Development of a Camber Measurement System for Skis and Snowboards

by

Timothy F. Pier

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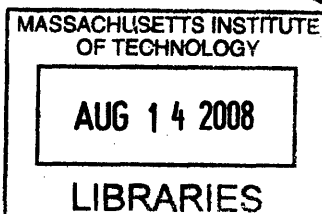Department of Mechanical Engineering

Certified by:_____
Dr. Kim B. Blair
Affiliate – Sports Innovation at MIT
Thesis Supervisor

Accepted by:_____
John H. Lienhard V
Professor of Mechanical Engineering
Chairman, Undergraduate Thesis Committee

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Abstract

At the request of K2 Sports, in Seattle, Washington, a machine was constructed to measure the base profile of skis and snowboards. The measurements to be taken included overall length, running surface length, locations of the contact points, tip and tail height, and maximum camber height, each of these values having a strong effect on the performance of the ski or snowboard.

Parts from two existing non-functioning machines, one acquired in K2 Sports' acquisition of Line Skis, and the other constructed by previous interns, were used to construct the new machine.

The new machine was designed to function by placing the ski on two parallel flat surfaces on the Line machine's frame with a gap between for a laser sensor. The guide rail and cart system from the past interns' machine was retrofitted with the motor and controls of the Line machine and a new drive belt to carry the sensor along the length of the ski. A Micro Epsilon optoNCDT 1401-200 laser sensor having a resolution of 100 μm and a data acquisition rate of 1kHz was used to acquire the height data as the sensor moved at a controlled speed along the entire length of the ski. Data was recorded using Micro Epsilon's ild1401 Tool software, and processed automatically through a National Instruments LabVIEW Virtual Instrument.

The machine was presented to K2 engineers on August 15, 2007. It accurately records the desired measurements which are helpful in predicting the performance effects of design changes to the ski or snowboard. The machine remains in daily use.

Thesis Supervisor: Dr. Kim B. Blair
Title: Affiliate – Sports Innovation at MIT

Development of a Camber Measurement System for Skis and Snowboards

Introduction

During the summer of 2007, an internship was held at K2 Sports on Vashon Island, Washington with the primary goal of developing a new machine to measure the camber profile of all types of skis and snowboards. The camber profile of a ski is the shape of the bottom of the ski measured vertically, and this shape is very important in the performance of the ski or snowboard for many reasons. Construction of such a machine had been attempted previously, and K2 had acquired a machine with this capability in purchasing the ski company Line, but both were nonfunctional, and data on camber profiles is integral to K2's design and manufacturing processes. Although the constructed machine is used to measure more than only the camber profile, it is commonly referred to as the Camber Machine in the laboratory, so this name will be used hereafter in referring to the new machine.
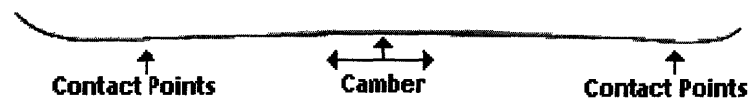

Figure 1: Camber profile of a ski. (www.abc-of-skiing.com)

Importance of Measurements

The Camber Machine was designed and built to determine values for many points of interest in the camber profile of skis and snowboards. Much of the reason for the development of such a machine was the need to learn how this shape affects the performance of the ski in different conditions. It was intended that the machine be used to measure prototype skis that could then be taken to an on-snow test to be tested and reviewed by expert skiers.

Participating in two weeks of such testing allowed the developer to understand exactly what is to be learned from this application of the machine as well as what aspects of the camber profile are most important to K2. While there exist some aspects of camber shape that are not fully understood, general knowledge exists on the effects of these points.

Skis are made with normal camber, where the unweighted ski rises up underfoot between contact points at the tip and tail, or with reverse camber or rocker, where some or all of the ski bends upwards away from the foot to allow the ski to float in soft snow conditions. In addition, the tip and tail heights are relevant in the ability or a ski or snowboard to avoid burrowing under the snow, and the length of the ski or snowboard plays a major factor in turnability. The known effects of these ski dimensions to be measured by the new machine are far more than summarized above, and they are outlined in the following sections.

Length of Ski

The first of these points of interest is not so much involved in the camber of the ski as it is in the overall dimension. The length of the ski was measured by the machine primarily for quality control as well as for assessment of relationship between the printed length and the physical dimension, as these vary quite frequently. Measuring the length of a ski is frequently done, so this step was taken out of the assessment process.

The length of a ski has an extremely strong effect on the performance of the ski. A longer ski will have a much higher stability while traveling at high speeds, and it can help the skier to feel more comfortable skiing in variable or soft snow conditions. In contrast, a shorter ski is known to turn more easily and is often far lighter. Short skis are easier for beginning skiers, and the reduced moment of inertia in a shorter ski allow it to move more quickly from turn to turn as well as spin more rapidly for ski jumping. Typically, the length of ski needed by a

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specific user is determined by three things. The first of these is the skiers height and weight, as a tall or heavier skier will need a longer ski. The second of these is the user's ability level, again because a more advanced skier can handle a longer ski. Finally, a skier chooses his or her appropriate ski length by the intended use of the ski. A longer ski is suited for very fast skiing or very aggressive skiing, but a shorter ski will perform better for many mogul skiers or for quicker turns.

Running Surface Length

Similar to the overall length of the ski, the running surface length of a ski is the length of the ski between the tip and the tail where the ski is actually weighted in contact with the snow. To the skier, this is the effective length controlling most relevant aspects of performance described above, with the exception of the ability to glide on top of soft snow—where the tip length comes into play—and the moment of inertia of the ski. Additionally, if a large length of the ski exists that is not typically in contact with the snow, this heavy mass will increase the negative effects of vibration. In the most modern slalom race skis made by the Austrian company, Fischer, there exists a large hole in the tip of the ski forward of the contact point in order to reduce this hanging mass.

Some skis are designed to have a fairly short running surface length over a longer overall ski length to create a long, buoyant tip for lifting the ski to the surface of soft snow. This design is known as rocker and is very popular in K2's product line. When this is taken to the extreme, with one contact point underfoot and the ski bending upwards towards the tip and tail, it is known as reverse camber. Reverse camber skis perform exclusively in deep soft snow conditions, but many users feel the shape reduces the effort needed for turning in these conditions by lifting the tip and tail above the level of the snow.

Tip and Tail Heights

It is important to have a tip of sufficient height to lift the front of the ski over varying terrain. It can also be important to have the tip of the ski higher than the surface of the snow in soft snow conditions to prevent snow from deflecting upwards from the tip of the ski into the skier. On the contrary, there are two factors limiting the tip height in skis. The first is that the weight of the tip affects the performance of the ski. A heavy tip will contribute to the effects of vibration as well as create a moment lifting up on the running surface of the ski, causing the ski to feel as though it is grabbing at the snow. Also, in some racing situations at high speeds, a low profile tip can reduce the drag caused by the air behind the tip as well as the lift created by air going under the tip of the ski.

The tail of the ski has many similar affects on the performance to the tip in some skis due to the frequency with which modern skiers choose to ski backwards, or switch. The height of the tail is very important in this situation because the skier cannot always see the approaching terrain. Skier confidence is also especially important in this situation. This height is also relevant when landing switch, specifically in soft snow. Because most ski bindings are mounted towards the tail end of the ski, it is very easy for the tail of the ski to dig into the snow, causing a very dangerous fall situation. The weight of the tail can be an issue for performance, and a high tail can kick snow up into other skiers when skiing at high speeds, but it is increasingly popular amongst ski companies to offer a wide range of so-called twin tipped skis.

Figure 2: Side view of K2 Dawn Patrol showing camber profile.

Camber Height

Obtaining the maximum camber height underfoot was very important to K2. This height has a strong effect in performance, and it has become evident little is known about the effect that varying the camber height can have on the skier's feel for a ski. Camber is necessary in many situations to keep the ski in contact with the snow over varying terrain, and can preload the ski to increase the power in transition between turns, but ski camber can have some negative effects on a skier's comfort as well.

Because the tip and tail are pressed down by the skier's weight at the center of the ski, where the camber is highest, the ski can feel as though it is grabbing at the snow. A skier can allow the ski to tip only slightly on edge, and because of the sidecut on many modern skis, this can cause the ski to initiate a turn unexpectedly. For this reason, extreme camber profiles, especially in stiffer skis, are reserved for racing skis and technical events such as slalom and giant slalom where the skier is almost constantly in a turn.

Machines on Location

The final machine was created using parts from two machines previously located at K2. One of these machines was acquired from Line Skis when K2 purchased the company, while the other was a failed attempt at creating a similar machine. A third machine, created by a K2 engineer for stiffness measurements was also used as a model for some aspects of measurement.

Line Machine

Upon arrival at the K2 Sports facility, two machines intended for camber profile measurement were on location. Both in disrepair sitting in the testing laboratory, the first of these was a machine formerly owned by Line (a ski company recently purchased by K2 Sports), and is subsequently referred to as the Line machine. It had components for flex testing as well as measuring camber profiles, and it was only for this flex testing that the machine was used at that time.
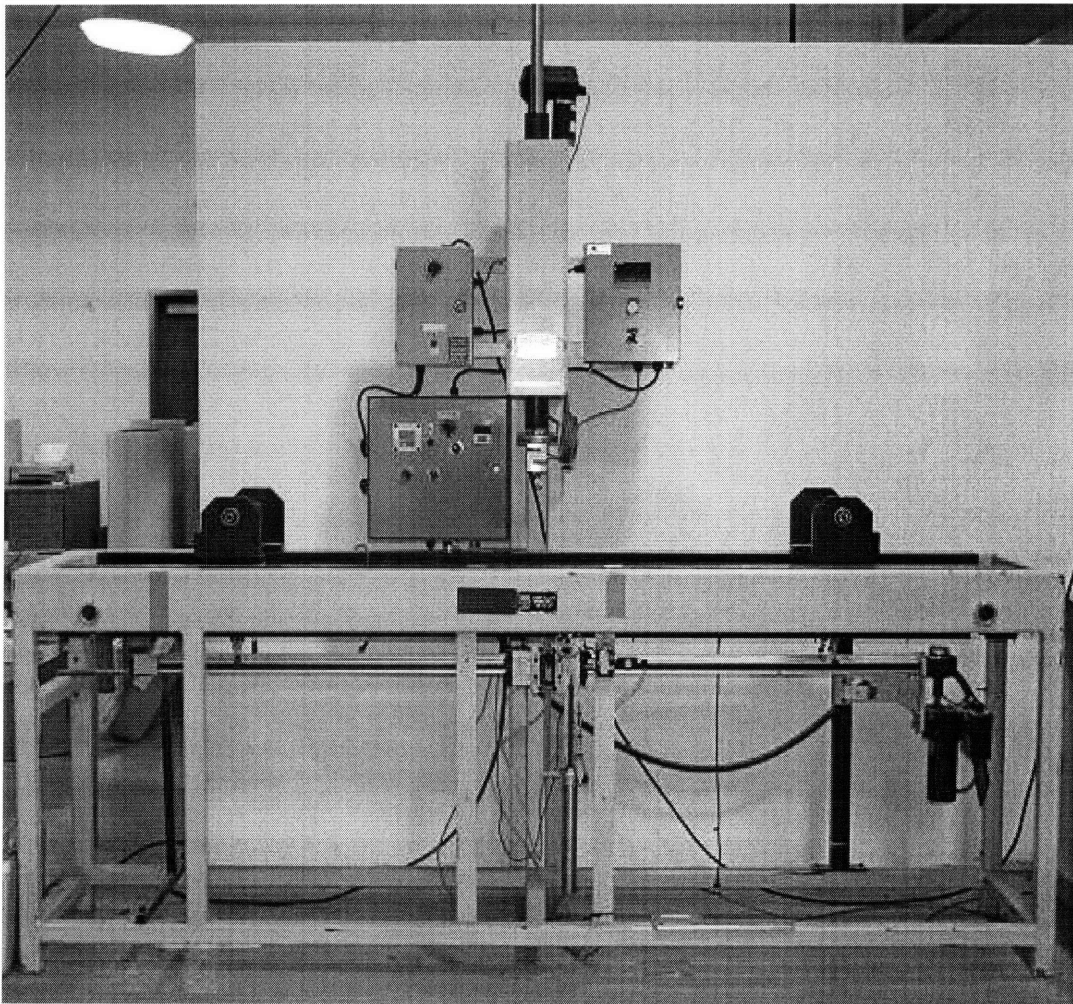

Figure 3: Original Line machine.

For flex testing, the machine was equipped with a variable speed screw-driven loading ram and a load sensor such that the stiffness of skis could be measured. The supports for skis, flex tested by loading at the center fo the running surface (a specification different for each ski), was achieved through horizontal steel bars. These removable bars fit tightly against the plates used for camber-related measurements and support the skis from their contact points at the tip and tail. With the bars removed, the machine was equipped with nine foot long plates that could slide laterally together allowing for the narrow gap for camber measurement in a heavy flat table supporting the ski.

To measure a ski or snowboard's camber, a long piece of extruded aluminum was used to guide a cart down the length of the ski. This small aluminum cart used two sets of opposing vertical bushings to fix itself to the rail and was belt driven. Fixed to the cart was an aluminum plate holding the actual displacement sensor. This linear displacement sensor was made up of a roller that remains in contact with the ski and a counter-weighting system. The counter-weight system consisted of a pulley to allow for a weight to provide an upward force on the roller and an air spring a flip of a switch could provide air pressure on the piston. This created for a constant contact force between the roller and the ski that could be varied based on the amount of pressure applied in the air spring. There was an electrical cable to carry data from this sensor, but its matching hardware counterpart was not locatable

Driving this belt system was a large motor connected to a pulley box on one end of the rail. The output shaft from the motor had a simple power coupling with rubber dampers. Connected to this were the toothed drive pulley and a rotary encoder, in series. This pulley, at sixteen millimeters wide AT5 to match the belt, guided the belt through a machined cover such

that the belt wrapped around one side of the extruded rail and fed through the center. The rotary encoder was at one point capable of outputting the relative angular displacement of the pulley and—assuming no slippage—the belt and relative cart displacements. Additionally, at the base of each of the removable bars (used to support the ski in flex testing as mentioned above) were located proximity sensors that were previously capable of triggering a relay to stop the cart's motion. One of these sensors had a broken cable while the other caused a relay to constantly trip. When disconnected, the cart actuation system returned to functionality.

This actuation system was controlled in a single box, having switches for power and direction as well as a variable speed control. This control box was situated to the left of the overhead flex structure, at a comfortable eye level and contained the majority of the electrical components of the original camber testing system. Included on this control box were controls for power, direction of travel, variable speed, and a single throw button to start the test. Additionally, a switch was present on the outside with no electrical connections as well as a digital display in similar condition. The prior uses for these parts were not discovered. Finally, a single fuse and a digital display for the encoder were present on the control box. The encoder display used units that were unintelligible.
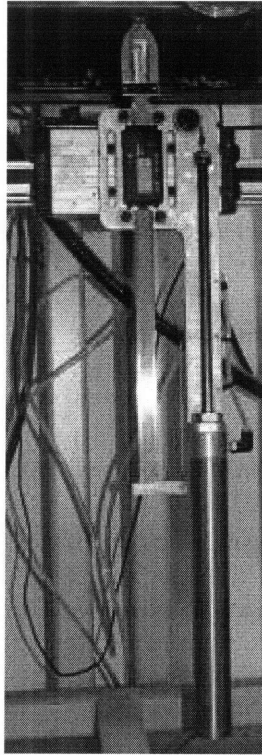
Figure 4: Line machine's contact sensor.

Problems with Line Machine

This line machine came with many serious issues. The focus of this paper is on the camber measurement aspect of the machine's capabilities, so it is in parts related to this purpose that the problems will be identified specifically. It was identified upon first inspection that the contact sensor was not functional in any way. The mass within the air spring had oxidized and was sliding only with too much friction to overcome the friction in the similarly worn pulley. This resulted in a contact sensor that was not able to maintain any upward force on the base of the ski, yet had that been functional other problems would have become evident. The data given from testing contact sensors came with a very   large amount of noise from the structure in the base of the ski as well as from the extended length of the arm allowing for some flexibility. Importantly, the intent of the counterweight design was to create a constant normal

force on the ski for consistency in measurement, but the force was only constant in the upward direction. This results in a varying normal force at sloping portions of the ski such as near the tip, a location of interest for K2 and a place where accuracy of the data is especially important.

Additionally, it was discovered later on during the design process that the aluminum rail along which the cart traveled had noticeable sag. The rail was set up to span nearly the nine foot length of the machine, and with no support in the middle, the weight of the rail alone was enough to make a sag that was recognizable with the naked eye. The maximum camber height underfoot is only a few millimeters in most skis, so a sag of one or two millimeters—this was at least that—will cause for a very severe error. It was also found that the length of the rail severely limited the length of skis that could be measured.

Another problem with the functionality of the Line machine was caused by the inductive cart stop switches. These switches were used to stop the sensor cart when it reached the end of the track. They were fit into welded rings on the support bars, and therefore were only functional when the sensor was used for flex testing. This is interesting because flexing the ski did not come frequently with using the cart, but this can be used to gain an understanding of the machine's past use. It seems probably that camber measurements were taken by Line while the ski was flexed. This flexed ski measurement can be used to plot the curve for EI(x). Unfortunately, the switches were causing problems within the machine. One simply had a broken cable, but the other was causing a relay inside the control box to constantly fire off, giving a rapid clicking noise and preventing any motion in the cart. When this switch was disconnected, the machine returned to functionality.

GSM Machine

The other camber measuring machine present in K2's testing laboratory was referred to as the GSM machine. This machine was the product of former K2 interns who were given an assignment to design and build a machine to measure ski camber profiles. This machine was intended to be hand driven, measuring the camber against a linear encoder to plot out the answers. The machine was never brought into working condition.
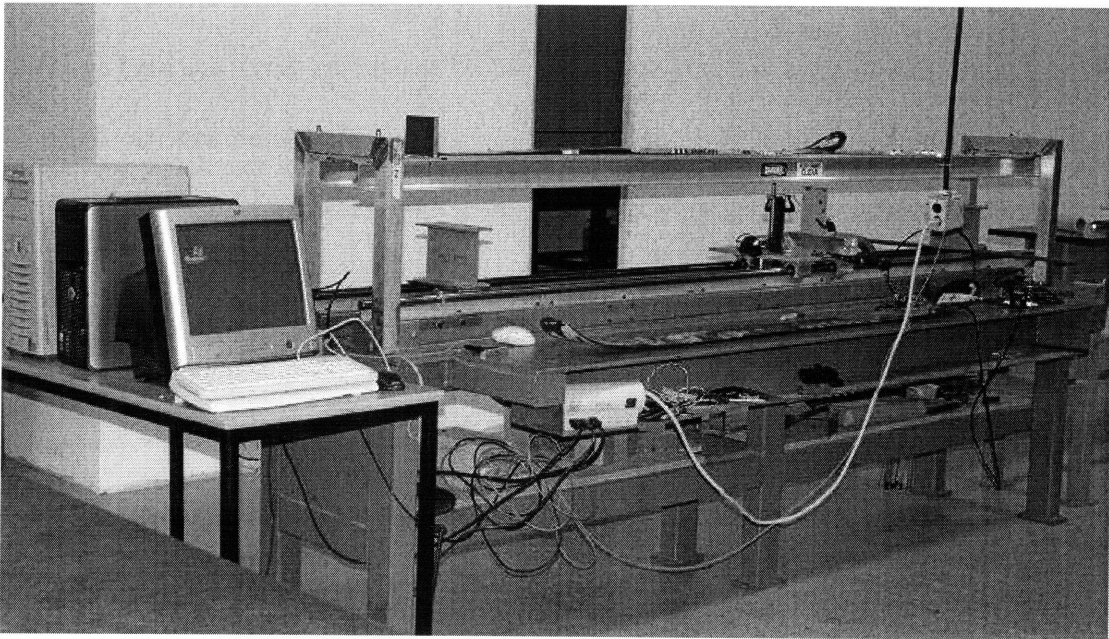
Figure 5: GSM machine.

For the GSM machine, a square aluminum cart was hand driven along 1" steel rods to carry a small contact sensor along the base of the ski. This analog displacement sensor has a continuous voltage output that was intended to be read simultaneously with a linear encoder. A rounded polymer tip was held in contact with the base of the ski by a compression spring. This data was recorded and processed by the test computer using a dedicated data acquisition board and National Instruments LabVIEW.

The table was built from steel, with a very heavy-duty ten-foot rail system using two 1"

steel rods. These rods supported the aluminum cart though four pillow block bearings, and the

cart was designed to be hand driven with the handle of a ski pole bolted to a side. This hand-

driven concept was advantageous in that measurements could be taken more rapidly by such a

method of actuation and the operator could collect more data points at more sensitive locations

such as contact points or the tip of the ski.

Supporting the ski was an aluminum structure, having glass plates as the ski table.

These two plates were used so that the ski could be lined up over the sensor and have a gap

down the middle for measurement. The reason for using glass was undetermined, but one of

the plates had shattered bringing a need for replacement. This table was hanging from the

aluminum structure by three bolts, two at one end spaced by washers to hang down

approximately one inch while on the other side the table rested on a nut that could be adjusted

to level the working surface.

Problems with GSM Machine

Unfortunately, the data generated by the sensor was reported as being very noisy. The

idea of a contact sensor giving analog data to the computer with accuracy in the vicinity of 100

microns could not reasonably be realized. Using the sliding polymer tip with the compression

spring caused the tip to bounce along the structure of the ski giving varied results. Variations

would be difficult to bring to functionality as well because without the option of sliding, a wheel

would require a relatively large force upwards against the ski and the ski cannot be loaded in the

downward direction due to the necessity that the measurement be taken without any flex in the

ski for consistency. It was found that even the compression spring chosen for the current setup

had sufficient force that it could actually lift some of K2's skis up from the table enough to invalidate the measurements.

Schiele Machine

There was a third machine present at K2 upon commencement of the project that was making measurements along the base of the ski. This machine was known as the Schiele Machine. Its intent was to accurately measure the stiffness along the length of the ski, shown as EI(x), and record that data. Though problematic, this machine was functional and in use, and it had some useful aspects that could be included in the design of the Ski Base Meausuring Machine. This machine used a non-contact laser sensor. Being quite old, this sensor had insufficient range to measure skis from one height, so the Schiele machine used a ball screw to raise and lower the sensor in an effort to keep the ski near the center of the sensor range. The height of the ski was the sum of the ball screw movement and the sensor distance.

This machine was frequently used for simple flex tests, and a program had been written so the user could set the ski in place, with bars supporting the ski at the pre-located contact points, and start the machine, which presses the ski in the center and measures the force required for a given displacement. This value of pounds per inch of deflection is displayed and recorded for all test skis and many others used in the design and manufacturing processes. Because this machine was in frequent use for these flex tests, a second machine was needed in order to study the camber profile in a convenient fashion.
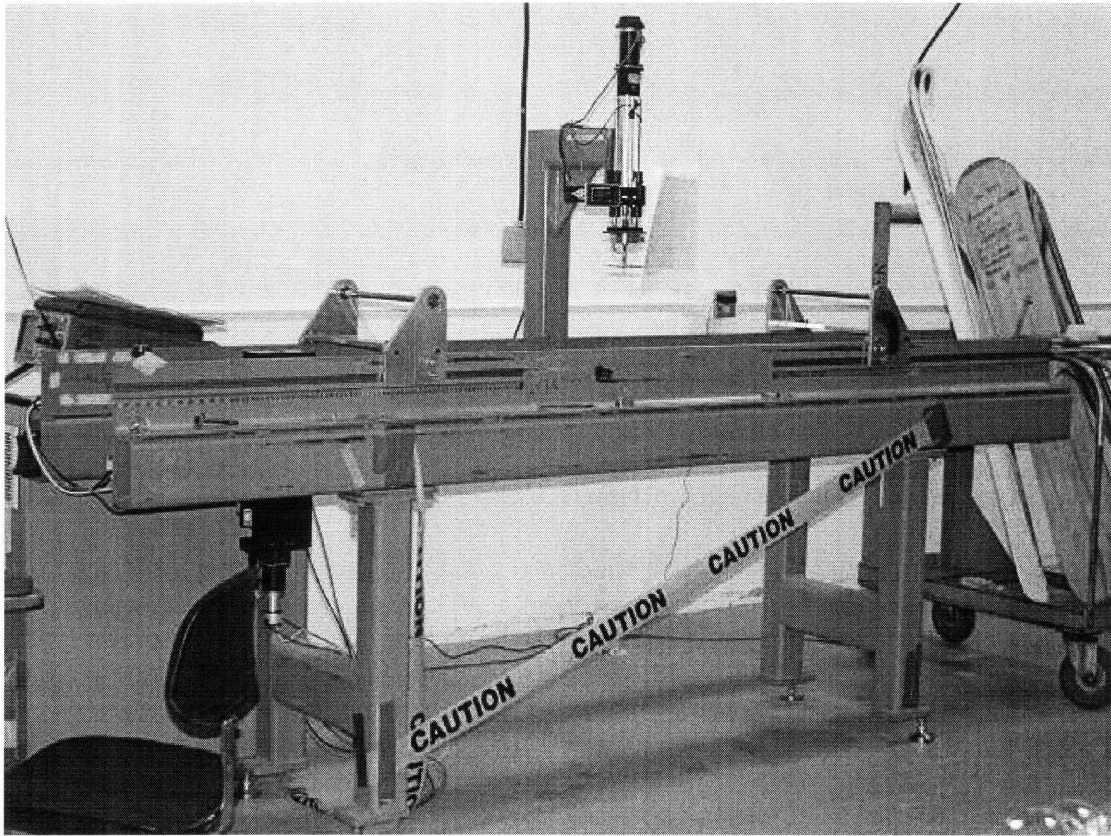
Figure 6: Schiele Machine.

Final Machine Design

The design and construction of the new machine was based strongly on the existing machines. The frame from the Line machine was used with the rail system from the GSM machine. The sensor selection process was also based strongly on experience from the existing Schiele machine. This sensor, used to measure the vertical distance to the base of the ski, was the most critical module in the new machine, and the selection process is described below.

Sensors Types

The primary decision to be made in the design of a camber profile measuring machine is in the selection of the sensor. The sensor selected must be capable of taking rapid data points along the base of a ski with a range greater than one hundred millimeters, and be able to measure past texture, color variations, and varying base materials. It was decided that results must be consistent to within one tenth of a millimeter, and the data output must work such that each point can be paired with its location. In the search for the appropriate type of sensor, several options were considered.

Contact Sensors

The first thing to mention about contact sensors is that they can be very cheap. There was a sensor of this variety on site at K2 upon the commencement of the project, which had previously been thoroughly tested as part of the GSM machine. There are some very positive aspects to a sensor of this type, such as the fact that the graphics on the base of a ski have no effect on the measurement, and the sensing range can be very high, but there are also many issues.

The fact that a contact sensor needs to be touching the ski with a constant force is a challenge from the start. As described in the section describing the Line machine, a constant upwards force is not necessarily a constant normal force. Additionally, as parts age and rust, the results will likely vary due to friction working against any change in sensor tip height. It was determined that a contact sensor could not be used when tests were not able to overcome the noise caused by the sensor tip moving in relation to the ski. The vibrations created were challenging to even out, and the tip was sometimes actually moving the ski. The analog output

on the sensor present on the GSM machine was also causing many problems as the data came with so much noise that the information was indiscernible.
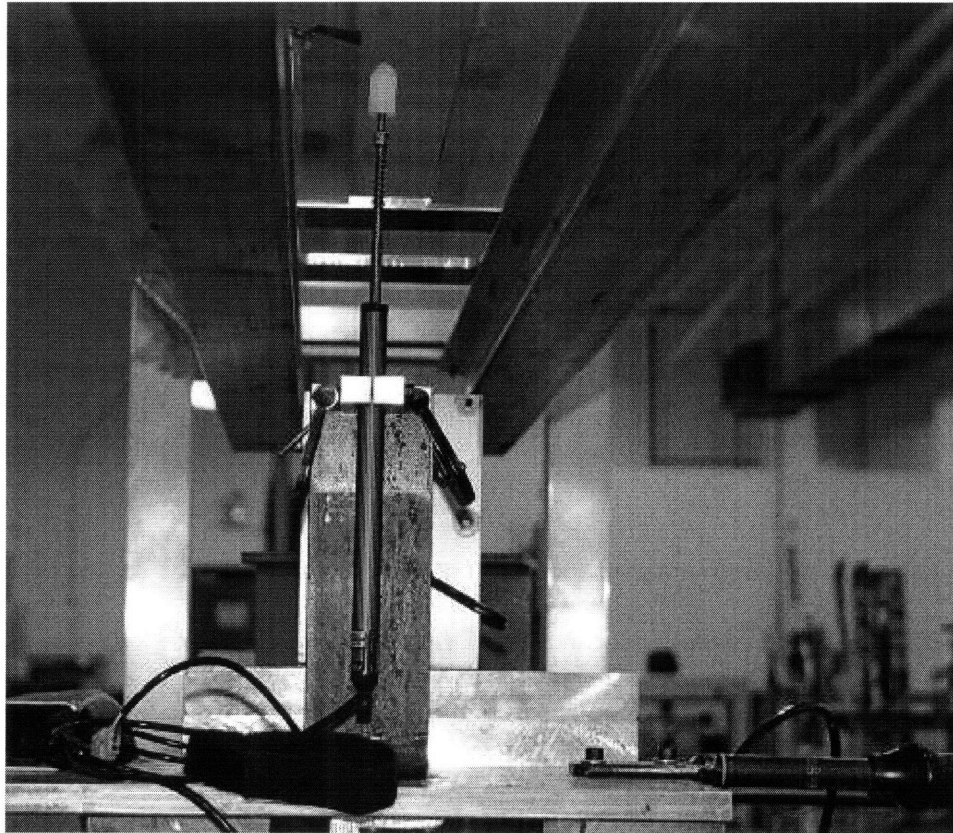
Figure 7: Contact sensor from GSM machine.

Keyence Sensor

Having decided that a contact sensor could not be used for effective camber measurements, laser sensors were investigated. Prior to beginning the thesis project, K2 looked into a non-contact sensor made by the company Keyence. Portrayed as highly accurate and repeatable, it turned out that the engineers on the project were very disappointed by the results. The cost of the sensor was over $5000, yet the performance was well below expectations.

The analog results were very noisy, rendering the high resolution of the sensor quite irrelevant. At the same time, the vibration of the cart was working against the measurement accuracy as well. While this sensor was far too powerful and expensive for the rest of the setup, it had a major flaw in that the laser responded differently to the varying colors in the base of the ski. This was something that was misrepresented by the company spokesperson who presented the Keyence sensor to K2, and something that made the engineers decide that this was not the appropriate choice for this application.

Micro Epsilon Sensor

The final sensor tested was a non contact sensor made by the company Micro Epsilon. This sensor was very similar to the Keyence product in description and application, but cost significantly less. The Micro Epsilon optoNCDT 1401 was quoted at only $2800. Because funding was to be split evenly between budgets for K2 Skis, K2 Snowboards, and the testing department, the aim was for an even $1000 per budget. Similar to the sensor from Keyence, the method of measurement was to project a laser on the surface to be measured and read the angle at which the point of light can be seen. From this angle, the distance to the surface is automatically calculated.

The resolution of the sensor perfectly matched the requirements of the new machine at one hundred micrometers, and the sensing range, from sixty to two hundred sixty millimeters from the sensor was found to be ideal. Data points are taken by this machine at one kilohertz, and they can be output either in an analog format as a varying amperage or digitally in two byte packages. This digital output was found to be extremely accurate, though fairly difficult to use.
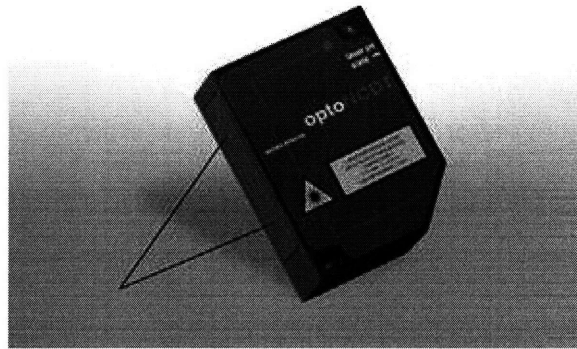
Figure 8: Micro Epsilon optoNCDT 1401-200. (www.micro-epsilon.com)

Micro Epsilon sensors come with their own proprietary software, and it was using this software that the product was tested in a one week trial. A sensor was shipped to K2 by the company, and test data was taken in an effort to evaluate the performance of this product. The software was capable of recording data in a graphical front end, cropping it, and saving it as comma separated values to be edited, processed, or simply reopened and viewed by other users in a spreadsheet format.

Using the Micro Epsilon software and Microsoft Excel, the sensor was tested in measuring an assortment of skis of varying profiles and graphical schemes as well as a machined flat aluminum surface. It was found that the noise created in transition between colors was fairly great, and that the vibrations in the cart carrying the laser, exaggerated by the length of the mounting arm, were sufficiently large to invalidate the data. These problems needed to be addressed in order for this sensor to work suitably, but it seemed as if this was the best selection from a performance standpoint as well as a price standpoint.

Measurement Troubleshooting and Data Filtering

To address the issues caused by color changes, it seemed as though the variations were pure noise, and could simply be averaged out. Many tests were executed on different averaging

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methods, most by printing out raw data and filtered data and holding the results over one another. Eventually it was determined that a one hundred ninety nine point running average was the most suitable for cleaning up the data. As it turned out, this averaging was also able to drastically reduce the problems caused by the vibrations in the motion system, and it was determined to be a great choice for method of filtering. Displayed in Figure 9 is a plot of the unfiltered data set behind the averaged data in a plotted profile of one of K2's products, a ski called the Antipiste.

Unfortunately, the graphics on some skis include transparent bases. In testing the Micro Epsilon sensor on these skis, it became clear that the sensor was taking some if not all of its readings from the first opaque layer of the ski, destroying the accuracy of the measurements. This was a serious problem for which a solution could not be found, but skis of this type are not common, and it was determined that a layer of tape along the base of the ski could be applied in the occasion that such a problem occurred in practice. Contact sensors had far greater problems, and of the available non contact sensors, none were shown to be able to read from a clear surface. Micro Epsilon's sensor was superior in other facets to the point where this issue could be overcome and therefore overlooked as well.
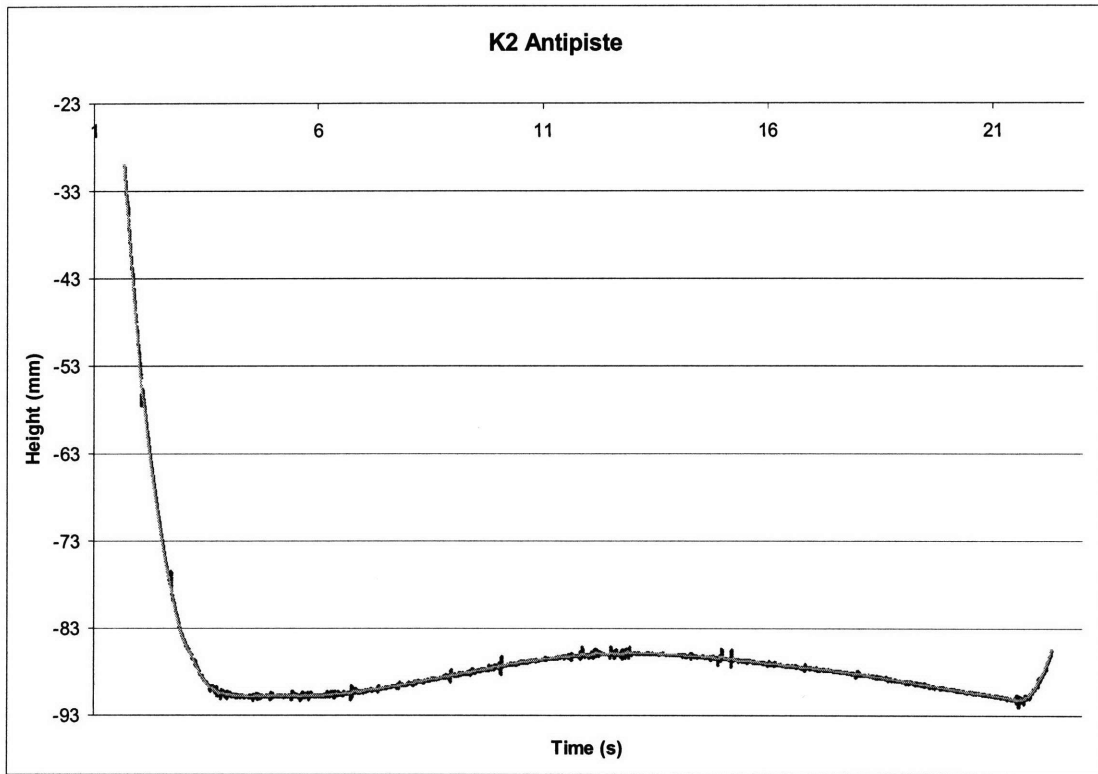
Figure 9: Camber profile of K2 Antipiste. Raw data (black) behind averaged data (grey).

For sensing distances, the Micro Epsilon optoNCDT 1401-200 sensor uses a class 2 semiconductor laser running at less than one milliwatt with a nearly constant two millimeter spot diameter throughout the sensing range. Interestingly, similar Micro Epsilon optoNCDT 1401 sensors having different sensing ranges than the two hundred millimeters of the 1401-200 have lasers that vary in diameter by as much as fourteen hundred ninety micrometers. Similarly to the method used by the Keyence sensor, the laser is shown normal to the face of the sensor, and an offset light receptor is able to read the angle at which the spot on the part to be measured is reflecting towards this receptor. Knowing the offset distance, the distance to the part can easily be calculated. Dimensions and angles for this calculation can be found in the attached datasheet for the Micro Epsilon optoNCDT 1401 line.

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Powering the optoNCDT 1401-200

The direct current power required for the sensor to function is 50 milliamps at 11 – 30 volts. Conveniently, this type of power, 12 volts specifically, is easy to find inside a desktop computer. As the sensor needed a wired connection to the computer for the RS232 output, it was decided that power should also be drawn from the power supply within this machine. The final connection of the sensor's power supply was wired from a spare power supply cord, and a toggle switch was installed in the soft metal cover for a PCI slot, allowing the laser to be powered on and off manually by a simple switch on the computer. This way the cord tangle could be minimized because both sensor cords would plug into nearly the same location on the back of the test computer.

Sensor Mounting Fixture

To mount the sensor to the cart, a fixture was machined such that the sensor could be held at the necessary distance from the ski base to the cart. This fixture was designed upon receipt of the sensor to allow for the measurement of the critical horizontal dimension between the two mounting holes. This dimension was important because the sensor mount was designed to only have a single hole for the top left mounting screw, while on the opposite side, a bolt could be used as a jam to hold the sensor level. This way, for horizontal measurements such as cart speed calibration, the sensor could simply be tipped up to the horizontal direction without the need for separate holes or unscrewing. With only one mounting screw in this "tipped up" orientation, the sensor may have some slip and fail to maintain an identical orientation though multiple measurements, but achieving sufficiently precise horizontal alignment was found to be quite feasible, and the sensor was quite stable over the needed time to take a few repeated measurements.

It was necessary that the sensor's height could be adjusted to allow for flex measurements from the support bars, so the mounting flexure was designed with slots for the bolt heads to allow for this height flexibility. This design was replicated from the contact sensor previously on the Line machine because at the point of fixture design the Line machine's condition was unchanged from the start of the project. The cart at this point in time had slots to allow for T-shaped nuts to be inserted and pivoted to lock in place. This way the sensor was flexible in the horizontal mounting location as well as the vertical mounting location. Also, it was simpler to design the machine with these slots than to determine the exact necessary separation between holes. With the horizontal and vertical slots, the joint could allow for any manufacturing or design errors. . As there was no CAD software available for intern use, the part was drawn by hand and verbally communicated. This part was fabricated by K2's machine shop employees

Time versus Distance for Locating Data Points

It was determined that measurements should be taken in a vertical distance versus time format as opposed to vertical distance versus horizontal distance. This decision was based largely upon the experience of the creators of the GSM machine, who had been unable to align each data point from the displacement sensor with an encoder value. While it should be possible to input encoder data and sensor data to the test computer in a simultaneous manner, this proved to be quite difficult, and as the machine was capable of moving the sensor at a constant repeatable speed, it was determined that simply using the time stamp with each data point, the location of the measurement could be determined using the first data point as the reference point. For the precision of this measurement, it was necessary to measure the

velocity of the cart very accurately, and the process for taking this measurement is described in the section describing the use of the Micro Epsilon sensor.

Speed Calibration Data

$y = 84.273x - 828.38$

Distance (mm) vs Time (s)
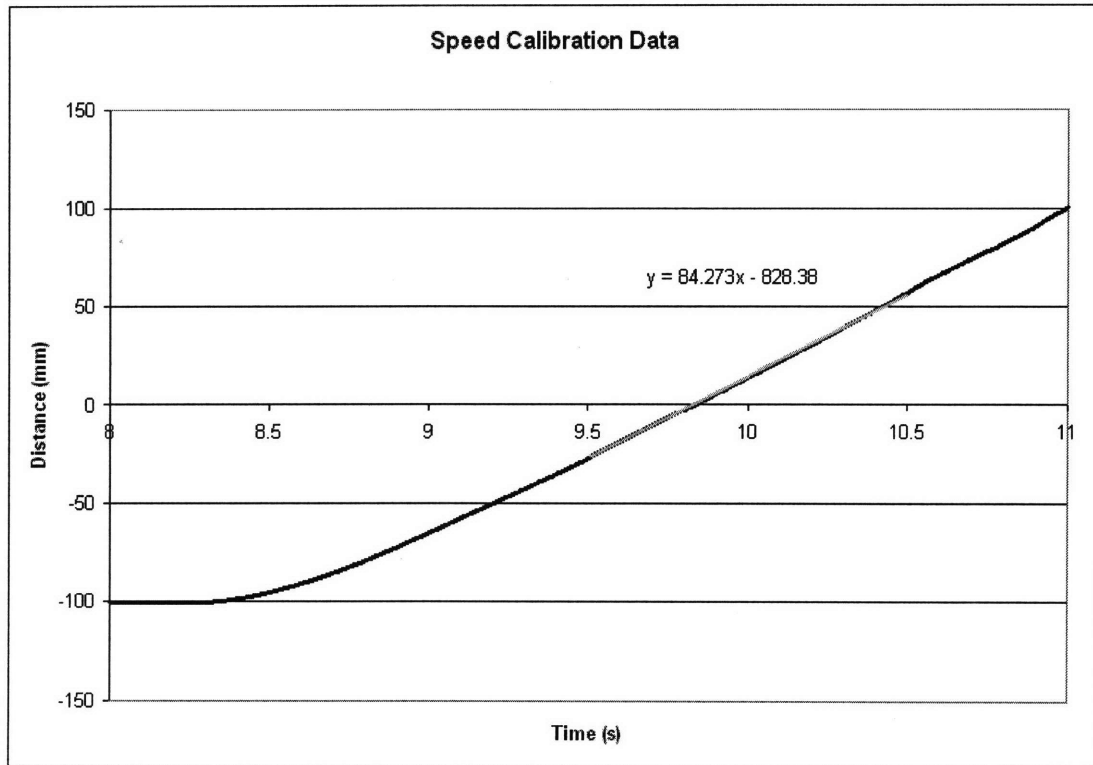
Figure 10: Cart speed calibration data showing acceleration from rest to sustained velocity of 84.273 mm/sec.

Line Control Box

The first of the major changes made to the Line machine were made to the machine's motion control box. As described in the section discussing the Line machine's original state, this control box worked with the drive motor, an encoder and the two inductive sensing switches to control the sensor cart.

For velocity control, there was a switch capable of choosing the direction, a button that functioned to start the cart moving to the operator's left, and a dial for speed control. Drawn on this dial was a small mark to show that speed at which measurements were taken. The goal of

this mark was to improve the repeatability of camber measurements, but it was decided that this could be done more effectively with a switch to move from the dial's control to a preset measuring speed. This was achieved first by determining a functional speed using the dial, and then measuring the voltage drops across the dial. The relative resistances were determined, and an altered switch was installed to switch from "off" to "variable speed" and "constant speed". This switch was put in the location of the former power switch, so it did little to infringe on the appearance of the machine while strongly affecting the functionality.

Upon completion, the control box maintained most of its former functionality while becoming slightly more useful for measuring camber profiles in skis and snowboards. The directional switch remained as it was, with the need to have it in the upright direction for the start button to function appropriately. The switch for constant speed, on/off and variable speed was labeled for each, and the variable speed dial was kept functional and in the same state as before. The only negative change to the box was that the encoder display no longer functioned, but the prior display format was meaningless to the operator, so little was lost. Additionally, a switch and a display were left in the prior disconnected state to allow for former functions of the machine to be redeveloped in the future.
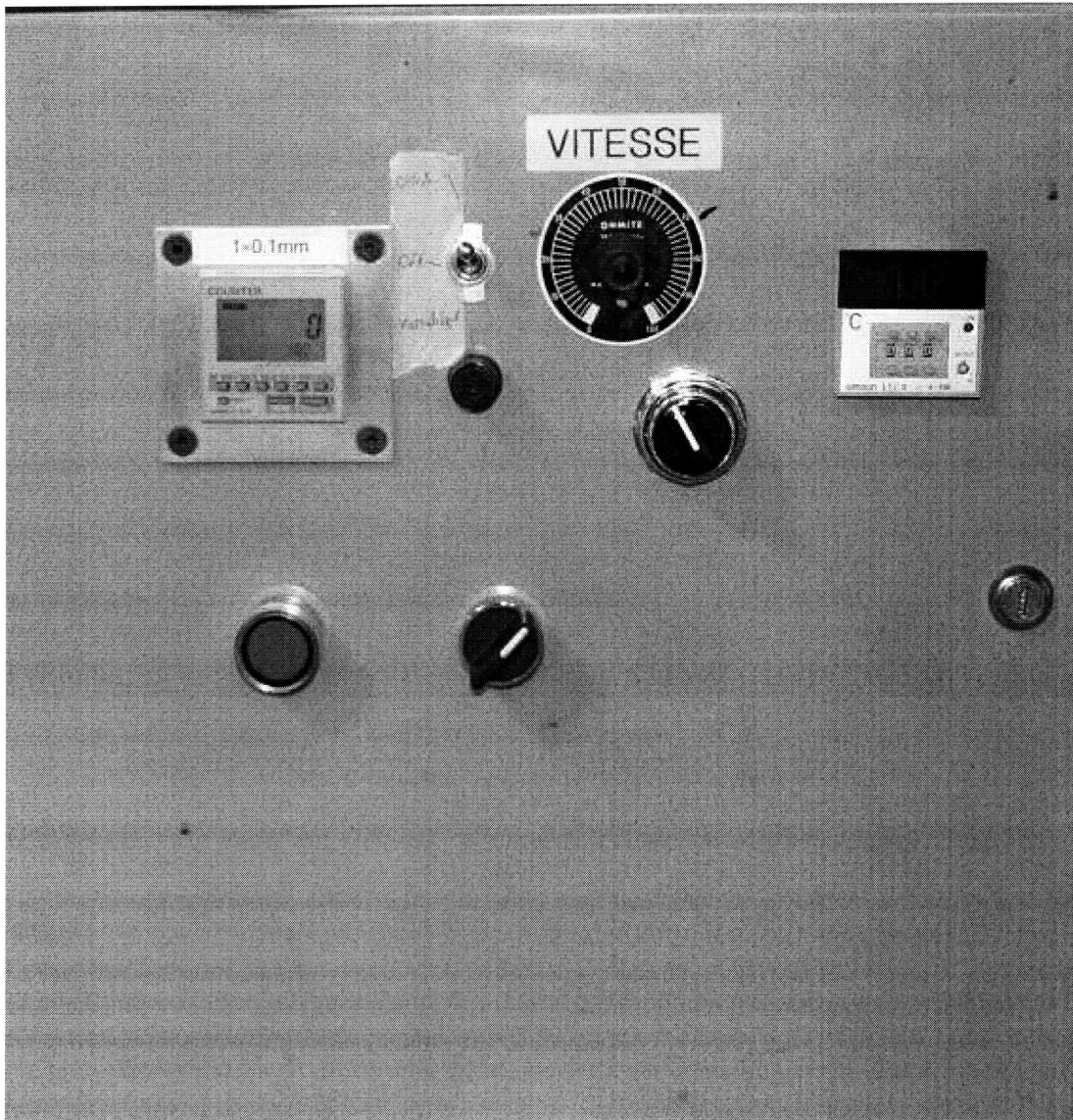
Figure 11: Line machine control box.
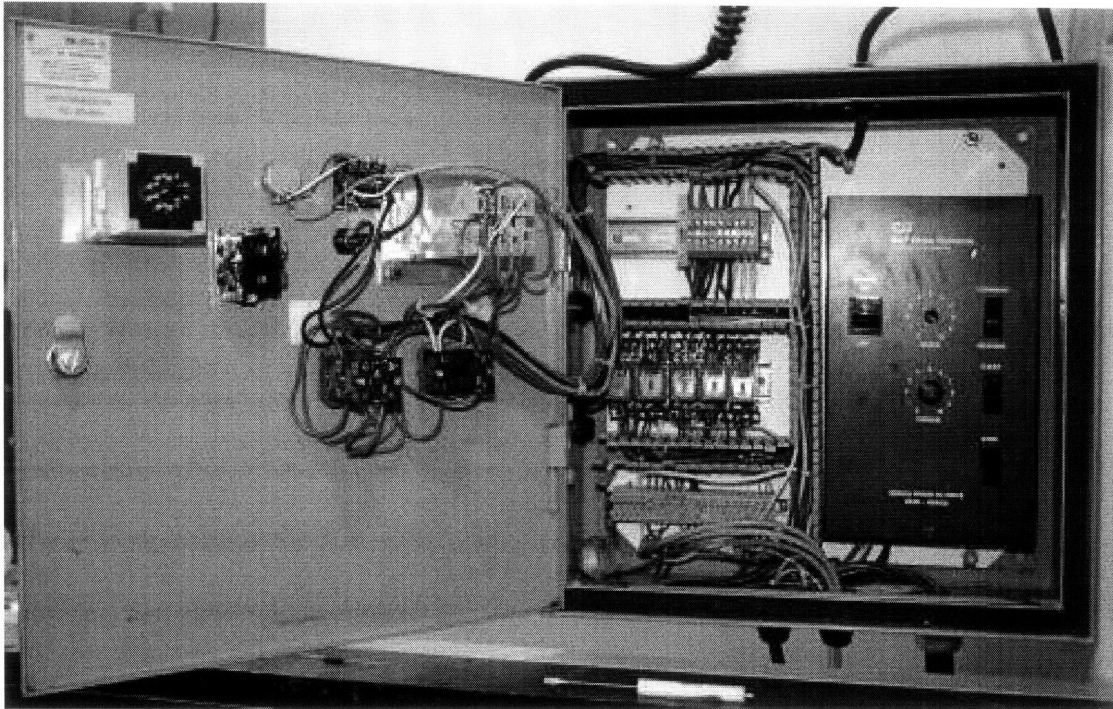
Figure 12: Interior of Line machine control box.

Inductive Proximity Switches

The other alteration to the motion control box came in the inductive proximity switches. The original switches were in a nonfunctional state, with one having its chord broken off and the other constantly switching off and preventing any cart travel. With this second switch disconnected, functionality was returned, and replacement parts were eventually ordered. These switches needed to be moved because their previous installation location allowed only for the switches to be used while the crossbeam ski supports were in use. As these beams were not to be used for camber measurements, new mounting brackets were constructed to mount the proximity switches to either end of the rails themselves.
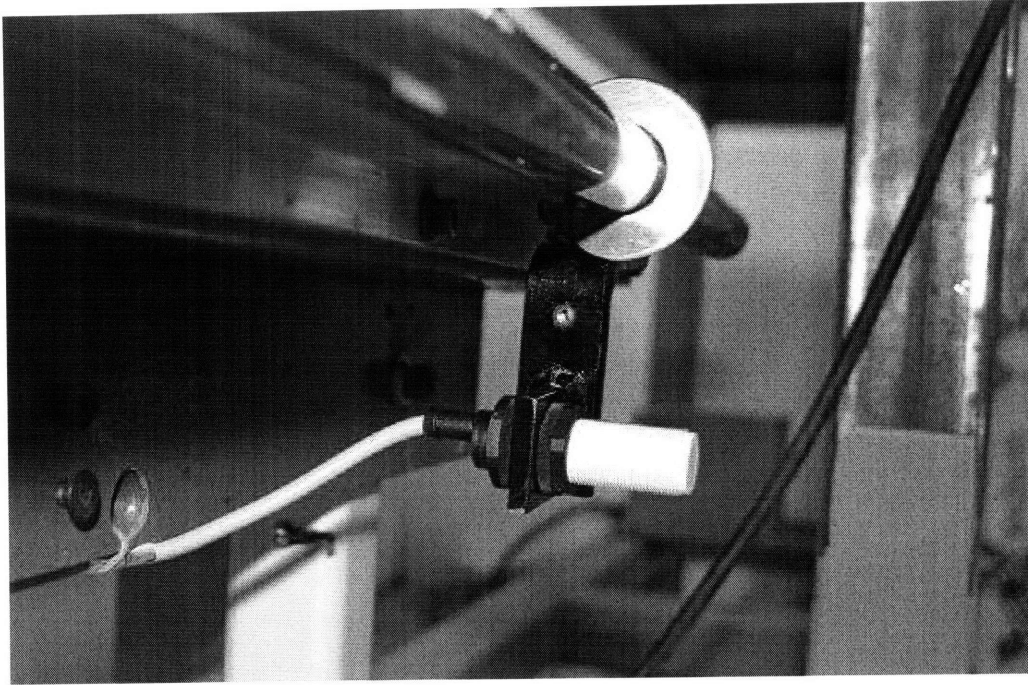
Figure 13: Inductive proximity switch on linear motion rail.

Linear Motion Rails

The rail system from the original line machine was found to have many problems. The old system was based off a lightweight aluminum extrude similar to 80/20, and actually was so weak it sagged in the center. On the GSM machine was a much heavier system including two steel rails at one inch in diameter. These rails were supported by aluminum braces set on rectangular steel tubes on a heavy steel plate. Calculations showed that this system could cover the one hundred seven inch span needed without significant sag in the weakest orientation, with the plate sitting horizontally. It was determined that assembly would be easier on both the rail to machine interface and the cart to sensor interface if the plate was oriented such that the former bottom was used as the back, with the rails facing out towards the operator. This way the steel plate could be fastened to the upright supports at either end of the machine frame without fashioning an independent support. Additionally, this orientation placed the cart in the

same plane as the sensor mount fixture, allowing for a far simpler connection than between perpendicular faces.

Connecting the rails to the legs of the machine was done using three machine screws at each side. Holes were drilled and tapped in the steel legs of the machine, and the relative holes were drilled in the rail plate. This plate had been fastened to the GSM machine by a large number of flat headed socket cap screws, and one of these screws was used for the new machine to set the rails in place. After fastening the rails at one point, they could be rotated around the point to level the system (using literally a level because the data processing was designed to account for misalignment anyways), before drilling and tapping the remaining five holes. These holes were tapped for five socket cap screws, and created a very solid interface between the rail plate and the legs of the machine.

Simply moving the rail system to the new location from the GSM machine was a challenge. It was estimated through calculating the mass of each part that the whole system weighs approximately three hundred pounds, so six people were put to work. Using a pair of hydraulic carts, the system was eventually slipped beneath the machine and stood on its side. That way, the first cap screw could be inserted, and using one handcart the system could be leveled effectively. While the large mass of the rail system made assembly a challenge, it was this very trait that allowed for the nine foot unsupported span.

Motion Control System

The motor from the Line machine was to be reused because the control system was already in functioning order, but the whole system had to be relocated to the new rails and cart, bringing about the need for a complete disassembly. A new timing belt needed to be purchased to allow for the increased length of the new design, and in order for the new timing belt to

interface with the drive pulley from the Line machine, it was necessary to identify the characteristics of the old belt. Eventually, an AT5 metric belt was ordered and upon delivery was installed into the machine.
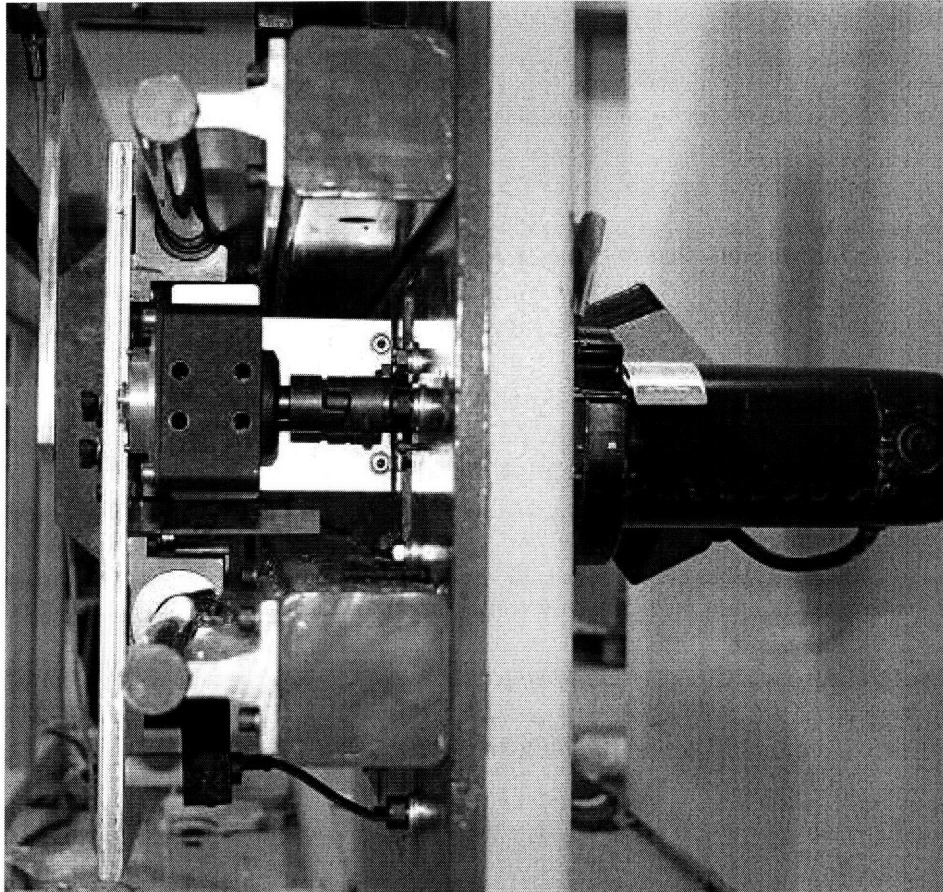
Figure 14: Motion control system.

The motor was removed from the old rail system and installed into the new system through a preexisting hole in the steel plate. This way the large dimensions of the motor could be out of the operator's way while the motor was still easily accessible for servicing. Additionally, the wires for controlling the motor could be kept to the back of the machine and out of the way of the moving parts on the front. It was determined that interfacing with the timing belt would be equally complicated for either motor orientation, so turning the motor on

its side relative to the former setup was not an unreasonable course of action. To hold the motor in place, holes were drilled and tapped in the steel plate, and the motor was screwed tightly into place.

Belt System

Included in the motor system was a dampening coupling. This coupling was a simply two pronged gear, with each tooth covering one eighth of the cross section. The remaining half was split into a rubber piece that fit between every gear interface. This design allows for some backlash, but in its application on this machine, it did not cause any issues. Opposite the motor on this coupling was a pulley system to drive the timing belt. The system was fairly simple, needing no gear reduction and following the same axis of rotation all the way through, but it was very effective in powering the timing belt. This pulley, one half inch in width, had teeth to interface with the belt and fit inside a case containing the bushings for constrained rotation. One side of this case was designed with two parallel slots to allow for the timing belt to reach from the drive pulley across the width of the machine.
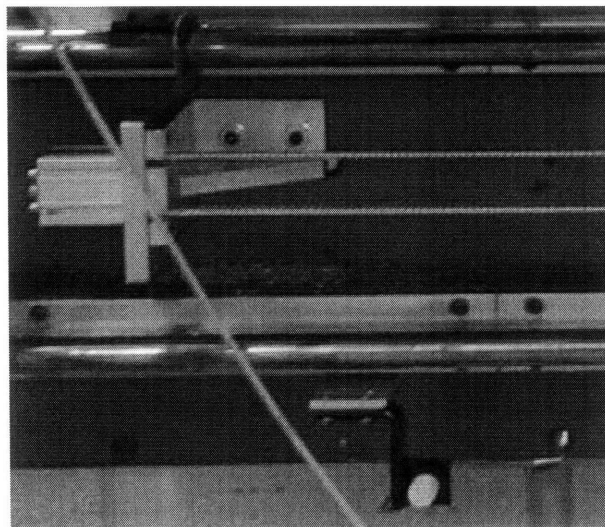
Figure 15: Belt tensioner and inductive proximity switch.

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The timing belt described above was used to power the sensor cart. Spanning the length of the cart, the belt allowed for dampening as well as power transmission. The drive pulley was also formerly connected to a rotary encoder as a part of the Line machine, but this encoder was removed when disassembling parts and was not used in the new design. At the other end of the rails, the original Line machine tensioning roller was located. This roller served to oppose the drive pulley, but also was used to tension the belt. Pressed into the roller was a bearing, which rolled around an aluminum axle. This axle stretched beyond the width of the pulley, and across each end a hole was drilled and tapped. Two screws pull this axle against a backing plate, with the heads of the screws pushing on that plate.

To support the pulleys at each end, aluminum frames were made. These two frames were made from the single motor mount by cutting the two parts of this motor mount in half and drilling, countersinking and tapping new holes. Additionally, slits were cut into these frames to allow for the timing belt to pass through.

Sensor Cart

For carrying the Micro Epsilon sensor during camber measurements, the rail and cart combination from the GSM was used. The cart, described in the section pertaining to the GSM machine, is a half inch thick aluminum plate perforated with tapped holes. The plate was wider at one end, allowing for the connection of a tube to contain the wires, but due to the orientation of the rails in the new machine, this tube could not be used in the new machine. The added width of the plate did not interfere with the new design, so the plate was kept in its original state. Supporting the plate was a set of four pillow block bearings. These were set on the rails from the GSM machine and were never removed. Having a variable preload though a

slot up one side and a preload screw, these bearings allowed the cart to travel along the rails very well constrained and with very little resistance.

Behind the sensor cart was located the fixture for fastening the cart to the timing belt. The belt being open ended, two separate clamps were used. A piece of rectangular extrude was fastened to the back of the cart after two holes large enough for the clamps and the belt to fit in. Two holes on each side were also drilled and tapped for the clamps to be screwed in. The clamps used were taken off the cart from the Line machine, and had teeth to interlock with the teeth in the timing belt. The belt was pinched against the aluminum fixture by this clamp, and any excess belt length was left inside the fixture out of sight. After clamping the belt tightly, the bolts on the tensioning pulley were cranked down, and the cart functioned flawlessly in the first test. Additionally, a piece of aluminum similar to the fixture on the back of the cart was cut to shape and bolted to the front of the cart to support the actual sensor mount.
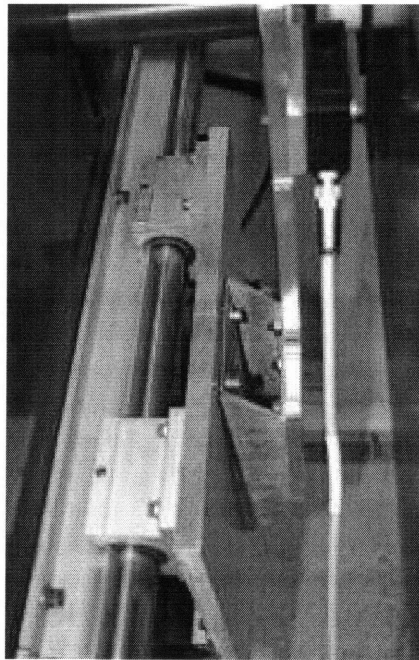
Figure 16: Sensor cart and sensor.

Data Processing and Recording

The majority of the data processing was conducted in National Instruments LabVIEW. This program is best described as a visual programming language made for data acquisition and the running of experimentation equipment. The LabVIEW Virtual Instrument was made to display the filtered, processed data as a plot. It was also made to display values for the speed of the cart and the measured points of interest including ski length and the running surface length, the tip and tail contact points, the tip and tail heights, and the location and value of maximum height underfoot. The calculations for each of these points and are outlined below. Unfortunately, a method was not found in LabVIEW to read the data directly from the sensor or to crop out unnecessary data points, but a user-friendly method for carrying out these steps is described in the attached document of standard operating procedures. This includes recording the data using the Micro Epsilon sensor's included software and editing the data briefly in Microsoft Excel.

Creating the Plot

The first step in data processing was to put the data points into a reference frame. The axes needed to be defined, and this was done using the two minimum points, or contact points, as was previously done on a tabletop. To do this, a K2 test engineer would set the ski to be measured on a flat steel table and by sliding a piece of paper underneath the ski, the points where the ski first contacted the table cold be located to within about two centimeters. Additionally, because the form of the machine made most users set the tail of the ski to the left because it seemed intuitive to let the laser start at the tip of the ski, the data was fully reversed in LabVIEW before any calculations were started. This was deemed necessary because measuring the ski by hand is most often and most easily done from the tail, and it was important

to make the data found on the new machine match with data from other sources. Additionally, the first and last ten data points were removed because the fringe effects at the tip and tail of the ski threw the data off significantly.

The minimum heights could be located on the new machine to a far higher accuracy than by hand, and by applying the slope between these two points and the values at these points, the horizontal axis was defined. For the vertical axis, it was assumed that deflections were small, so changes in height were not affected by the lack of alignment between the sensor and the tabletop. To flatten the plot, the differences in value and index of the contact points were divided and multiplied by the total index value. This number, minus the measured height at the first contact point, was the correcting factor to be added to every height value to reorient the plot to horizontal.

Finding Points of Interest

After displaying a plot of the camber profile, the second application of the LabVIEW Virtual Instrument was to display the values for the points of interest listed above. It is described above how the contact points were found, and these locations—as measured from the tail of the ski—were displayed first. Additionally, it was simple to find the running surface length—the distance between the two contact points—and the total ski length. Both lengths were calculated by multiplying the index value of the measured locations by predetermined the speed factor.

Camber Height Machine Data Analysis

Ski A Information:	C07 Anti Piste, Right ski.					Height [Y] (mm)	Position [X] (cm)
Test Date:	4/10/2008				Max Camber:	5.57	81.44
	OVERALL LENGTH:	177.78	TIP HEIGHT	64.0	ACP:		7.42
	RUNNING SURFACE LENGTH	145.74	TAIL HEIGHT	7.3	FCP:		153.16
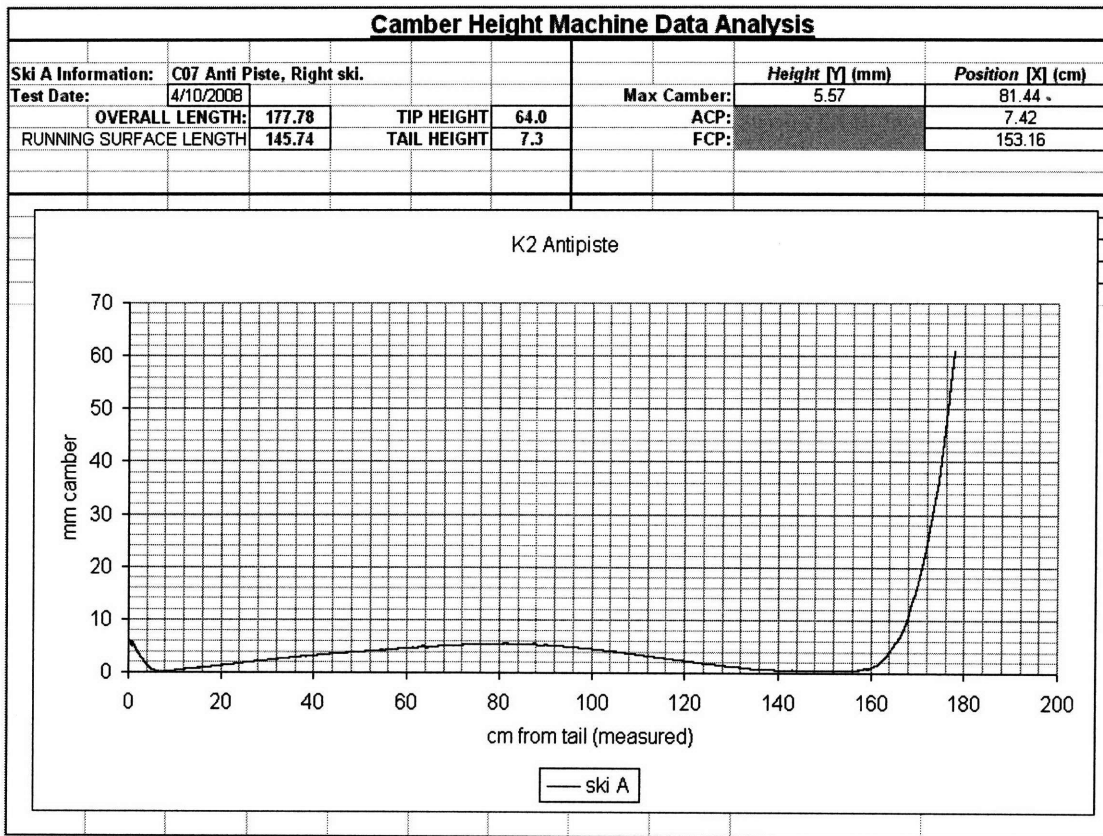
Figure 17: Final Microsoft Excel data readout and graph for K2 Antipiste ski.

The next data points to be determined were the tip and tail heights. It was found that due to the high sampling rate of the sensor at one thousand samples per second, removing the ten data points at each end of the ski did not bring issue to the matter of tip and tail height. These points were simply determined as the mean of the next ten values at each end of the ski.

The final point of interest to be measured was the location and value of the maximum camber height underfoot. The point was found by trimming the array to the contact points and simply picking out the maximum value. This value and its location were displayed in the LabVIEW front end and all data points displayed were also output by LabVIEW into a Microsoft Excel file.

Final Machine

Per request of K2 Sports, a machine was developed to measure the camber profile of a wide range of skis and snowboards. The project was completed through retrofitting a preexisting machine with better suited parts, some from another non functioning machine and others new. The machine and accompanying software are capable of determining values for ski or snowboard length, running surface length, camber height, and tip and tail height as well as the locations for the two contact points and the location of maximum camber height. In addition, the program is able to process the raw data to output a clean, filtered plot of the camber profile of the test subject.

The final camber machine was presented to the engineers of K2 Skis, Snowboards, and the testing department on Wednesday, August 15, 2008. The standard operating procedures were put on display, and K2 continues to use the machine frequently in the present. Attached is an updated standard operating procedures document K2 engineers have created since minor modifications have been made to allow for flexed measurement and a macro has been made in Microsoft Excel to display the data in a report format. Also attached are figures depicting the data taken since the modifications.
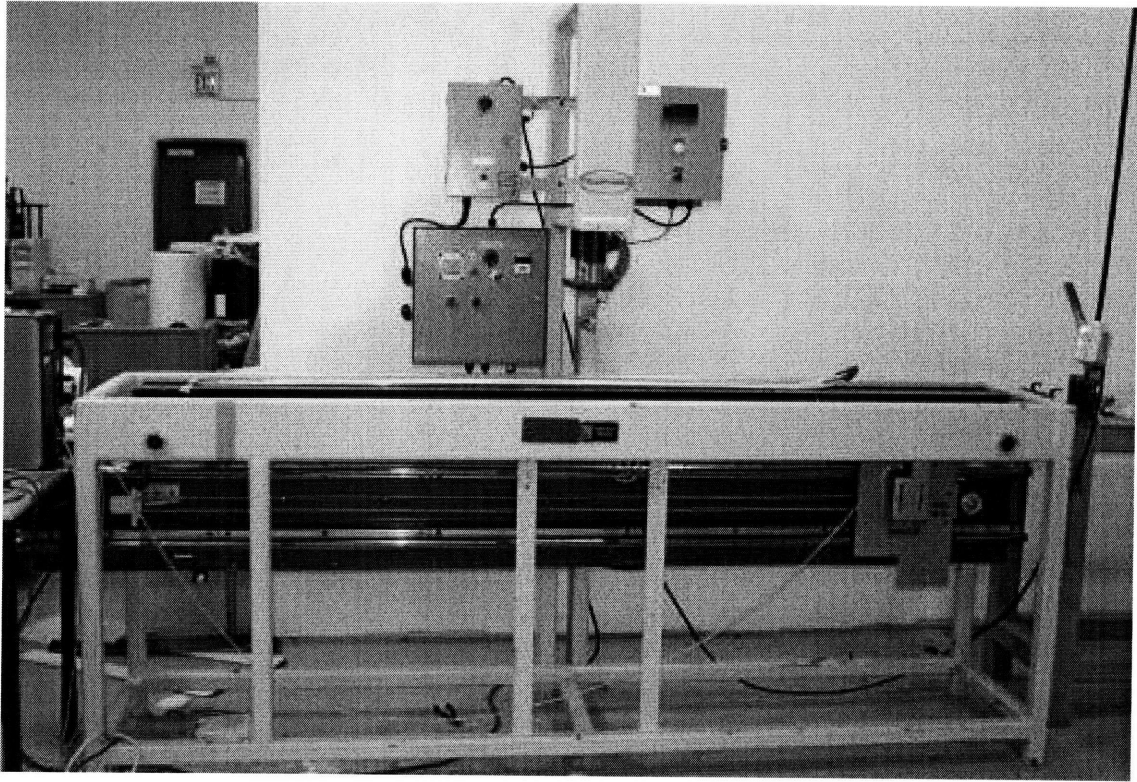
Figure 18: Finished Camber Machine.
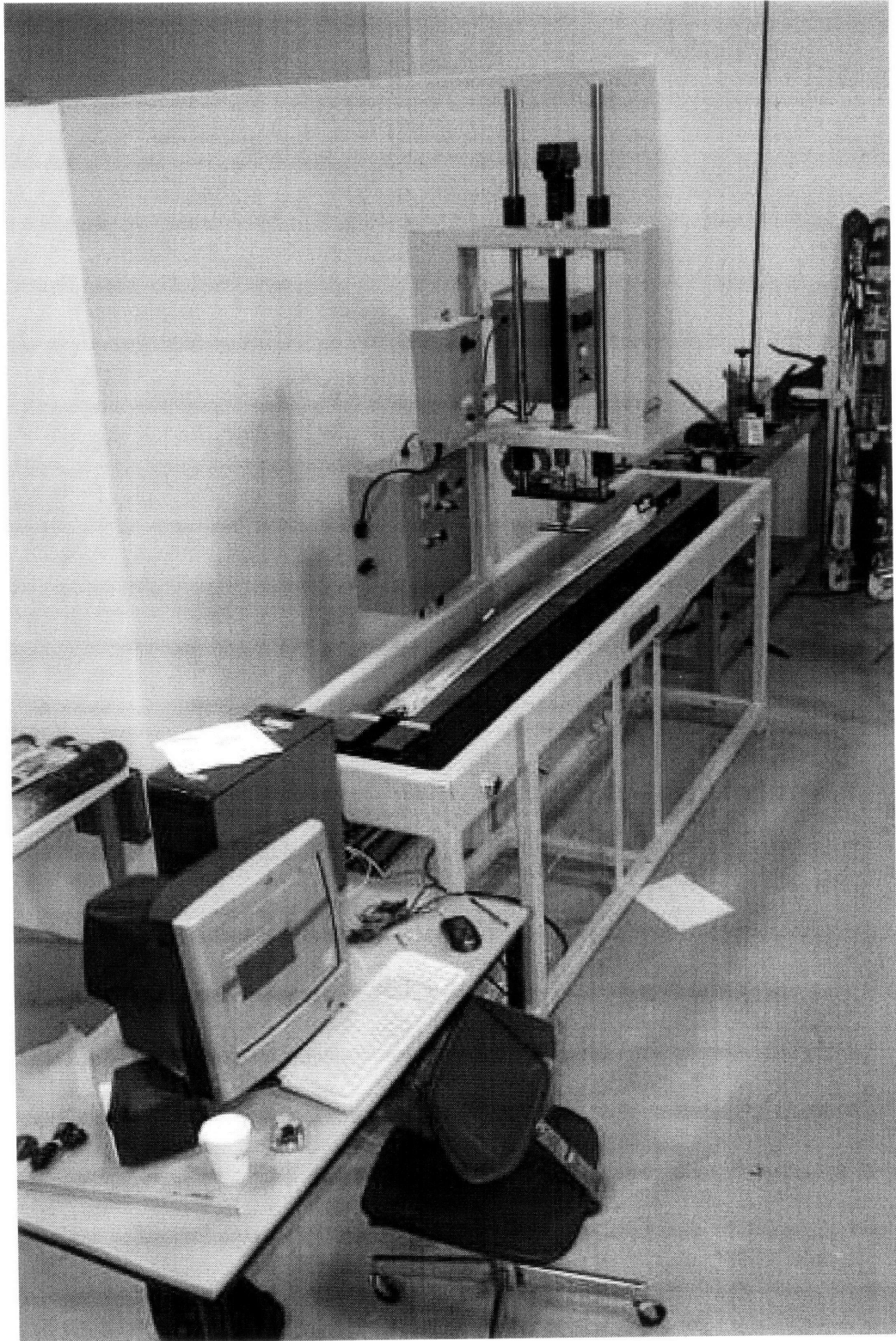
Figure 19: Full view of finished Camber Machine and test computer.

Appendix

Original Standard Operating Procedures

Steps:

- Set tail of ski at masking tape on left side of track.
- Run cart past ski tip to automatic stop. Sensor on (switch on back of computer). Machine to constant speed, direction control switch neutral (machine control box).
- Open ild1401 program on desktop into data acquisition.
- Click to start data acquisition, and quickly press the green button on the machine.
- At end of scan, click to stop acquisition and resize viewing window to 'show all'.
- Save data from ild1401 and open *.csv in Excel.
- Delete constant sensor values at beginning and end of file and resave.
- Run 'camber measurement ue.iv' on *.csv.

Labview should display data and filtered graph, as well as saving a new excel file.
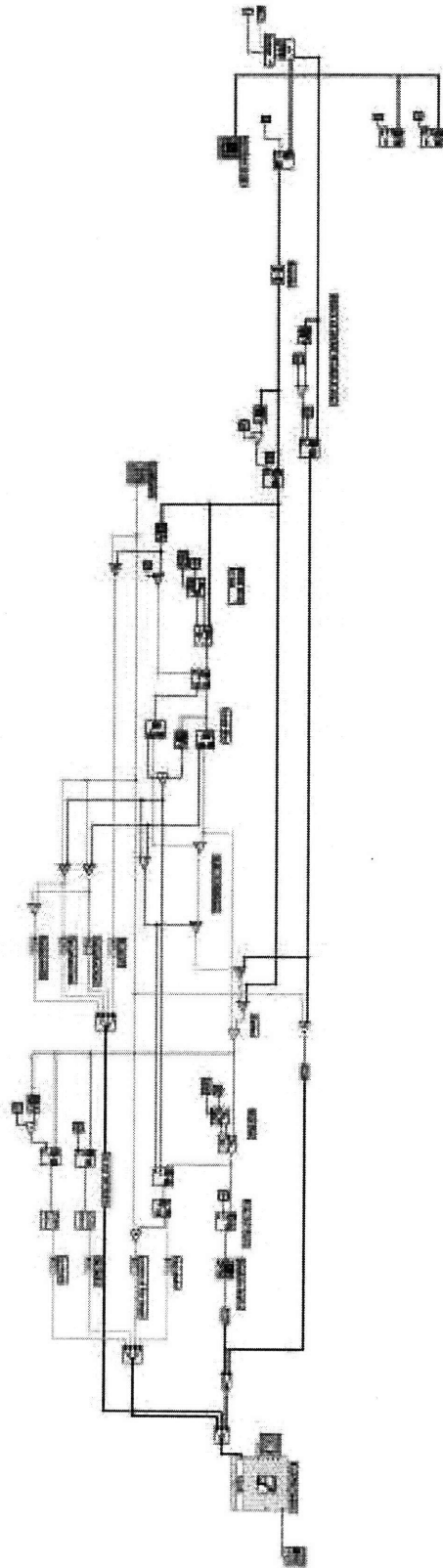
Figure 20: LabVIEW Virtual Instrument block diagram.

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Updated SOP for modifications made to machine since completion:

SOP for Making Camber Measurements With LINE/KARHU Machine

Updated: 4/8/08

All the files needed to collect and process the data are here:

C:\camber files

<u>**Prepare The Machine**</u>

Remove the simple supports. Move 'flat beam' supports to center (stops). Take care not to squish the laser sensor.

Use the "X axis speed controls' to jog the sensor to the right-hand side of the machine. The sensor carriage will stop at the end.

Place a ski on the support beams, with tail at the masking tape on the left.

Flip the metal speed selector switch to the top position, for *CONSTANT SPEED*.

Flip the X-axis direction selector to the center position (in between *"X AXIS LEFT"* and *"X AXIS RIGHT"*.

Turn on the Laser sensor – there is a metal switch installed in the back of the computer (K2 Corp #C 2396). Flip this up.

<u>**There are basically 5 steps to collecting, processing, and storing the data:**</u>

1. Collect the y-axis data with the sensor software (saves .slk file)
2. Use an Excel macro to strip the empty data from the ends (saves .xls file)
3. Re-save this .xls as a .csv file
4. Import this .csv into Labview, which does some data analysis, converts the (time,y) data into (x,y) data for the ski camber curve. (saves a .LVM file)
5. Paste the data from the .LVM file into a .xls template – used for easier file-handling and overlaying of data sets.

Collect Data

1. Open the **ILD1401 Tool 1.43** program that collects data from the sensor. Select the **'Start Data Acquisition'** button. *This will change to a window with a graph. In the lower left-hand corner is a button with green lettering labeled "Start DAQ".*
2. **Click the Start DAQ button**
3. **Shortly after clicking the on-screen butto**n, press the Green button on the machine labeled **"START DATA COLLECT"**.
4. Once the sensor has stopped, click on the **"STOP DAQ"** button.
5. Resize the viewing window by clicking the **"SHOW ALL"** button.
6. Click on the **"Save Displayed Data"** in the bottom left-hand corner. *This will save the raw data in .SLK format to* `C:\camber files\raw data\` *(It will also save a .CSV file, but we don't need this.)*
7. The file name for the scanned ski will be displayed in the lower left-hand corner window. **Take note of the .slk file name & location.**

Strip end data with the macro

1. Stick the .slk files to be stripped here: `C:\camber files\slk_files_to_be_processed`
2. Open the file: STRIP_THE_SLK_FILES_MACRO.xls (found here: `C:\camber files`)
3. Click on "Tools", "Macros" – and RUN the Macro called "Cleanup" *This will open the .SLK file, strip the zeros, delete the original file, and save the 'stripped' data as an .XLS file here:* `C:\camber files\stripped_data_files`
4. Verify that all the files have been moved. Now we can 'process' the data using the Labview .vi

Save the .xls as a .csv

Run the Labview routing to process the .csv data

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1. Open the file: **C:\camber files\Camber Height Measurement ue(3).vi**
2. Type in the ski serial number and ID in the "Ski Info" field.
3. Run the program (Ctrl-R, or click on the arrow in the toolbar). *The program will prompt you to open the .csv file.*
4. The Labview program will save it as an .LVM file here: **C:\camber files\final_camber_data** with the file name indicated in the Labview front panel.

Paste the .LVM data into our template, save the .xls file

1. Open the .LVM file
2. Select the data from columns A-M and as many rows as needed.
3. Paste the data in the location indicated in this file: **Camber Height Measurement Template.xls**
4. Save-As this template with a sensible filename.

Camber Height Machine Data Analysis

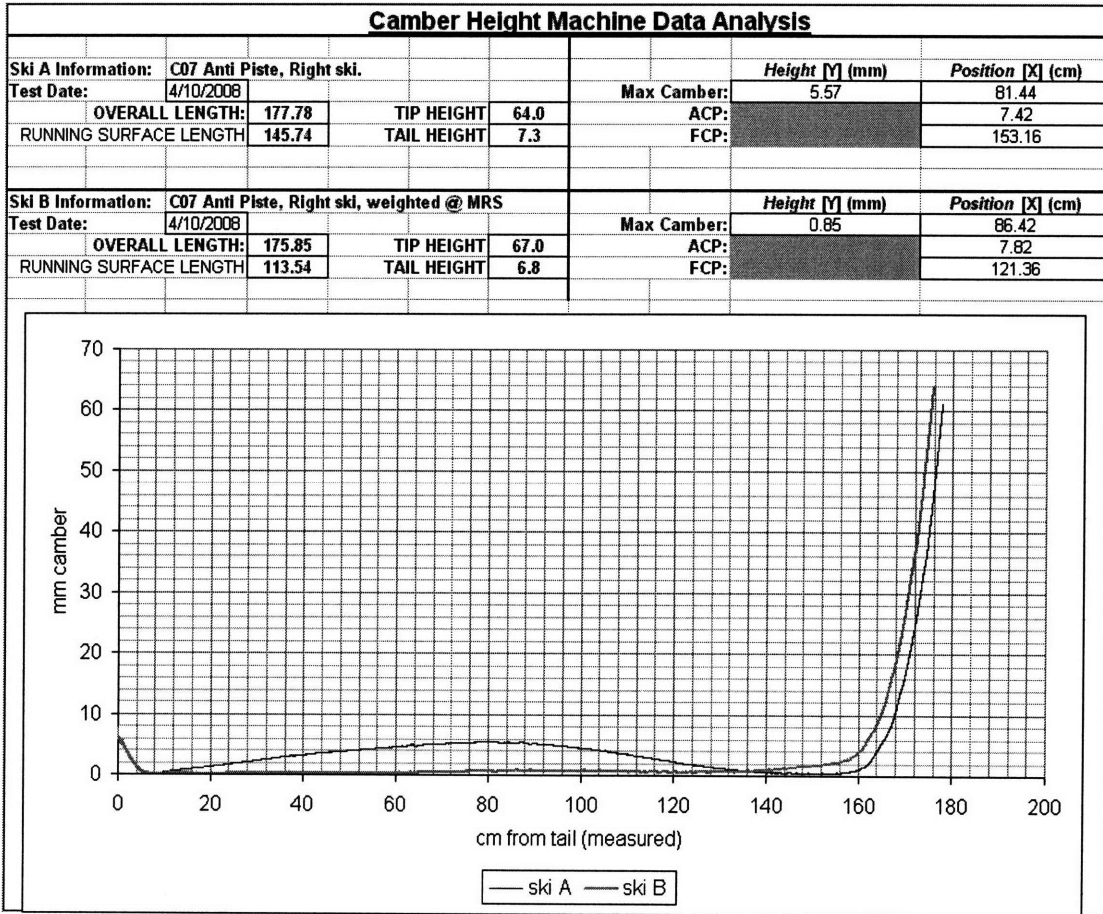| Ski A Information:	C07 Anti Piste, Right ski.					Height [Y] (mm)	Position [X] (cm)
Test Date:	4/10/2008				Max Camber:	5.57	81.44
OVERALL LENGTH:	177.78		TIP HEIGHT	64.0	ACP:		7.42
RUNNING SURFACE LENGTH	145.74		TAIL HEIGHT	7.3	FCP:		153.16
Ski B Information:	C07 Anti Piste, Right ski, weighted @ MRS					Height [Y] (mm)	Position [X] (cm)
Test Date:	4/10/2008				Max Camber:	0.85	86.42
OVERALL LENGTH:	175.85		TIP HEIGHT	67.0	ACP:		7.82
RUNNING SURFACE LENGTH	113.54		TAIL HEIGHT	6.8	FCP:		121.36

Figure 21: Present day data readout and chart for unweighted ski and ski pressed down at the center of the running surface to mimic skier load.

Camber Height Machine Data Analysis

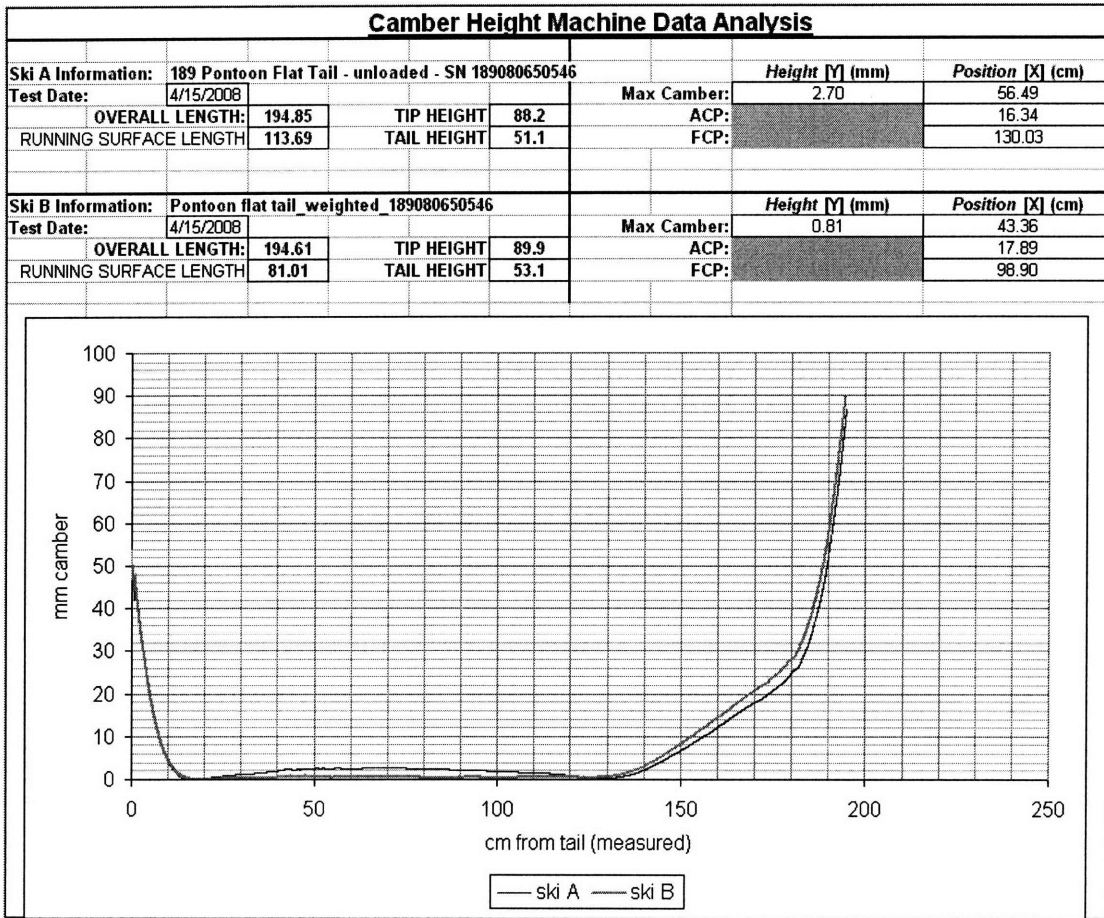| Ski A Information:	189 Pontoon Flat Tail - unloaded - SN 189080650546					Height [Y] (mm)	Position [X] (cm)
Test Date:	4/15/2008				Max Camber:	2.70	56.49
OVERALL LENGTH:	194.85	TIP HEIGHT	88.2		ACP:		16.34
RUNNING SURFACE LENGTH	113.69	TAIL HEIGHT	51.1		FCP:		130.03
Ski B Information:	Pontoon flat tail_weighted_189080650546					Height [Y] (mm)	Position [X] (cm)
Test Date:	4/15/2008				Max Camber:	0.81	43.36
OVERALL LENGTH:	194.61	TIP HEIGHT	89.9		ACP:		17.89
RUNNING SURFACE LENGTH	81.01	TAIL HEIGHT	53.1		FCP:		98.90

Figure 22: Microsoft Excel readout depicting a very different camber profile on a powder-specific K2 Pontoon ski.

Camber Height Machine Data Analysis

Ski A Information:	Obsethed unweighted SN-189073520652				Height [Y] (mm)	Position [X] (cm)
Test Date:	4/15/2008			Max Camber:	4.06	105.78
OVERALL LENGTH:	206.01	TIP HEIGHT	51.9	ACP:		41.75
RUNNING SURFACE LENGTH	128.97	TAIL HEIGHT	57.0	FCP:		170.72

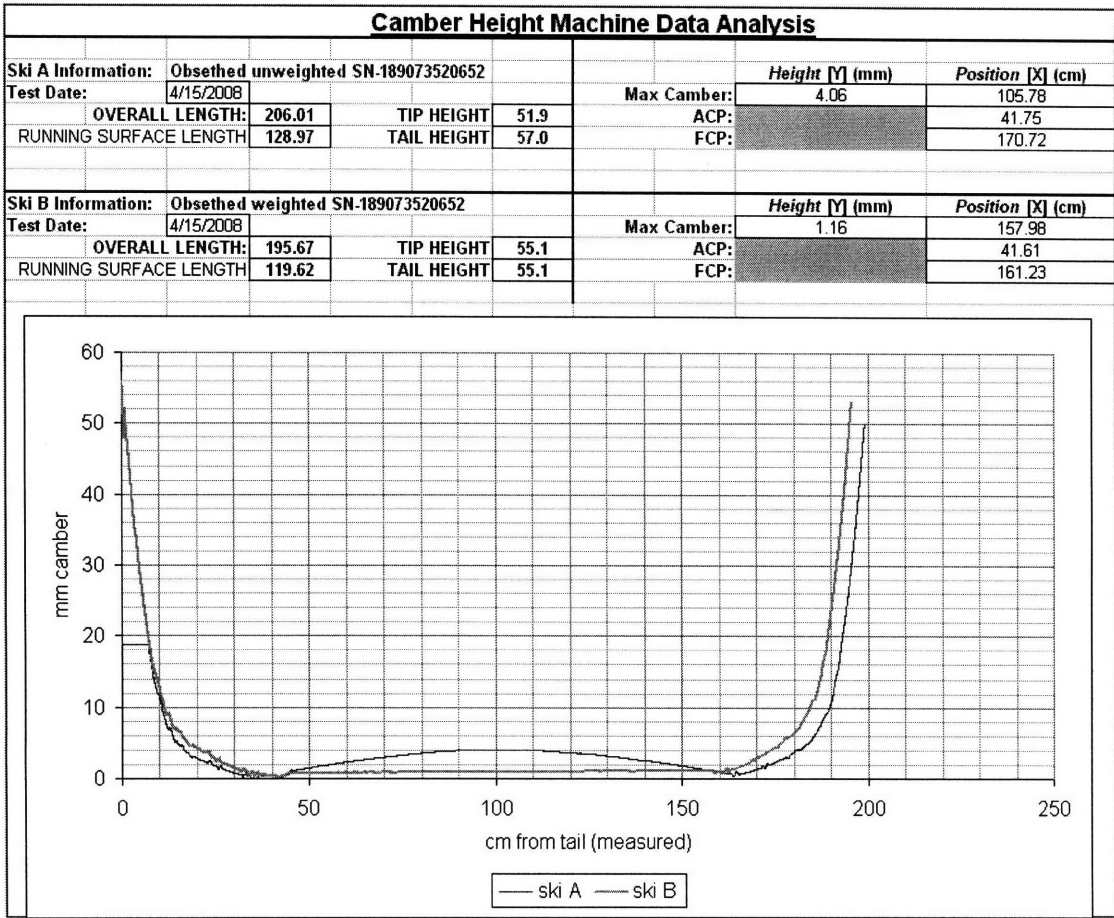| Ski B Information:	Obsethed weighted SN-189073520652				Height [Y] (mm)	Position [X] (cm)
Test Date:	4/15/2008			Max Camber:	1.16	157.98
OVERALL LENGTH:	195.67	TIP HEIGHT	55.1	ACP:		41.61
RUNNING SURFACE LENGTH	119.62	TAIL HEIGHT	55.1	FCP:		161.23

Figure 23: Third camber profile, showing a twin-tipped ski. K2 Obsethed.

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