Quarterly Progress Report

TPF-5(039)	Falling Weight Deflectometer (FWD) Calibration Center and Operational Improvements
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Reporting Period:	**January 1, 2006 through March 31, 2006**
Project Status: **(Tasks 1-5)**	Work completed through end of period: 65.0% Project funds expended (pct. of total budget): 70.4% Expected completion date: September 6, 2006

Status of the Project

At the end of the sixth quarter of work the project is entering the final stage of development. The basic research has been completed. All that remains is testing with various brands of FWDs, and the refinements that are likely to follow from that. Production of equipment sets and training of the calibration center operators will follow. It still seems possible to complete this work and file a final report by September 8, 2006.

It is unclear whether the project is on schedule or behind schedule. If we had followed the original research plan, we would likely be on the original schedule at this time. But that is pure speculation. The original research plan, as stated in the July 2004 proposal, was to continue to use the concrete block and aluminum beam from the original SHRP procedure, adding one accelerometer to measure beam movement and another to detect triggering. As soon as the project got underway in October 2004, we agreed to a request from the COTR to try to use an accelerometer as the reference deflection device. That was a major departure from the proposed research plan, and it has added many unplanned tasks to the project. (Nevertheless, it was a good idea.)

Using an accelerometer to measure beam movement would have been easy because only one or two significant digits would be needed. The correction for beam movement would seldom be more than 10 microns. However, when using an accelerometer as the reference deflection sensor, at least three and preferably four significant digits are required. Peak deflections are generally in the range of 500 microns or more. It is a much more challenging task to find a suitable accelerometer and develop integration software that can achieve that goal and perform as well as the LVDT currently does. This has added many development tasks and many hours to the project agenda.

Progress on every Task has been made in the sixth quarter, although our commitment to complete the Task 1 Report eluded us due to the urgency of the other tasks. The details of the project tasks are described in FHWA's Statement of Work which is posted at the TPF-5(039) Web site

Activity during the reporting period

The focus during the first three months of 2006 was mainly on two activities: 1) development of a suitable multi-sensor stand for use in reference and relative deflection sensor calibration, and 2) furtherance of the software development for use in the calibration. Substantial progress has been made on both of these items. We also conducted a shaker table study with limited success. This will be discussed in the section on Problems Encountered.

Multisensor Stand Design

Initial investigation of a low-profile, circular multisensor stand had shown that type of design to be infeasible. This was reported in the previous Quarterly Report. Thus we decided to concentrate our effort mainly on columnar designs.

One goal of this project is to conduct reference calibration on all deflection sensors simultaneously. The current SHRP calibration procedure does reference calibration on one sensor at a time, and this takes several hours to complete. In an effort to speed up the overall process, simultaneous reference calibration on all sensors could save a lot of time.

We are seeking a stand design where position in the stand is not significant. An error due to position is a bias error, meaning it is not random. If position is significant, then the calibration procedure must have each sensor in every position in order to cancel out the effect. This requires rotation of the sensors, which adds a lot of time, requires replicate sets of testing, and is a tedious process with some types of deflection sensors.

We began by evaluating the various types of multisensor stands that are provided for relative calibration by the FWD manufacturers. With assistance from several FWD manufacturers and also from the Pennsylvania Calibration Center, we obtained a complete set of the relative calibration stands that are used with each of the various types of FWDs. Most manufacturers have a single design, although the KUAB company has one stand design for their seismometers and a second design for their geophones. [We learned that there are only three KUAB machines in the U.S. that use geophones, and apparently only one of those machines is operational.]

Using our Dynatest FWD and its geophones, we evaluated each of the stand designs. By performing several relative calibrations with each design, we could determine through data analysis if position in the stand is significant. Typical results are shown in Figure 1 for the original design of the Dynatest relative calibration stand. All sensors were in all positions, and five replicate drops were made in each position (this is called a set). The blue circles indicate the

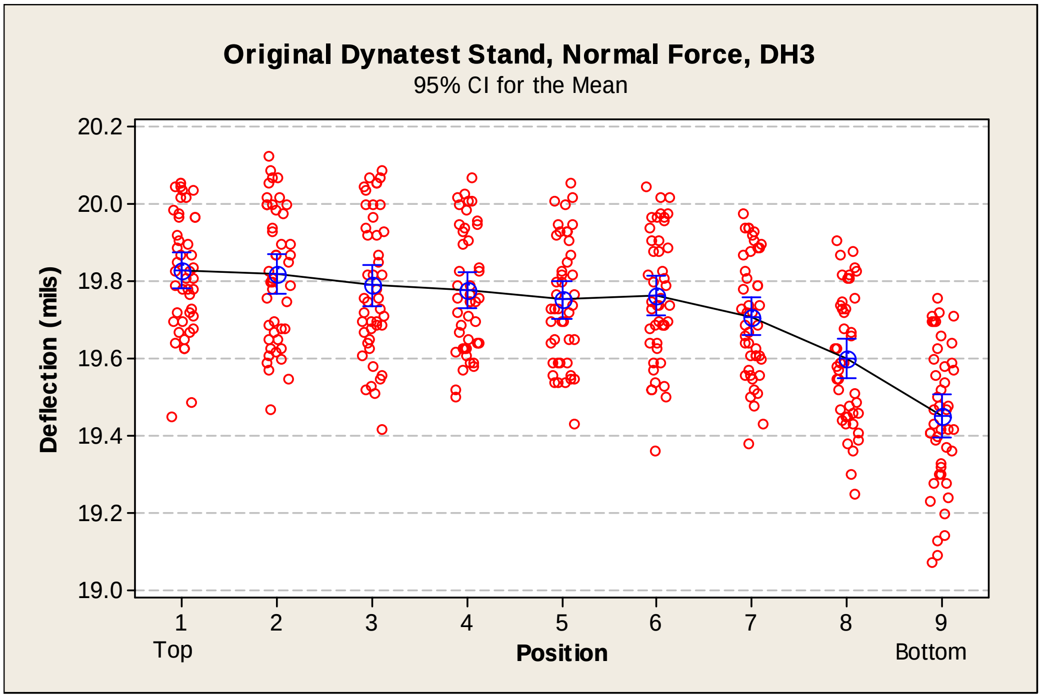

Figure 1 – Original Dynatest relative calibration stand. The blue circle means range from 19.45 to 19.85 mils, a 0.40 mil (10.2 micron) span, or 2 percent of reading. Thus, position in stand is strongly significant in this design.

mean deflections for each position, and the vertical blue bars indicate the 95 percent confidence interval on the mean.

If position in the stand was not significant, all positions would have the same mean. An analysis of variance (ANOVA) shows that the data in Figure 1 are strongly significant with regard to position. We experienced similar findings for the Carl Bro stand and the KUAB seismometer stand. We found this was so because the stands were too flexible. We were not able to experiment with the JILS or the KUAB geophone stands using our Dynatest geophones.

We concluded from these results that a very stiff stand is required to insure that position will not be significant. We developed several prototype designs for evaluation (Figure 2). The stiffest of the designs is the ladder stand, shown to the immediate left of the wrench in the photo. The large channel stand is the third one from the left. Both designs proved to be satisfactory.

The several stands were substantially heavier than the Dynatest design, and it quickly became evident that it was not possible to manually hold the stands in place. Vertical accelerations greater than three g's were recorded, and it required more than a 75-pound downward force to keep a 25-pound stand in contact with the test pad. If contact was not maintained, this distorted the time history of the deflection wave and added to the variability of the results.

Thus several means of attaching the stand to the test pad were investigated (Figure 3). We tried putting a single, threaded mount in the test pad, but we found that a better approach was to use

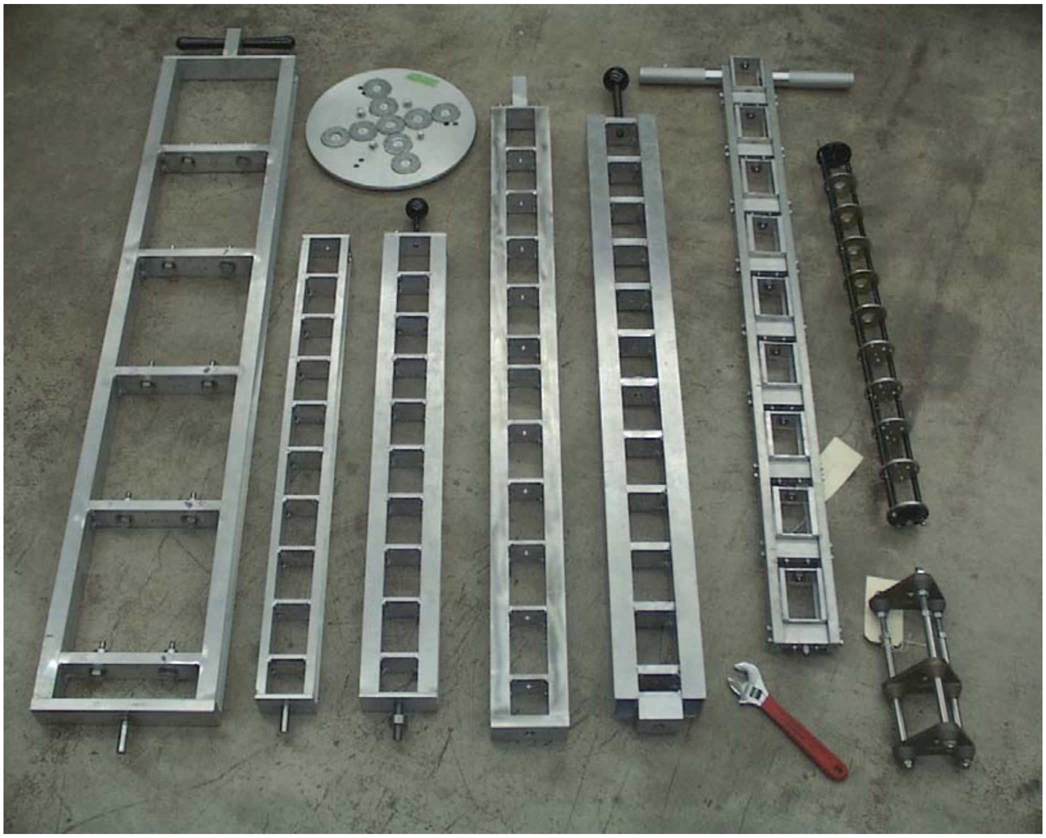

Figure 2 – Prototype stand designs. The stand on the far left was developed for two columns of KUAB seismometers. The next four designs were developed to hold geophones. The stand in the middle (fourth from left) is a second generation design for Dynatest, JILS, or Carl Bro geophones interchangeably. The extra shelf at midstand is for the accelerometer. The stand second from right (above the wrench) was designed by the KUAB company for their geophones. The stand on the far right (above) was designed by Dynatest, and a portion of the JILS design is shown on the lower right. The circular platter stand, which did not work, is at the top. Additional manufacturer's stands from Carl Bro and KUAB were too large to be included in the photo.

the two-bolt mount that was already in place for the SHRP sensor holder. The two designs in Figure 3 use the two-bolt method of attachment.

One of the most promising designs involved the ball joint swivel mount and the stiff ladder stand. Results for this combination are shown in Figure 4. While several downward force levels were tried, we found that down pressure did not matter very much with the two-bolt mounts. However, if the stand was left entirely free, with no one holding on to it, that added variability to the results.

The ANOVA for the data in Figure 4 showed that position in the stand was only slightly significant at the $\alpha = 0.05$ level. Furthermore, the range of error due to position was only 0.02 mil (0.5 micron). Errors of this magnitude are so small as to have no practical effect on the calibration factors.

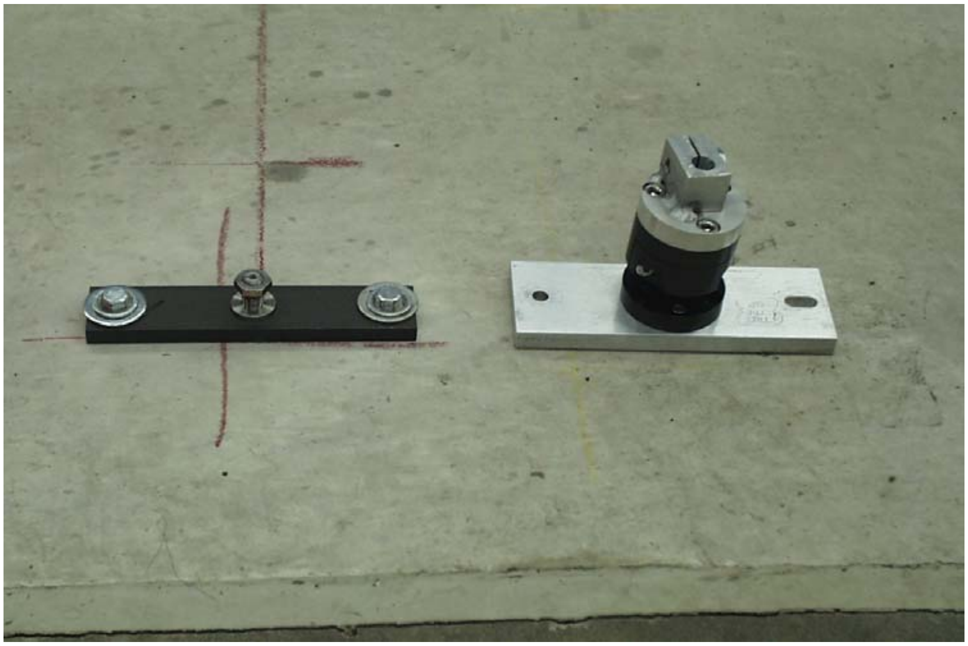

Figure 3 – Stand hold down designs. On the left is the direct anchor with a threaded coupling. On the right is the ball joint swivel with a clamp coupling. Both devices can be attached to the test pad using the inserts for the SHRP sensor holder.

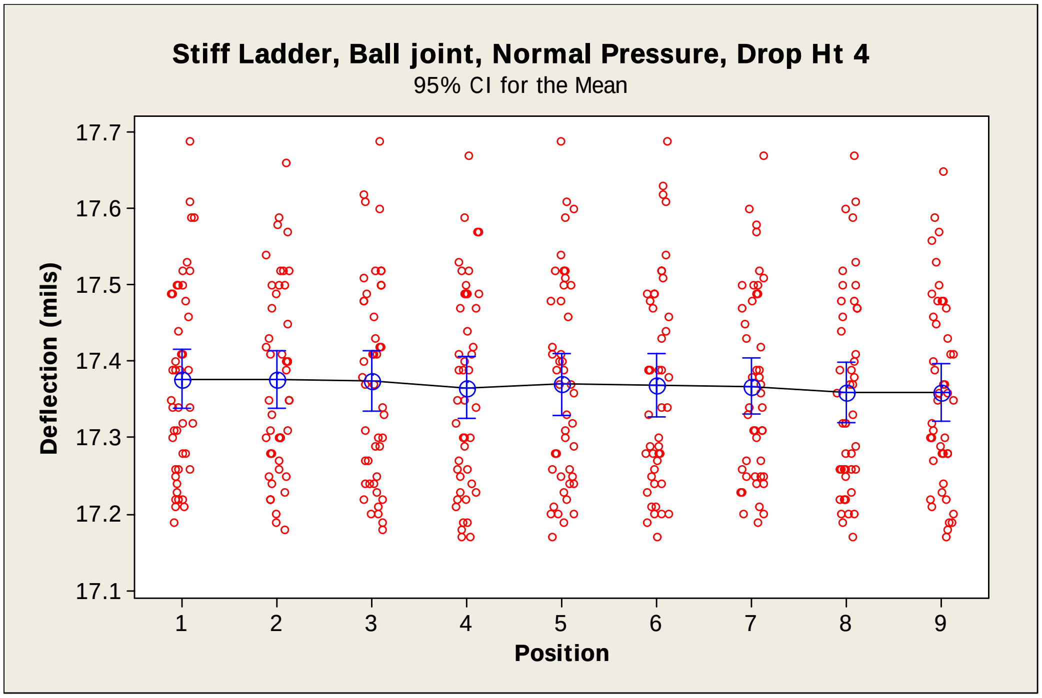

Figure 4 – Relative calibration results for the stiff ladder stand anchored to the test pad with the ball joint swivel hold-down. Position is barely statistically significant. The range of the position means is only about 0.02 mil (0.5 micron).

We considered two main parameters when evaluating the adequacy of the stand designs. These were the range of the means due to position and the unattributed error. The range of the means is illustrated in Figures 1 and 4. Generally it is nearly linear from the top to the bottom of the stand, with the deflections being slightly larger at the top. The closer this number is to zero, the less significant is position in the stand.

The unattributed error is calculated in the ANOVA. Statisticians refer to this as the error due to error, which seemed to us to be a rather nondescriptive term. The usual three-way ANOVA for relative calibration involves three factors, sensor, position, and set. The mean-square error due to each of these factors is evaluated in the ANOVA. The remaining error, not attributable to the three factors, is the unattributed error. This is the random measurement error of an individual reading of the deflection sensor. In our experience with FWDs over a period of 25 years, this number can be expected to be less than 0.08 mils (2 microns).

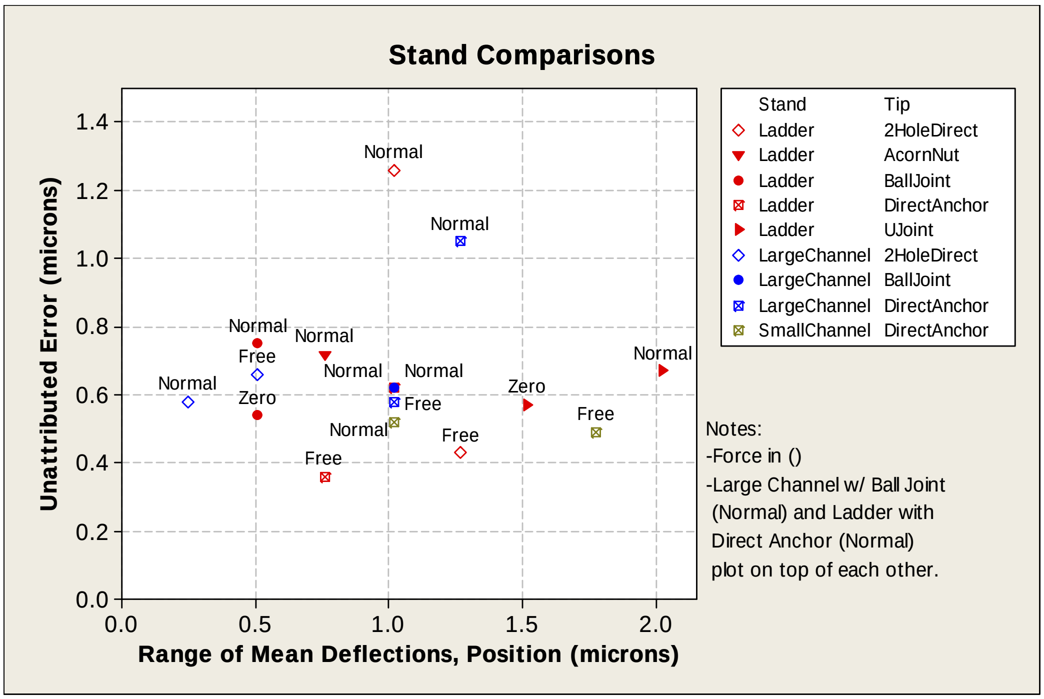

Figure 5 – Comparison of various stand designs and hold down methods in terms of the results from relative calibration.

A comparison of some of the various combinations of stand designs and hold-down designs is given in Figure 5. The best designs are in the lower left corner of the chart. The amount of downward force used is noted next to each data point. Both the direct anchor and the ball joint swivel gave good results. Normal to light levels of down pressure gave good results. And both the ladder stand and the large channel stand gave good results.

While the bias error due to position in the stand could not be entirely eliminated, we found it possible by using good design to make that error very small, less than one micron. We feel this is so small that we can greatly reduce the extent of rotation of sensors in the stand.

Additional experiments were conducted to see if misalignment of the sensors in the stand or tilting of the stand affects the calibration results. To check misalignment, some sensors were purposely set as much as ¼" off the centerline of the column. Misalignment of this amount is easily noticeable visually. To check tilting, the stand was held out of vertical plumb by as much as 3 degrees. Again, this is easily noticeable visually or with a bubble level. No adverse effect was noted in the data for either error.

The power of the statistical data analysis is illustrated in Figure 6. Each data point represents the average of five drops per set from the highest drop height. The sensors were rotated through all positions during the relative calibration test.

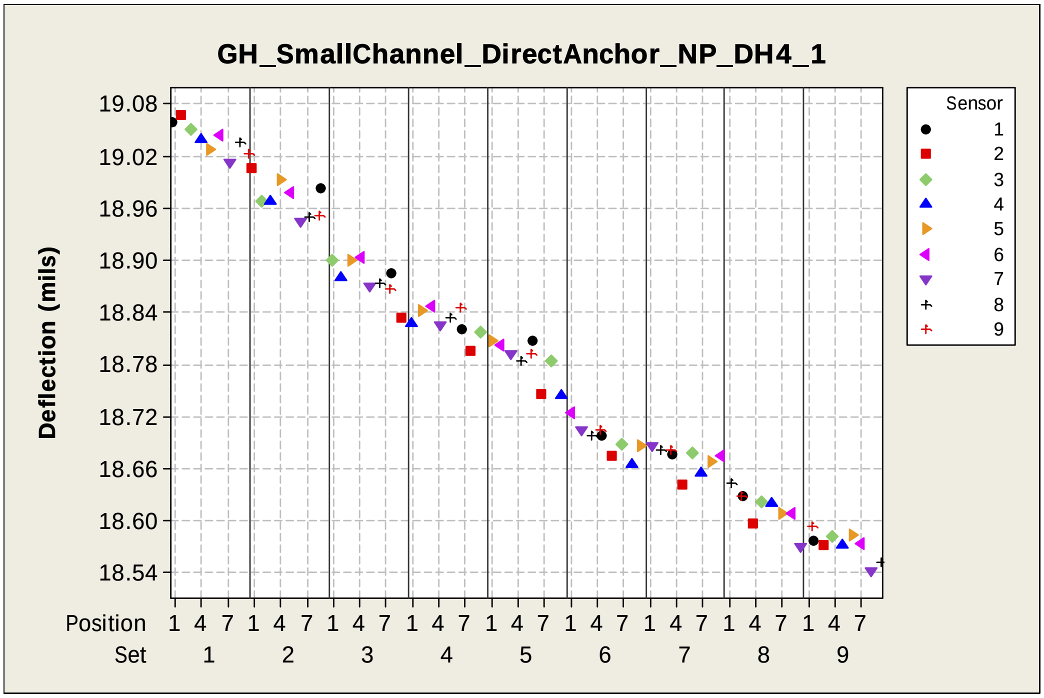

Figure 6 – Variability of sensor deflections due to set as well as position in the relative calibration test. (Note: 0.04 mil = 1 micron)

It can be seen that the largest source of deflection variability is attributable to set. That is because the physical properties of the test pad materials are changing during the course of the test, as repeated drops are applied. The ANOVA results for this test, reported in Figure 5 for the small channel-direct anchor, show the range of deflections due to position was slightly more than 0.04 mil (1 micron) and the unattributed error was 0.02 mil (0.5 micron). We believe there is no way these small effects could be determined visually from the data in Figure 6.

Conclusions. The following conclusions have been drawn from the study of stand designs.

- If a very stiff stand is used, the bias error due to position will be less than 0.04 mil (1 micron).

- The accelerometer should be placed at the mid-height of the stand. Since the bias error due to position is nearly linear, the largest errors will be at the top and bottom of the stand, and those errors will be about 0.5 micron or less.
- By simply rotating the sensors in the stand once, top to bottom, the bias error due to position can be cancelled out.
- A reasonable effort should be made to align the sensors vertically, one above another, in the stand.
- The stand should be held vertical as indicated by a bubble level.
- The stand must be physically attached to the test pad.
- A person must hold on to the stand while the testing is done.
- Several stand designs and hold down designs are satisfactory. A decision regarding which design to use must be based on operational considerations, after the designs have been tested with all makes of FWDs.

Software Development

We began the software development project by converting the old DOS-based FWDREFCL software to Visual Basic 6. Then we converted the calls to the old Keithley DAS-16 data acquisition board to calls to the new Keithley KUSB-3108 DAQ board. That effort was nearly completed by the end of the fifth quarter. During this reporting period we concentrated on the new features that would allow us to use an accelerometer in place of the old LVDT as our reference sensor. Mainly this required us to develop new subroutines for double integration of the acceleration signal. We also had to develop a means to calibrate the accelerometer, and that uncovered some problems that are discussed in the next section.

To facilitate this development and to avoid the need to continuously rewrite the VB6 software, we used an Excel spreadsheet for the integration, and a LabView program for the accelerometer calibration. As these procedures began to take form, we added the VB6 subroutines to the new software. The new program has been tentatively named *WinFWDCal*. During the next quarter we will test the software with all makes of FWDs.

It is important to understand that the hardware development, the development of new calibration procedures, and the software development go hand-in-hand. One cannot be completed before another. Changes in one area generally beget changes in the other two. We expect that the software will be the last facet of the project that will put into final form.

To facilitate the electronic transfer of data from the FWD computer to the Calibration Center computer, we have a PDDX (pavement design data exchange) file reader in WinFWDCal. However, since very few if any FWD owners have the capability to create output files according to the AASHTO file standard, we launched into a project to create a PDDX file conversion program. This software reads the native file output from each make of FWD and creates a new file according to the AASHTO PDDX standard. Two manufacturers, Dynatest and JILS, have the capability to create PDDX files, but many FWD owners are not using the latest versions of the FWD software. Furthermore, the PDDX files created by the FWD field programs are set up for input into the AASHTO DARwin software. These PDDX files depart in some places from the AASHTO standard.

We have found that the AASHTO PDDX standard also does not include the current load cell calibration factor in the file. This poses a problem for FWD calibration. Thus two actions must be taken.

- The problems with and conflicts between the PDDX file formats need to be brought before AASHTO and reconciled.
- We must create a small file in each FWD that comes in for calibration, which will contain the information that is needed for calibration, but is not in the native file output.

During the quarter we worked on both of these items, while we were writing the PDDX file conversion software. We expect that it will be a long time before AASHTO takes action to solve the basic problem. Thus we expect that at some future time the WinFWDCal software will require revisions to conform to the new standard.

Problems encountered during the reporting period

Accelerometer Hysteresis or Drift

Early in the quarter we conducted a shaker table study to assess the frequency response of the accelerometers and the LVDTs that we were using. At the same time, we had a student engaged in studying the effect of changing temperature on the accelerometer response.

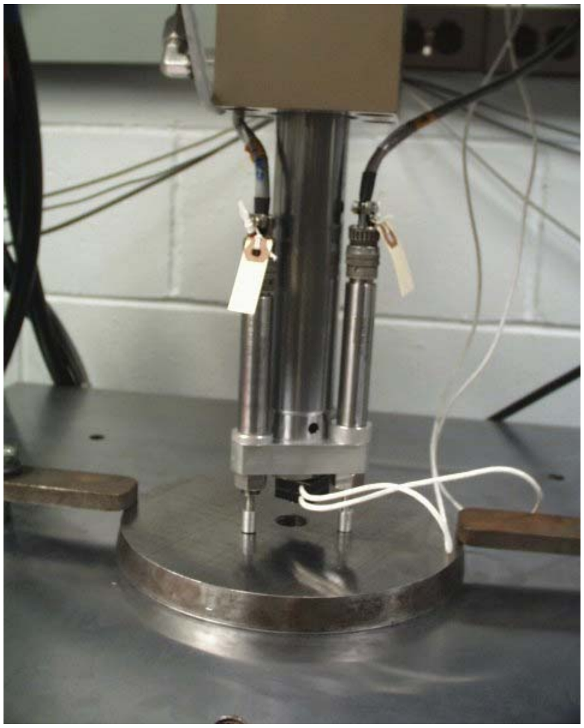

Figure 7 – Shaker table study to investigate frequency response of sensors. Left photo: Apparatus holding three LVDTs and two accelerometers symmetrically about the moving piston. Right photo: Control instrumentation with test frame in background.

A large amount of time was invested in preparing for and carrying out the shaker table experiment. Data were collected at four levels of displacement (0.5, 1.0, 1.5 and 2.0 mils) and over a variety of frequencies from 0.25 Hz to 60 Hz. The equipment for the study (Figure 7) was provided without charge to the project, but scheduling the use of the equipment was difficult.

Soon after the shaker table experiment was completed, the student doing the temperature study began reporting unexpected responses from the accelerometer. She was using Earth gravity to calibrate the voltage response of the accelerometer in terms of g's. By flipping the accelerometer over on a level surface, she could get calibration points for +1.0 g and –1.0 g. But there seemed to be no consistent pattern from one day to the next in the voltages she was getting.

We discussed the problem with the accelerometer manufacturer, Silicon Designs. It seems they are aware of the problem, but it is not mentioned in their technical literature. They called it a hysteresis effect. It only has significance if one is trying to use the accelerometer at the highest level of accuracy, which we are doing.

The hysteresis effect occurs when the accelerometer is reoriented in Earth gravity (i.e., "flipped over"). The output voltage immediately begins a small and predictable change. The rate of change is fastest at first, and it gradually slows down over time. The rate of change is also faster at high temperatures and for accelerometers with high sensitivity (i.e., low maximum g rating). The hysteresis occurs in the same way whether the accelerometer is powered, or if it is just sitting at rest without input voltage.

In an e-mail, the manufacturer described the problem for a 20 g accelerometer as follows.

> *All of our accelerometer models also exhibit what we call Acceleration Hysteresis which is about 0.3% of the applied acceleration after 1 hour at room temperature. If the device is held in the -1g position for 1 hour, then moved to the +1g position and an output reading is immediately taken, and then another +1g reading after 1 hour, the difference between the two +1g readings will likely be 0.3% of 1g (or 3 mg). If the +/-1g dwell times are extended to 1 day, the difference in +1g readings will likely be 0.5% of 1g (or 5 mg). For 6-day dwells the reading difference will likely be 1% of 1g (or 10mg). There is very little additional change for dwells longer than 6 days. This drift phenomenon is also dependent upon temperature. The error figures cited above are for room temperature, but they double for every 35C increase in temperature. This means that the error at +95C will be approximately 4 times greater than at room temperature, and the error at +125C will be approximately 7 times greater than at room temperature (25C).*

The time base for our ±5 g accelerometer is about four times faster than is described above. Thus it takes about 15 minutes for a 0.3 percent change, about 6 hours for a 0.5 percent change, and about 36 hours to equilibrate at a 1 percent change. There is no further change after 36 hours.

We have devised an accelerometer calibration procedure that will compensate for the hysteresis effect. First, the accelerometer must be equilibrated in the upright position for at least one day (thus the output voltage at +1g is not changing). Second, the accelerometer is flipped to the –1g position and a voltage reading is taken within a few seconds (this assures the hysteresis effect will have a negligible influence on the voltage). Next, the accelerometer is immediately put back into the upright position and allowed to sit without use for at least two to three minutes (so that it can re-equilibrate in the +1g position). This provides a repeatable relationship between the measured output voltage and the 2g acceleration change, as long as the accelerometer remains upright.

The discovery of the hysteresis effect posed problems for the data that was taken during the shaker table experiment. We used flip calibration, but without regard to the time that the accelerometer was in any given position. And while flip calibration was done regularly, no record of the timing was kept, as we were unaware then that it mattered. This could lead to unquantified errors in the sensitivity (g's per volt) somewhere between 1 and 2 percent.

A second error in the data was found after the experiment was completed. The test frame of the shaker table is on the second floor of a steel frame building. There was a noticeable amount of vibration of the floor slab at the larger displacements and higher frequencies. The vibration was unmeasured. While it had no effect on the LVDT data, it confounds the accelerometer data.

Together, the hysteresis errors and the floor vibration render the shaker table data unusable. The limits of time and manpower prevent us from repeating the experiment. Still, it is our general impression from the data that the accelerometer is responsive over the entire range of frequencies of interest, and that the calibration data supplied by the manufacturer is apparently accurate.

Work completed by task

The six tasks referred to below are described in detail in the Statement of Work on the TPF-5(039) pooled-fund web site. Progress was also made on all tasks during this quarter.

Task 1. Communication, Coordination and Reference Resources

Task 1a is complete. All protocols, software, and drawings of the currently used FWD equipment that are available are in hand. One set of this information will be transmitted to the COTR.

Task 1b will continue throughout the project. This task provides for a dialog with the FWD manufacturers and the calibration center operators. We feel this dialog should continue for the duration of the project.

During the reporting period we contacted the Calibration Center Operators and arranged to visit the Pennsylvania, Colorado and Texas centers early in the next quarter.

The Task 1 report is essentially finished. All it requires is a bit of reorganization of the tables and a final edit.

Task 2. Modify Calibration Process

Task 2a is nearly complete. Our revised calibration procedure combines reference calibration and relative calibration into a single procedure, with electronic data transfer from the FWD computer to the Calibration Center computer. The software is being modified to support this approach.

We are committed to use of the accelerometer as the reference deflection sensor. We have found the accelerometer is unbiased and repeatable, provided that the calibration procedure noted on page 11 is used to overcome the hysteresis problem.

We need an unbiased reference sensor and an unbiased stand for the calibration procedure. We have developed a nearly unbiased sensor stand, and the small bias error can be cancelled out by simply inverting the sensors in the stand. The full rotation of sensors through all position in the stand is no longer necessary.

A goal for streamlining the calibration procedure was established at the April 2005 meeting of the Technical Advisory Committee (TAC). The Committee asked that we expedite the procedure so it can be completed within three hours. We have been able to complete the new procedure in well under two hours, so we feel the goal has been achieved.

While the new software has the ability to read the FWD data from a PDDX file format, we have found there are problems with the AASHTO standard for PDDX files. We will work with COTR and the AASHTO committee in an effort to reconcile the problems.

During the quarter we finished the project of gathering a database of calibration test results. The database of calibration results will prove to be an asset when we assess whether the revised calibration procedures meet or exceed the accuracy and precision of the current procedures.

Task 2b will not be necessary. In FWDREFCL we have been successful with developing "about triggering" for the Keithley KUSB-3108 DAQ board. This means that an event such as the falling mass striking the load plate can be used to detect the release of the falling mass. We have found that this technique will work with both load and deflection sensor calibration. Thus it will not be necessary to develop an automated mechanism to trigger data acquisition at the release of the mass.

Task 2c will not be necessary. The LVDT/beam/block assembly will be eliminated through use of the accelerometer as the reference deflection sensor. Thus it will not be necessary to develop an automated mechanism to correct for movement of the beam.

Task 3. Hardware and Software Upgrades and/or Development

Task 3a is nearly complete. All major aspects of the conversion of the software to a Windows environment have been completed. Cosmetic refinements are still being made. The new software, WinFWDCal, is able to collect and report data from the accelerometer, and convert it to displacement units. The new software can read data from the FWD in a PDDX format.

During the coming quarter we plan to test the software concepts on the KUAB, JILS and Carl Bro FWDs. We anticipate that this will require further, minor refinements of the software.

No effort was made on Task 3b during this reporting period. We do not plan to purchase hardware for distribution to the Calibration Centers until the COTR has accepted the modified procedures. We plan to test the new procedures, hardware and software on all makes of FWDs during the coming quarter. If that is successful, then we will request approval to purchase hardware for distribution to four centers during the last quarter of this contract.

Task 4. Calibration System Testing, Installation and Operator Materials/Training

Task 4a is continuing. Collection of a database of calibration test results is complete. This will be used to verify that the new procedures equal or exceed the previous calibration procedures.

We have substantially exceeded the goal of developing a new procedure that can be completed with three hours.

During the next quarter we will arrange visits to several of the Calibration Centers to use the new equipment and software with the JILS, KUAB, and Carl Bro FWDs. This will give the Calibration Center Operators the opportunity to provided feedback on the new features, and give them a bit of training in the use of the software.

Task 4b is continuing. We are documenting the WinFWDCal software, developing flow charts keyed to the software. As various activities are concluded we prepare brief internal reports for the file, which help to organize the data and will expedite the writing of the software and hardware documentation.

No effort was made on Task 4c during this reporting period. Efforts to involve the Calibration Center Operators in testing the new procedures and equipment will begin early in the coming quarter. Formal installation of the new equipment and training for its use will not proceed until the COTR has accepted the modified procedures.

Task 5. Presentation and Reporting

There were several activities during the reporting period.

- We met with the COTR during the TRB Annual Meeting in January.
- Dates for the next meeting of the Technical Advisory Committee meeting were set. Arrangements have been made to meet in Denver, CO on April 27-28.
- Travel arrangements for the TAC members are being made.

Task 6. Miscellaneous Support for TPF-5(039)

This task is not included in the current contract. Effort on this task is not anticipated before fall 2006. It will require separate task orders.

Work planned during the coming quarter

By the end of the next quarter we expect the procedures, hardware and software to be in final form. Near the end of the quarter we plan to seek the COTR's acceptance of the new calibration procedures.

Under Task 1 we will continue to maintain a dialog with the FWD manufacturers and Calibration Center operators.

Under Task 2 we will make whatever adaptations of the proposed procedures are necessary to assure compatibility with the KUAB, JILS and Carl Bro FWDs.

Under Task 3 we will finalize the hardware and make whatever adaptations of the software are necessary to assure compatibility with the KUAB, JILS and Carl Bro FWDs.

Under Task 4 we will test the procedures, hardware and software with the KUAB, JILS and Carl Bro FWDs at the Pennsylvania, Colorado and Texas Calibration Centers, respectively. Depending on the outcome of these tests, we may decide to test the equipment and procedures at the Indiana Calibration Center to give us exposure to the EMF radiation that has posed problems for them in the past.

Near the end of the quarter we expect to begin drafting the final report.

Under Task 5 we will meet with the Technical Advisory Committee near the end of April.

Task 6 – Not included in the current contract.