 75 Hz. The consumer ski on the left is much more active at the torsion mode in the shovel (more red area) than is the racing ski on the right.

In general, compliance and accelerance maps with logarithmic color scaling are best for a broad overview of the spatial distribution of dynamic behavior. However, logarithmic scaling may conceal important distinctions. In this case, the response at the torsion mode is known to be important at high speeds. Figure 7 shows the same accelerance map comparisons as in Figure 6, but with linear color scaling and zoomed in on the torsion mode area. The difference between dynamic behaviors of the two skis is much more evident. These data are consistent with the usual reports from ski racers that laminated metal/glass skis (Figure 6b) are more stable and quiet than regular fiberglass skis (Figure 6a). Note again that while racers prefer the behavior illustrated in Figure 6b, recreational skiers may not push their speed limit and may actually prefer the light and livelier behavior of the fiberglass ski on the left.

Figure 8 shows the individual FRFs for these two skis at the location of maximum torsional response (horizontal sections through Figures 6a and 6b). Clearly, the main difference between the two skis in Figure 8 lies in the torsion and mixed-mode range of 75-120 Hz.

Damping

More damping in a ski or snowboard fundamentally means lower dynamic response to the impulsive forces from the uneven hill surface. Up to a point, this improves the control and handling of the ski and raises the "speed limit." The authors have evaluated a number of methods used by different vendors to add damping to a ski. Some vendor claims are based on modal analysis test-

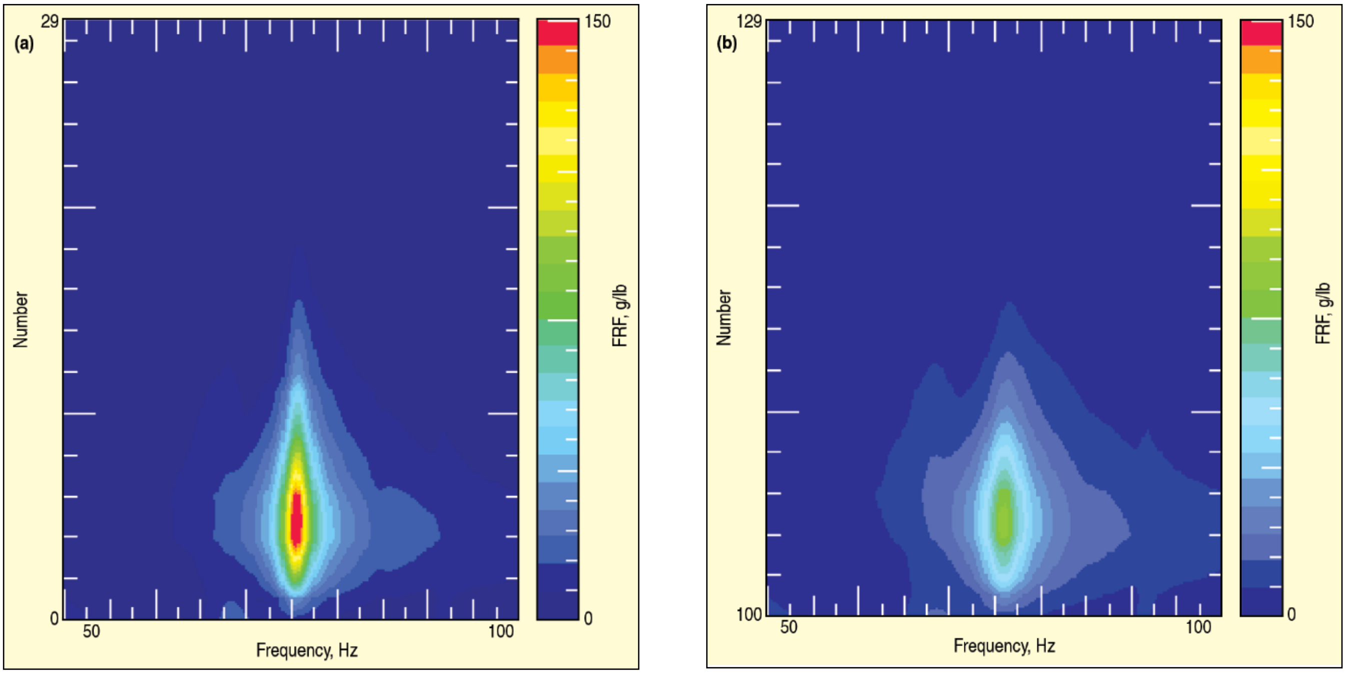


Figure 10. Focus on torsion mode from Figures 9a and 9b.

ing with idealized (free-free) boundary conditions. The damping measured during such tests is usually around 0.5%. However, in the real world, boots, bindings and suspensions usually bring a ski's baseline damping to 3% to 5%. Therefore, a 30% increase in free-free ski damping (say from 0.50% to 0.65% of critical damping) may not be very noticeable on the snow.

The most effective damping device the authors have tested is the viscoelastic standoff damper sold by Damping Technologies Inc. (DTI), Mishawaka, IN. This self-adhering lightweight damper consists of a stiff graphite panel stuck to an array of standoff spacers with a gummy material. The device is used extensively by the aerospace industry for making aircraft cabins quieter and reducing instability of thin panels exposed to airflow. The following data demonstrate how it modifies the dynamic behavior of a ski.

Figure 9a is the accelerance map of the forebody of a wood/fiberglass consumer ski, 174 cm long. Figure 9b is the same ski with a patch of DTI damper applied near the shovel. Figure 9c is a photo of the ski, approximately aligned with the measurement positions on the map. Note that the patch was applied at a slight angle to be more closely oriented with the direction of maximum torsional strain. The maps are mostly identical, except that the amplitude of torsional accelerance has been reduced by half.

Figures 10a and 10b better illustrate the torsion mode area, showing a linear color scale and close-up of the torsion mode. Figure 11 shows the superposition of the driving-point FRFs at the same point on the ski near the location of maximum torsional response. This damping device reduced the torsional accelerance by approximately 50%.

Conclusions

The dynamic property most responsible for adverse ski behavior at high speeds on hard snow is a highly active torsion mode. Higher torsional vibration of a ski forebody directly affects edge control and stability, particularly during turns. Bending modes can also affect performance, but to a lesser degree. Two approaches have been shown that diminish the torsional response. The addition of layers of high-strength aluminum to the ski layup raises the torsional stiffness and lowers the dynamic accelerance. The addition of a viscoelastic standoff damper appears to achieve the same result. This study was the result of a cooperative testing project between Boeing Technology Services, Seattle, and K2 Corporation, Vashon, WA.

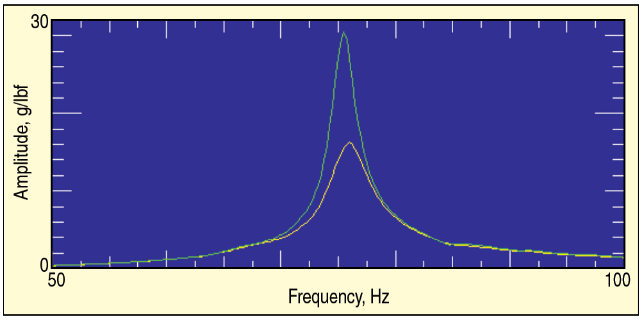


Figure 11. FRFs from location of highest response in Figures 10a and 10b.

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