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16. Abstract

A Rolling Dynamic Deflectometer (RDD) has been developed by making modifications to a vibroseis truck. The RDD can make continuous profiles of pavement flexibility or stiffness can be measured under heavy loads. The RDD employs a servo-hydraulic vibrator to apply static hold-down and vertical dynamic forces to two sets of dual loading wheels. A total force (static plus dynamic) of 150 kN (33,000 lb) can be applied to the pavement surface while the RDD is moving at velocities of 3 to 6 km/h (2 to 4 mph). Dynamic deflections of the surface are continuously recorded with an accelerometer located on a set of receiver wheels positioned mid-way between the loading wheels.

The loading and monitoring systems of the RDD have been calibrated, and initial testing has been performed at the Texas Transportation Institute (TTI) pavement test facility. Eight flexible pavement sections, covering a range in flexibility, have been successfully tested. Loading frequencies of 22 and 40 Hz have been used with a wide range in dynamic loads. The RDD was able to make measurements of: longitudinal variability within each section, differences in flexibility between sections, and nonlinearities in flexibility at several sections. Finally, a comparison between RDD and FWD measurements show the flexibilities measured by both methods are consistent with each other, and closely related.

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DEVELOPMENT AND PRELIMINARY INVESTIGATION OF A ROLLING DYNAMIC DEFLECTOMETER

Kenneth H. Stokoe, II
James A. Bay

Research Report 1243-3

Research Project 0-1243
Automated Equipment for Characterizing the Properties and Thicknesses of Pavements

conducted for the

Texas Department of Transportation

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

Center for Transportation Research
Bureau of Engineering Research
The University of Texas at Austin

December 1994
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IMPLEMENTATION STATEMENT

The results of this research indicate that the Rolling Dynamic Deformation (RDD) is a valuable tool for accessing the condition of highway pavements. The RDD is capable of measuring continuous flexibility profiles of pavements over long distances. As the RDD is currently configured, and given our present understanding of the effects of RDD loading, the RDD can be used to (1) detect weak or soft zones in a pavement system, (2) determine changes in pavement and subgrade conditions, (3) provide quantitative and qualitative comparisons between different pavement systems, (4) determine nonlinear pavement flexibility by loading over a wide range of force levels, even up to failure, and (5) evaluate load transfer mechanisms at joints and along pavement edges. With further improvements, the RDD should be able to provide even more information about pavement systems. For instance, including more measurement points should enable the determination of the thicknesses and moduli of pavement and subgrade layers. By using the RDD to load over a wide range of frequencies, more information can also be obtained about the constitutive properties of pavement materials.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

DISCLAIMERS

Kenneth H. Stokoe, II (Texas No. 49095)
Research Supervisor

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ABSTRACT

Nondestructive testing (NDT) is an important part in optimizing any pavement management system. At this time in the United States, NDT is performed at discrete points on the pavement to evaluate the properties of the pavement layers. Techniques such as the Falling Weight Deflectometer (FWD), the Dynaflect and the Spectral-Analysis-of-Surface-Waves (SASW) are used. A new technique is presented in this report. It is called the Rolling Dynamic Deflectometer (RDD) and is a large truck on which a servo-hydraulic vibrator is mounted. The vibrator is used to apply large vertical dynamic loads (up 150 kN (33,000 lb)) to rolling wheels which contact the pavement. A receiver wheel located mid-way between the loading wheels is used to monitor the dynamic deflections. The truck is driven at a slow speed (about 5 km/hr (3 mph)) and continuous profiles of pavement flexibility are measured under heavy traffic and overload conditions. Descriptions of the equipment, calibration results and test procedures are presented. Several examples involving tests of flexible pavements and comparisons with FWD results are included. The results show that the RDD can be used to: 1) determine uniformity along pavement sections, 2) measure differences in average flexibility between different sections, and 3) observe nonlinearities in a given pavement section. Additional, the RDD has the potential to perform many other functions such as load-transfer and cycles-to-failure studies.

TABLE OF CONTENTS

SUMMARY

A Rolling Dynamic Deflectometer (RDD) has been developed by making modifications to a vibroseis truck. The RDD can make continuous profiles of pavement flexibility or stiffness can be measured under heavy loads. The RDD employs a servo-hydraulic vibrator to apply static hold-down and vertical dynamic forces to two sets of dual loading wheels. A total force (static plus dynamic) of 150 kN (33,000 lb) can be applied to the pavement surface while the RDD is moving at velocities of 3 to 6 km/h (2 to 4 mph). Dynamic deflections of the surface are continuously recorded with an accelerometer located on a set of receiver wheels positioned mid-way between the loading wheels.

The loading and monitoring systems of the RDD have been calibrated, and initial testing has been performed at the Texas Transportation Institute (TTI) pavement test facility. Eight flexible pavement sections, covering a range in flexibility, have been successfully tested. Loading frequencies of 22 and 40 Hz have been used with a wide range in dynamic loads. The RDD was able to make measurements of: longitudinal variability within each section, differences in flexibility between sections, and nonlinearities in flexibility at several sections. Finally, a comparison between RDD and FWD measurements show the flexibilities measured by both methods are consistent with each other, and closely related.

CHAPTER 1. INTRODUCTION

Nondestructive testing (NDT) techniques have been utilized for several decades in the field to determine the properties of pavement systems. The most common techniques used in the United States are the Falling Weight Deflectometer (FWD), the Dynaflect and the Spectral-Analysis-of-Surface-Waves (SASW) technique (1-4). Each of the methods requires the equipment to be stationary during testing. Therefore, it is difficult or impossible to obtain continuous or nearly continuous profiles either longitudinally or laterally along the pavement. To overcome this limitation of sampling at discrete points, a Rolling Dynamic Deflectometer (RDD) has been developed with which rapid measurement of continuous profiles of pavement flexibility or stiffness under heavy traffic and overload conditions can be performed. This device can move down the pavement at speeds of 3 to 6 km/hr (2 to 4 mph) and continuously record pavement deflection under a significant static and large dynamic loads. This deflectometer presently represents a "one-of-a-kind" piece of equipment. In the following paragraphs, a description of the device is given, calibrations of the loading and monitoring systems are presented, and examples of test data are shown. Several field studies with flexible pavements, including comparison with FWD results, are also presented.

CHAPTER 2. DESIGN AND CONSTRUCTION OF THE ROLLING DYNAMIC DEFLECTOMETER

2.1 DESCRIPTION OF THE ROLLING DYNAMIC DEFLECTOMETER

The Rolling Dynamic Deflectometer (RDD) is shown in Fig. 2.1. This device consists of a vibroseis truck, which is typically used as a wave source for exploration geophysics, that has been modified to apply dynamic loads through a pair of loading wheels and to measure the resulting displacement of the pavement. The vibroseis truck has a gross weight of about 195 kN (44,000 lb) on which a servo-hydraulic vibrator is mounted. The vibrator has a 3400 kg (7,500-lb) reaction mass which is driven hydraulically to generate vertical dynamic forces as large as 310 kN (70,000 lb) peak-to-peak over a frequency range of about 5 to 100 Hz. The basic components of the RDD are shown in Fig. 2.2. When the reaction mass is driven by the hydraulic system as illustrated in Fig. 2.3, the resulting vertical dynamic force is applied to two sets of loading wheels which contact the pavement. Simultaneously, the hydraulic system can be used to apply a constant hold-down force to the loading wheels ranging from 67 to 180 kN (15,000 to 40,000 lb) through a system of air springs. This system is presently under modification so that hold-down forces ranging from 13 to 180 kN (3,000 to 40, 000 lb) can be applied. Deflections generated by the dynamic force are measured at a receiver wheel assembly mid-way between the loading wheels.

The static and superimposed dynamic forces are transferred to the pavement through two sets of dual loading wheels as shown in Fig. 2.3. The use of wheels to transfer the load permits continuous loading to be applied while the complete system is moving. The wheels are quite rigid in that they have a solid, aluminum rim that is coated with hard urethane. This type of wheel was selected to minimize resonances that might occur with pneumatic wheels loaded in this manner. Each wheel is 460 mm (18 in.) in diameter and 127 mm (5 in.) wide. A total force (static plus dynamic) of 150 kN (33,000 lb) can be applied to the pavement surface through the loading wheels at this time. However, in the future, the wheels could be modified to allow a peak-to-peak force as large as 310 kN (70,000 lb) to be applied if this ever became desirable. The reaction mass and servo-hydraulic system are already capable of generating this force level. This point is important, because it highlights the fact that the force is coming from the inertial by the reaction mass moving at high frequencies.

The servo-hydraulic vibrator is capable of generating many types of dynamic loading functions. For instance, transient (like the Falling Weight Deflectometer (FWD), steady-state (at any frequency from 5 to 100 Hz), swept frequency, chirps or random-noise types of loads can be generated. In this initial study, steady-state excitation superimposed on a constant static load was employed as illustrated in Fig. 2.4. Dynamic deflections of the pavement surface (due only to the peak-to-peak dynamic loading) are then recorded mid-way between the two sets of loading wheels. These deflections are recorded with an accelerometer located on a set of two receiver wheels as shown in Fig. 2.3. Two wheels were used to support the receiver (accelerometer) simply for stability during movement. Wheels were again used in this part of the rolling device as an inexpensive way of accomplishing continuous measurements. "Rigid" wheels similar to the loading wheels, but slightly smaller, were used. The term rigid is used to differentiate these wheels, which are composed of only solid materials, from pneumatic or fluid filled wheels. The twin receiver wheels, termed "receiver wheel assembly" hereafter for convenience, are isolated from the loading mechanism and truck by the support arm shown in Fig. 2.2.

The basic operation of the RDD involves driving the truck at a slow speed along the pavement while applying dynamic loading and simultaneously measuring the resulting dynamic deflections. The accelerometer on the receiver wheel assembly only monitors vertical dynamic motion, not any vertical deflections resulting from the static load. In these initial studies, measurements have been performed with the truck rolling about 5 km/hr (~3 mph), loading frequencies ranging from 20 to 40 Hz have been used, and only one measurement point (mid-way between the loading wheels) has been employed. There is no reason, however, why multiple measurement points at varying distances from the loading wheels could not be monitored.

2.2 CONSTRUCTION OF THE ROLLING DYNAMIC DEFLECTOMETER

The construction of the RDD required four major modifications of the vibroseis truck. First, the solid loading plate of the vibroseis truck was removed and replaced with a new loading

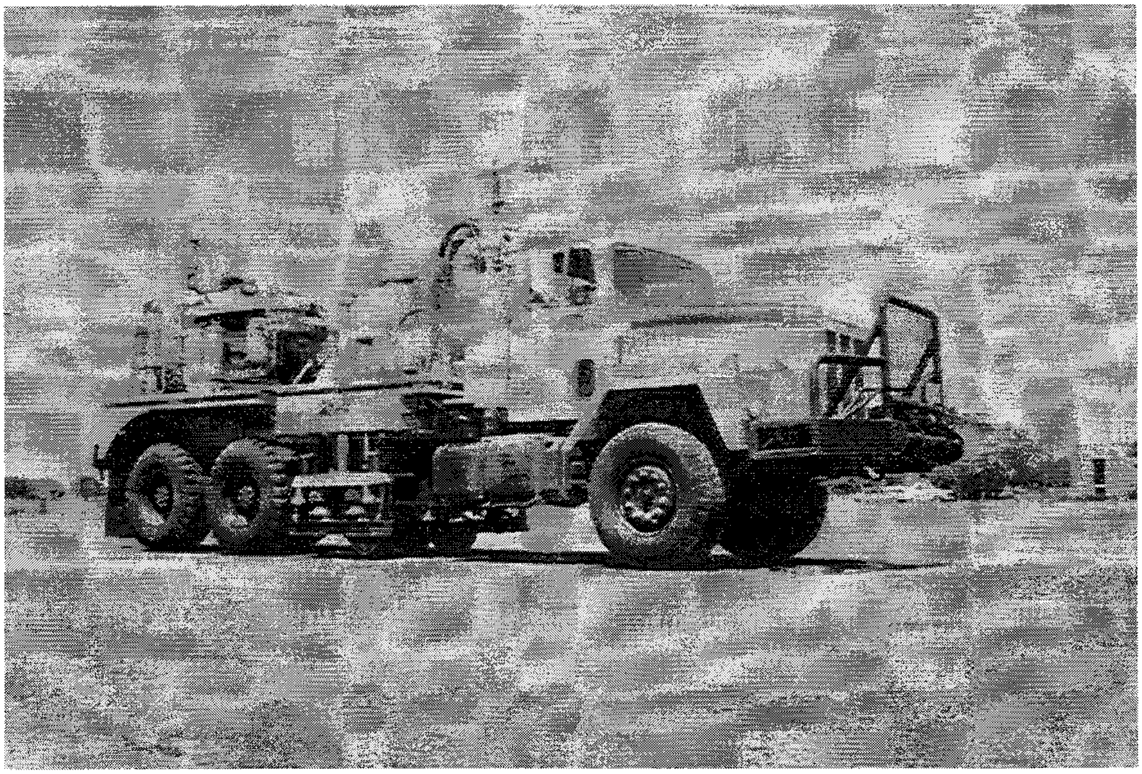


Fig. 2.1 Rolling Dynamic Deflectometer (RDD)

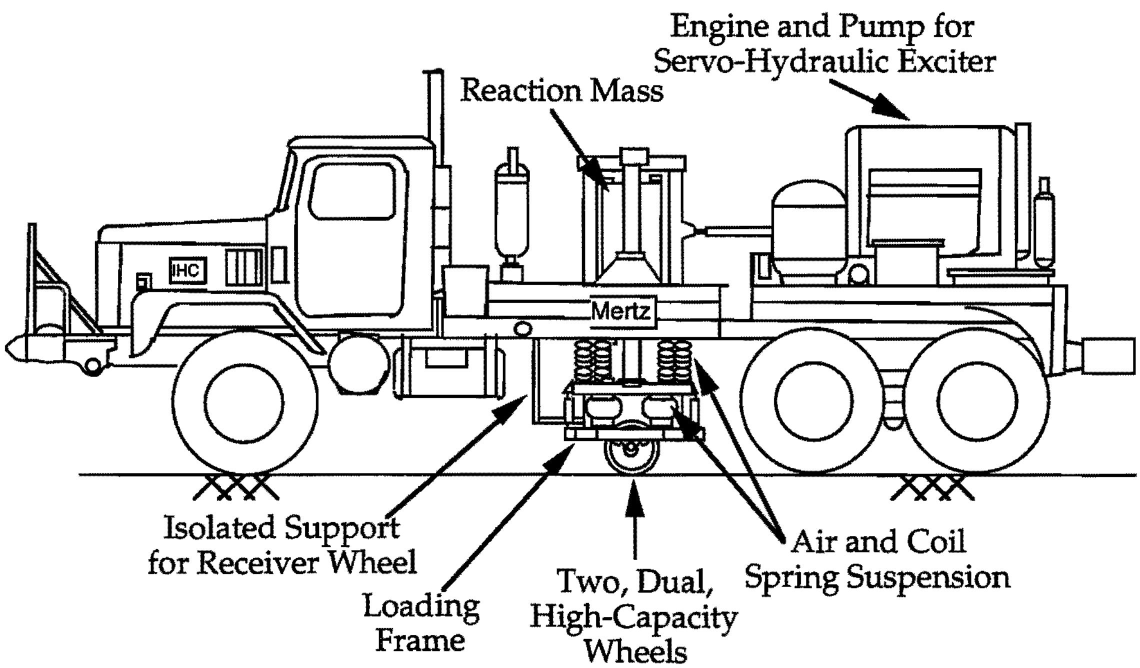


Fig. 2.2 Basic Components of the Rolling Dynamic Deflectometer (RDD) Used to Measure Continuous Pavement Flexibility Profiles

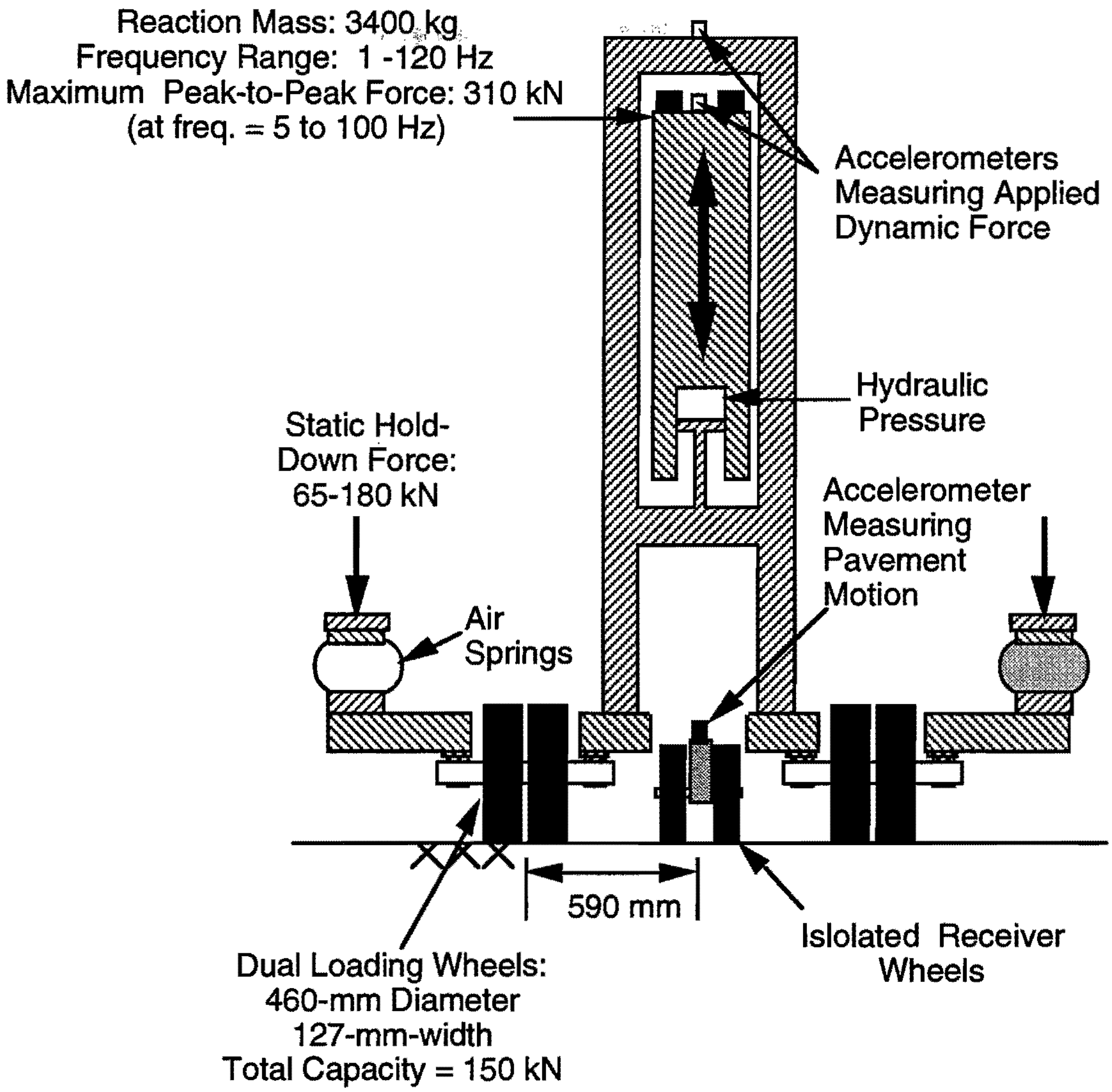


Fig. 2.3 Front Cross-Sectional View of Dynamic Loading and Monitoring Systems of the Rolling Dynamic Deflectometer (RDD)

frame to which the bearings and loading wheels were attached. This loading frame is shown in Fig. 2.5. The loading frame was constructed of steel wide flange sections and steel flat bar stock. The load frame has all of the brackets and attachment points necessary connect it to the vibroseis suspension and loading systems. Most of the components used in the load frame are shown in Fig. 2.6. This photo showes a single receiver wheel. This is as the RDD was initially constructed. However, in initial tests it was found that the receiver did not track straight with this configuration so a second wheel was added for stability. Drawings for all of the load frame components are included in Appendix A.

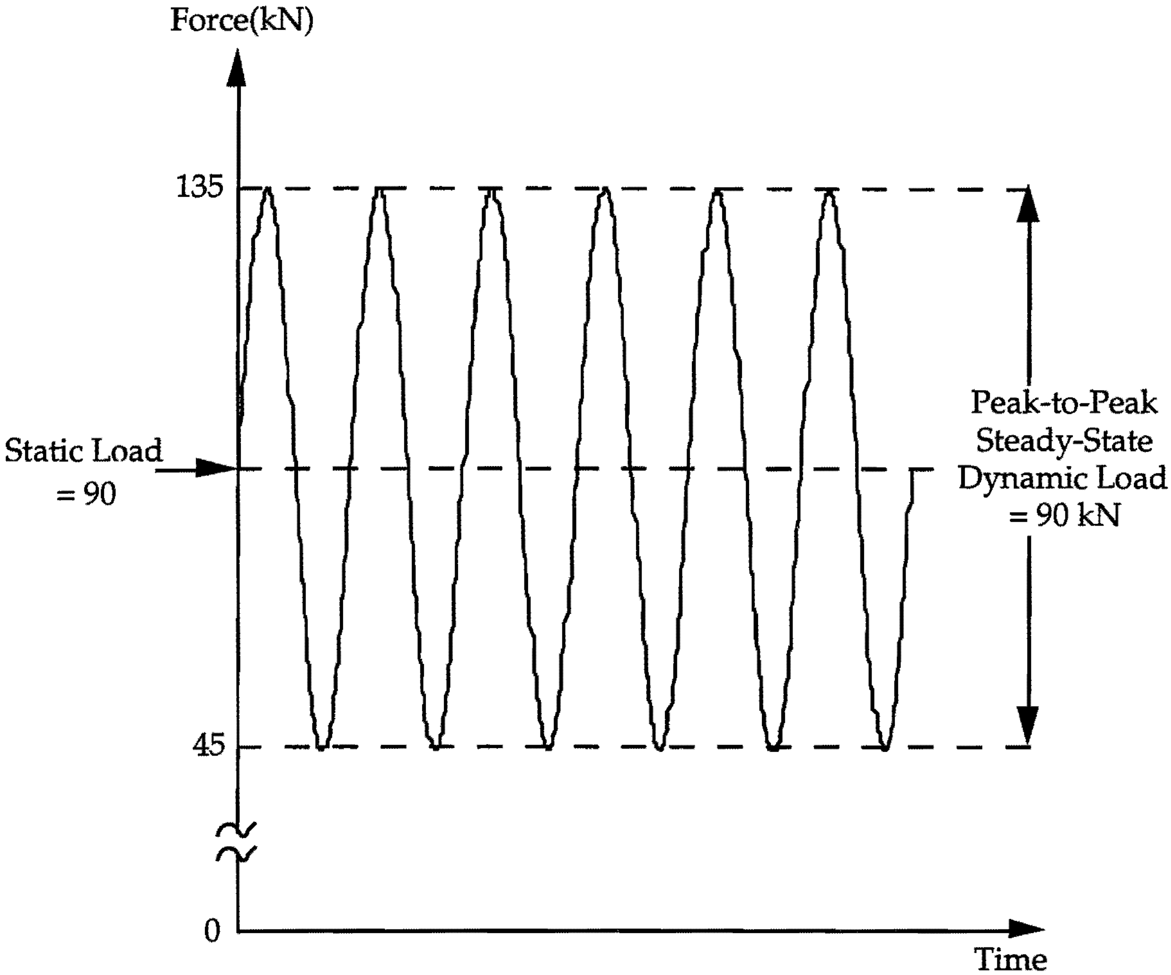


Fig. 2.4 Example of Combined Static and Steady-State Dynamic Loads Applied Continuously by the Rolling Dynamic Deflectometer (RDD)

The second major modification to the RDD was the addition of coil springs to the load frame suspension. The RDD suspension system is shown in Fig. 2.7. Load is applied through the loading foot and air springs. The load frame is supported laterally by the radius rods. The chains lift the load frame and wheels. The coil springs stabilize the reaction mass and stilt structure to prevent tipping. When modifications to the truck's hydraulic system are complete the coil springs will also be able to lift on the load frame, making it possible to operate the truck using static forces less than the combined weight to the load frame, stilt structure and reaction mass. Drawings for all the additional load frame suspension components are included in Appendix A.

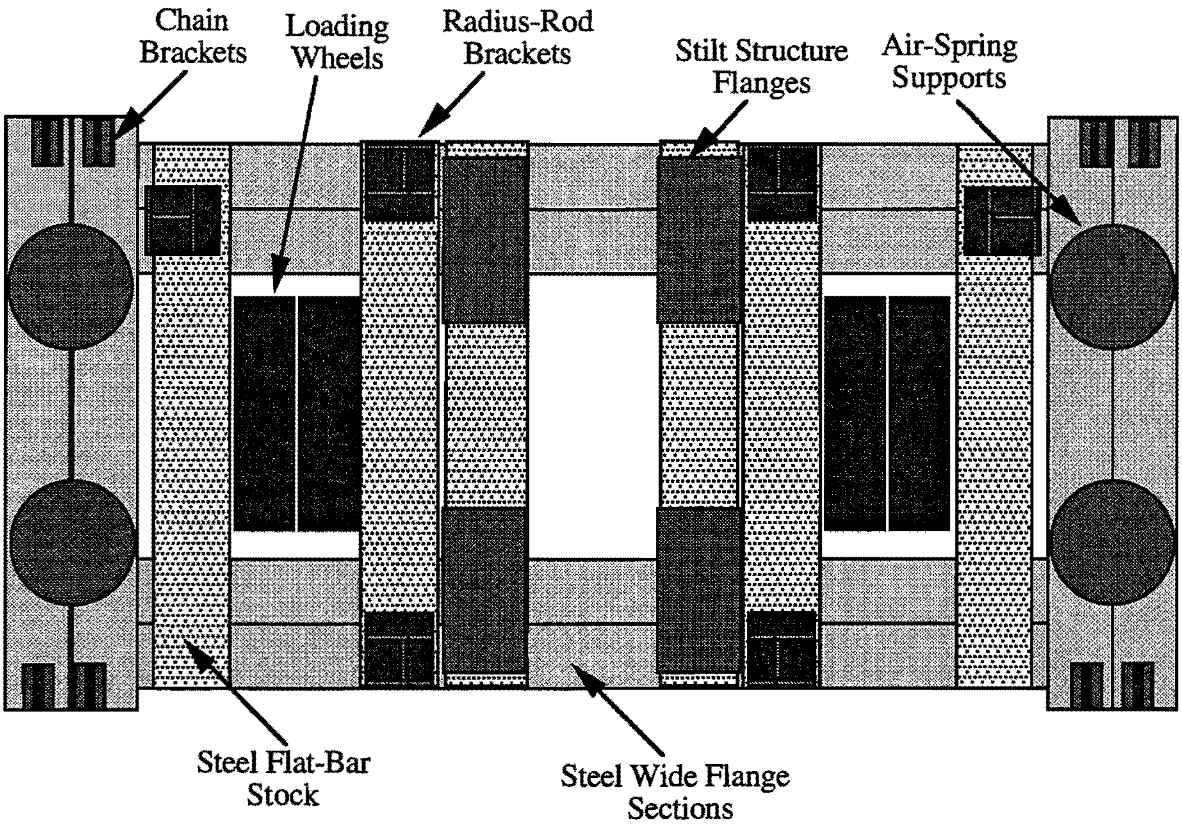


Fig. 2.5 Top View of Loading Frame Used to Transfer Forces to Loading Wheels on Rolling Dynamic Deflectometer

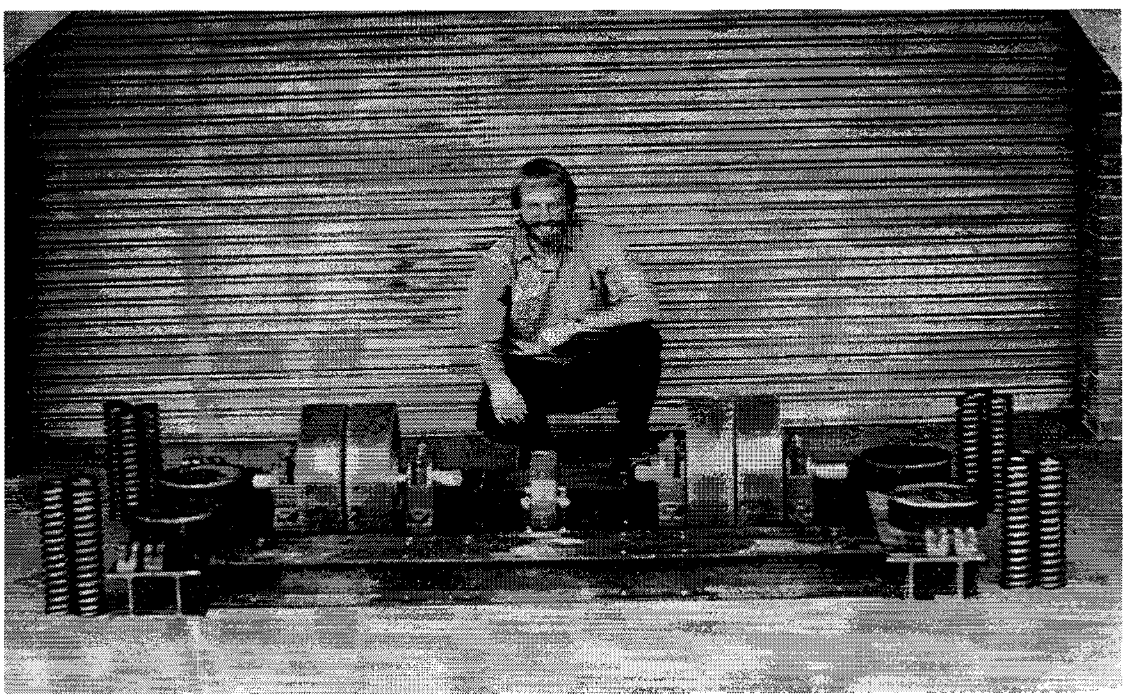


Fig. 2.6 Components Used to Construct Load Frame for Rolling Dynamic Deflectometer

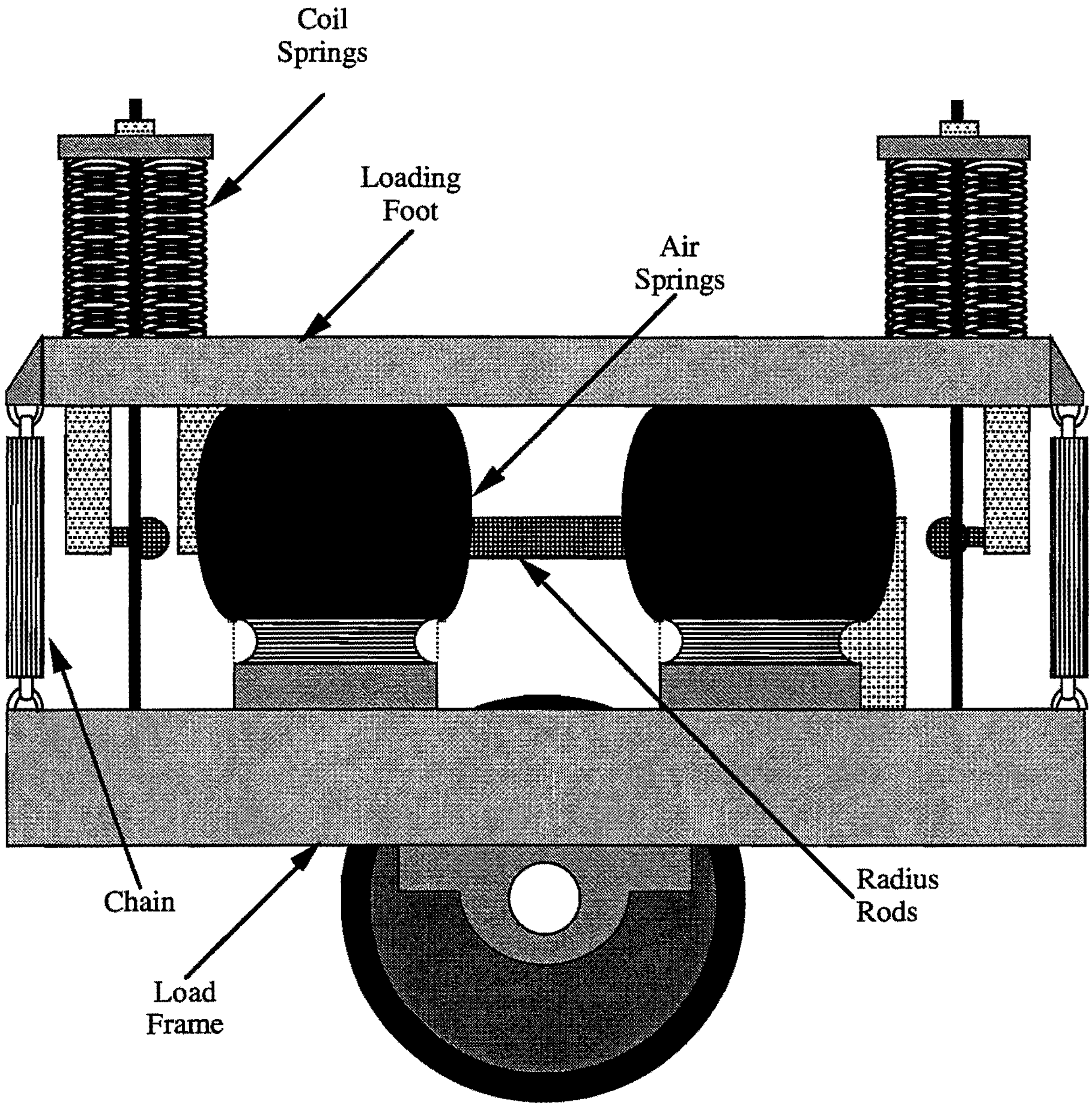


Fig. 2.7 Side View of Rolling Dynamic Deflectometer Load Frame, Showing Suspension System

The third major modification to the RDD was the addition of support rods to the stilt structure to resist over-turning loads induced in the stilt structure and reaction mass by acceleration and deceleration of the truck. These support rods are shown in Fig. 2.8.

The last major modification to the vibroseis truck was the addition of a receiver wheel assembly, which is supported by the truck frame and rolls on the pavement at the midpoint between the two loading wheels to measure dynamic deflections induced in the pavement. Fig. 2.9 shows this wheel and its support structure. The wheel support structure needs to attenuate

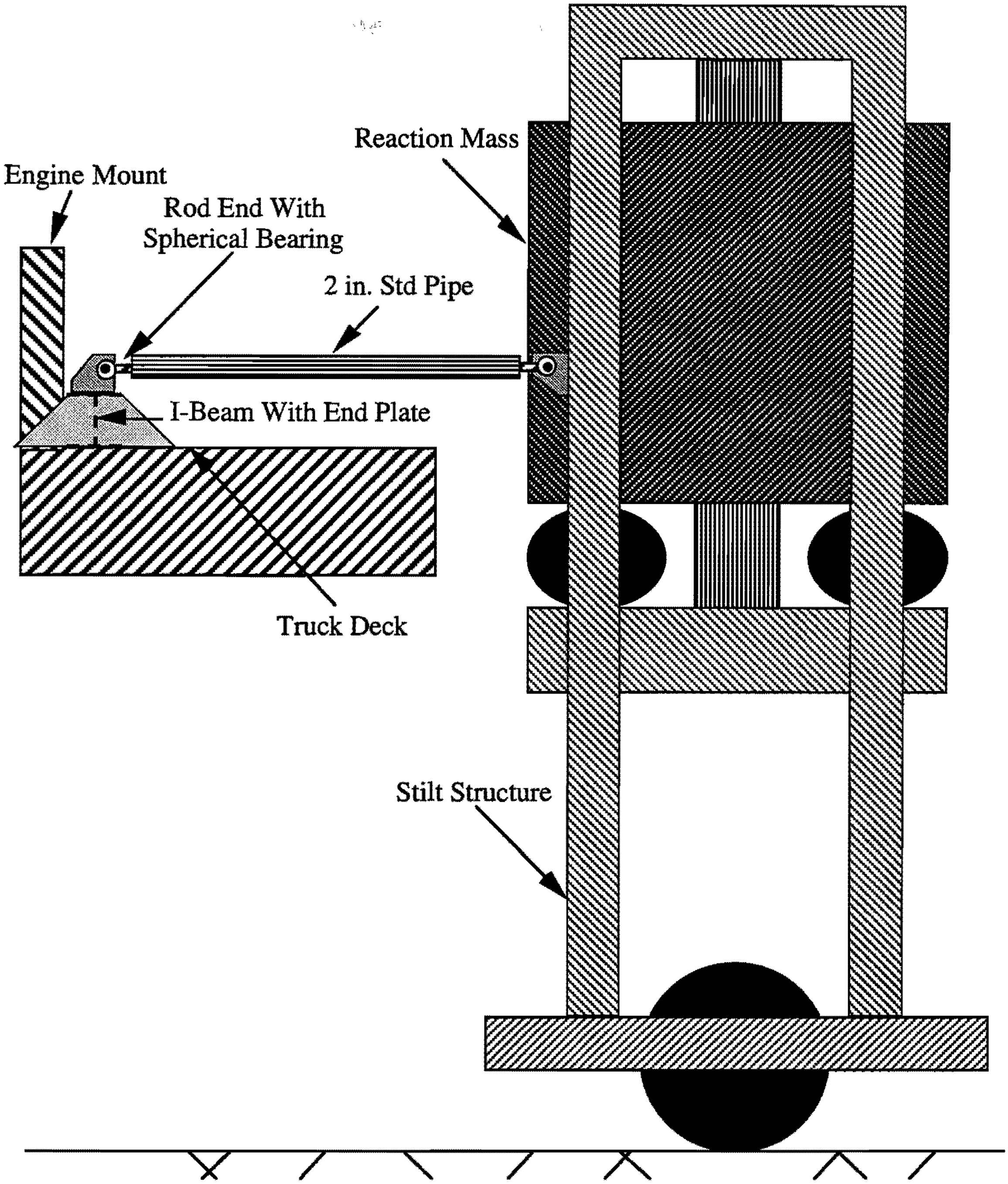


Fig. 2.8 Side View of Rolling Dynamic Deflectometer Stilt Structure, Reaction Mass and Support Rods

vibrations from the truck and hydraulic vibrator. This was achieved by using rubber isolators between the truck and the support structure, and between components in the support structure. More importantly, a pivot point between the vertical and horizontal arms of the support structure combined with a relatively long horizontal support arm significantly attenuate vibrations from the truck and vibrator. Based simply on geometry, rotational motions at the accelerometer resulting from vertical motions at the wheel or pivot point will cause less than a 0.01% error in measurements of vertical motion at the receiver wheel.

It was also important that the receiver wheel assembly tracks smoothly and straight along the pavement surface. This was achieved by using two solid steel wheels with urethane tires, 300 mm (12 inches) in diameter, spaced 130 mm (5 inches) apart.

The receiver wheel assembly support structure was designed so that the load frame will pivot the receiver wheel off the pavement when the loading wheels are lifted off the pavement. This is shown in Fig 2.10. This makes it convenient to move the truck between testing locations.

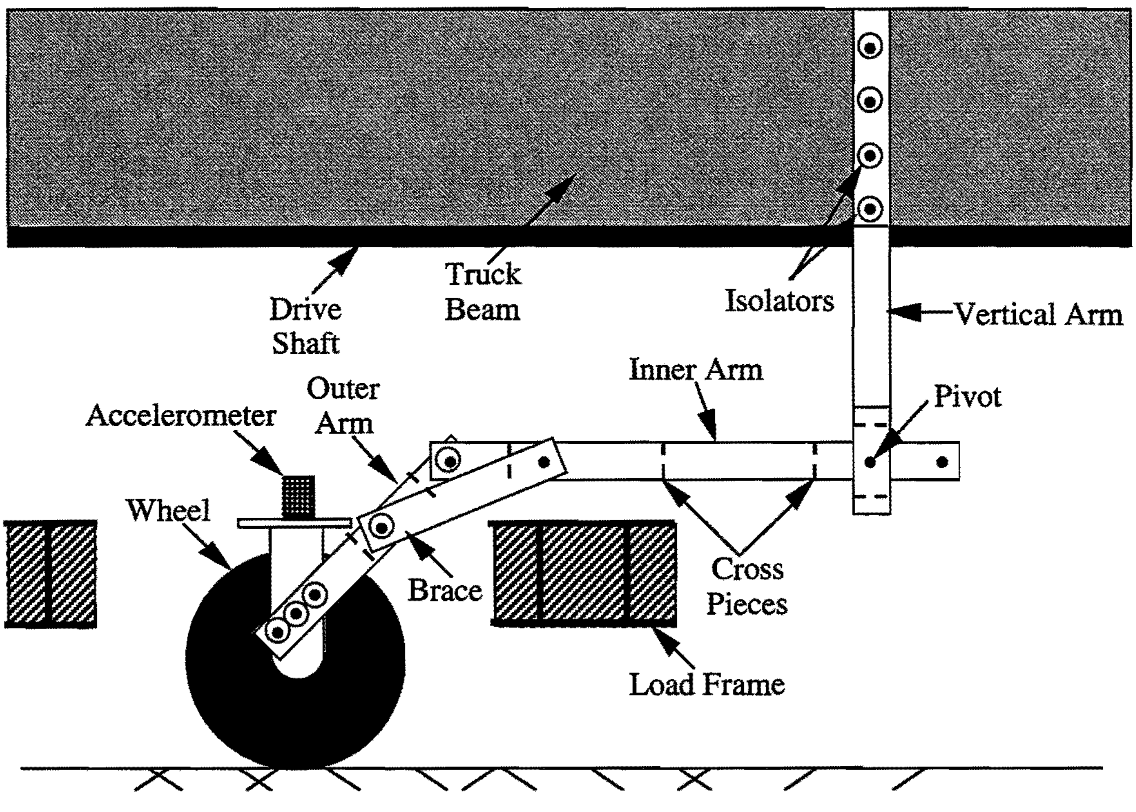


Fig. 2.9 Receiver Wheel and Support Structure Used to Measure Pavement Deflections with the Rolling Dynamic Deflectometer

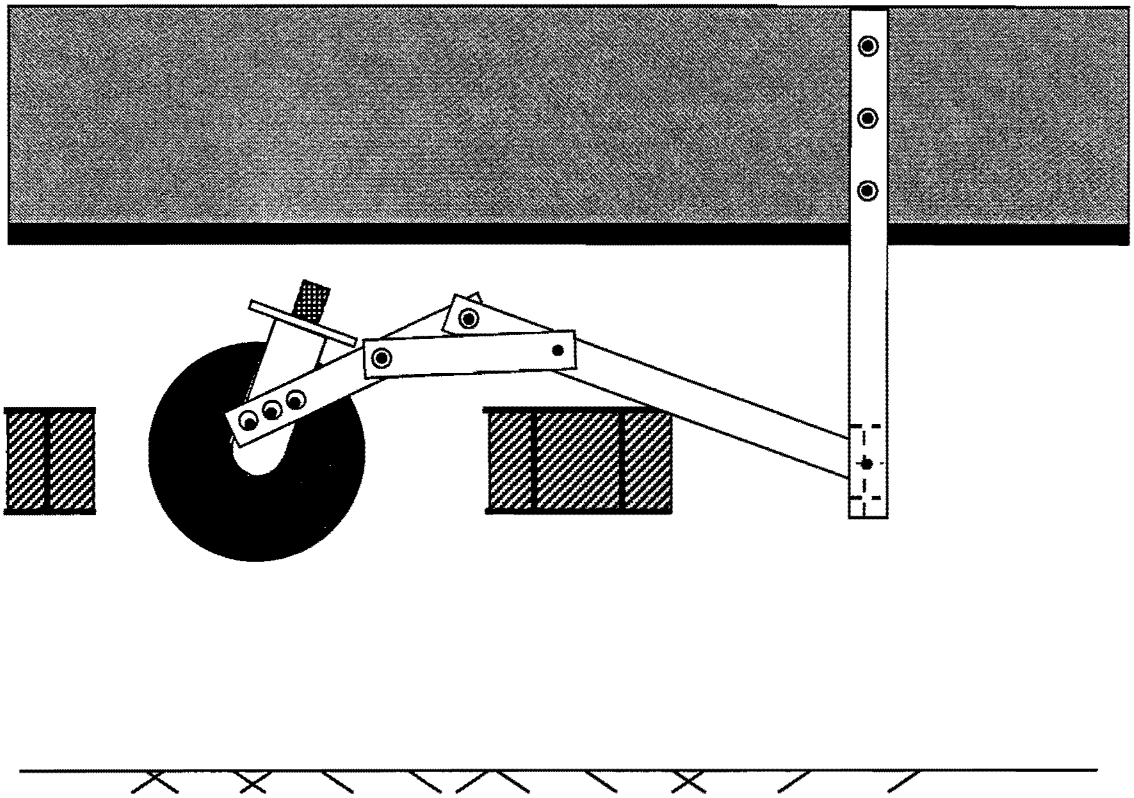


Fig. 2.10 Receiver Wheel and Support Structure Pivoted Up Off the Pavement

CHAPTER 3. EQUIPMENT CALIBRATION

To conduct stiffness or flexibility measurements while rolling, it is critical to perform dynamic calibrations of the equipment used to measure both forces and displacements. Any equipment resonances that fall within the range of excited frequencies will affect the dynamic response of the measurement systems and must be accounted for in the analysis of the recorded data. A set of weigh-in-motion (WIM) load cells were used to calibrate the static and dynamic loads applied in RDD testing (5). Fig. 3.1 shows one of the loading wheels lifted-up above a WIM load cell prior to calibration. A velocity transducer (geophone) was used to calibrate the receiver wheel assembly and an accelerometer was used to measure the dynamic displacements.

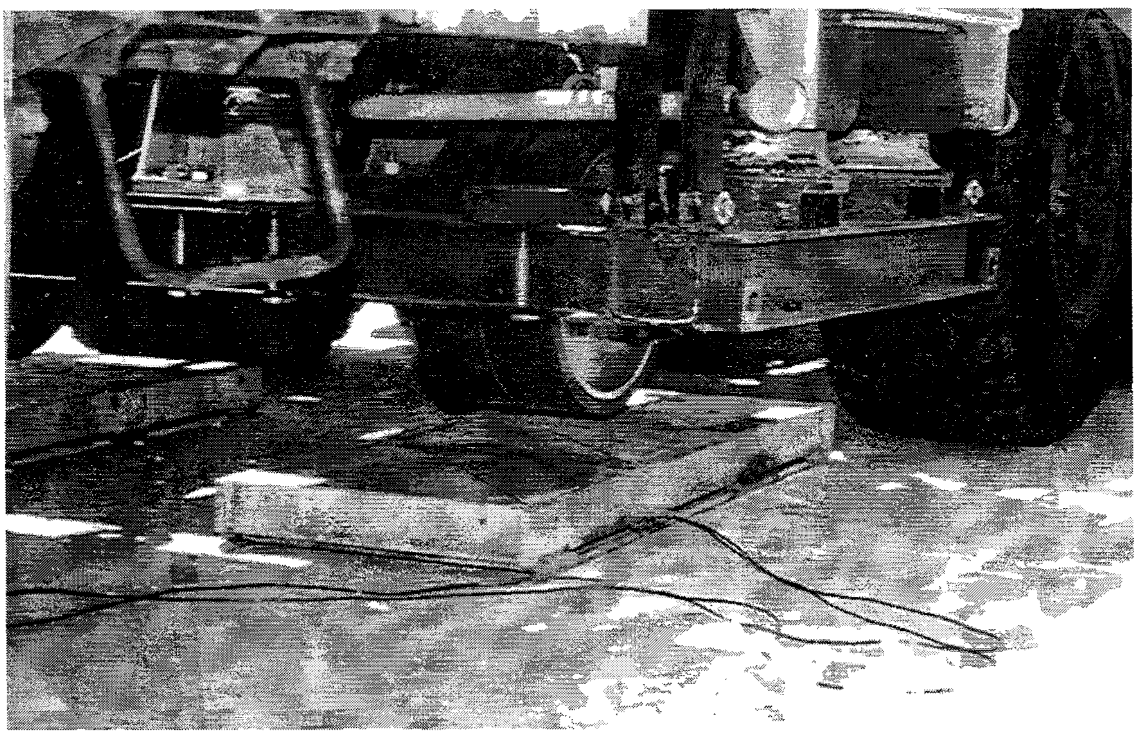


Fig. 3.1 Loading Wheel Above Weigh-in-Motion Load Cell Used To Calibrate Static and Dynamic Forces Applied by the Rolling Dynamic Deflectometer

3.1 STATIC FORCE CALIBRATION

The simplest calibration was the calibration of static load applied to the loading wheels. The static load is a combination of the dead weight of the reaction-mass, load-frame system and the force applied through the hydraulic cylinders. The static force was calibrated by comparing the pressure in the hydraulic cylinders with the force measured with the WIM load cells. This calibration curve is shown in Fig. 3.2. With no hydraulic pressure in the cylinders, a force of 55 kN (12,300 lb) was measured. This represents the dead weight of the reaction-mass, load-foot and load-frame system. The pressure control valve currently used on the RDD system applies a

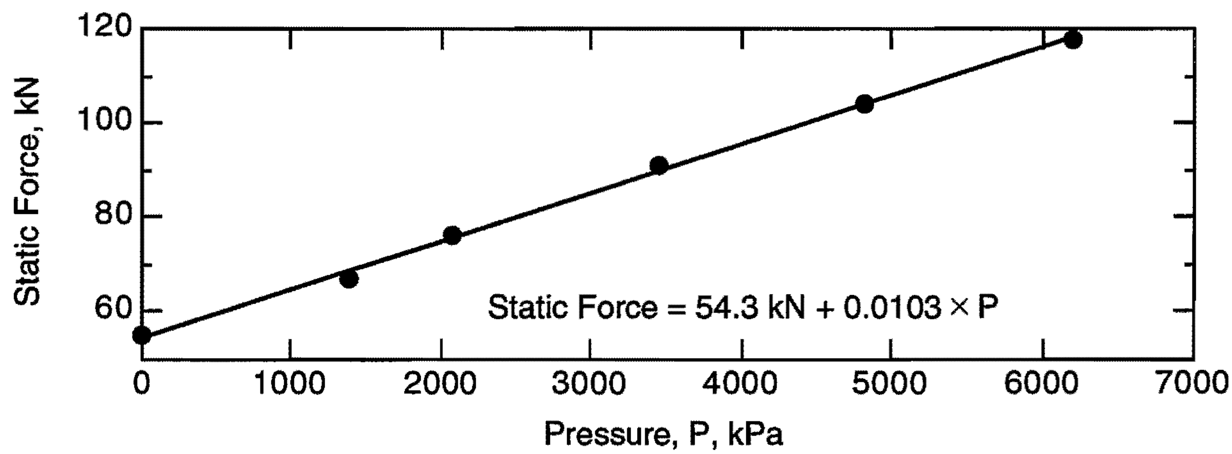


Fig. 3.2 Calibration of Static Load Applied by the Rolling Dynamic Deflectometer

minimum of 1380 kPa (200 psi) and a lifting force can not be applied with the hydraulic system while driving the reaction mass. Therefore, the lowest static force that can presently be applied is about 67 kN (15,000 lb). Future modifications will make it possible to apply much lower static loads.

3.2 DYNAMIC FORCE CALIBRATION

The dynamic force applied by exciting the reaction mass is measured by means of two accelerometers, one on the reaction mass and a second on top of the stilt Structure as shown in Fig. 2.3 and in Fig. 3.3. From Newton's second law, it can be determined that the dynamic force

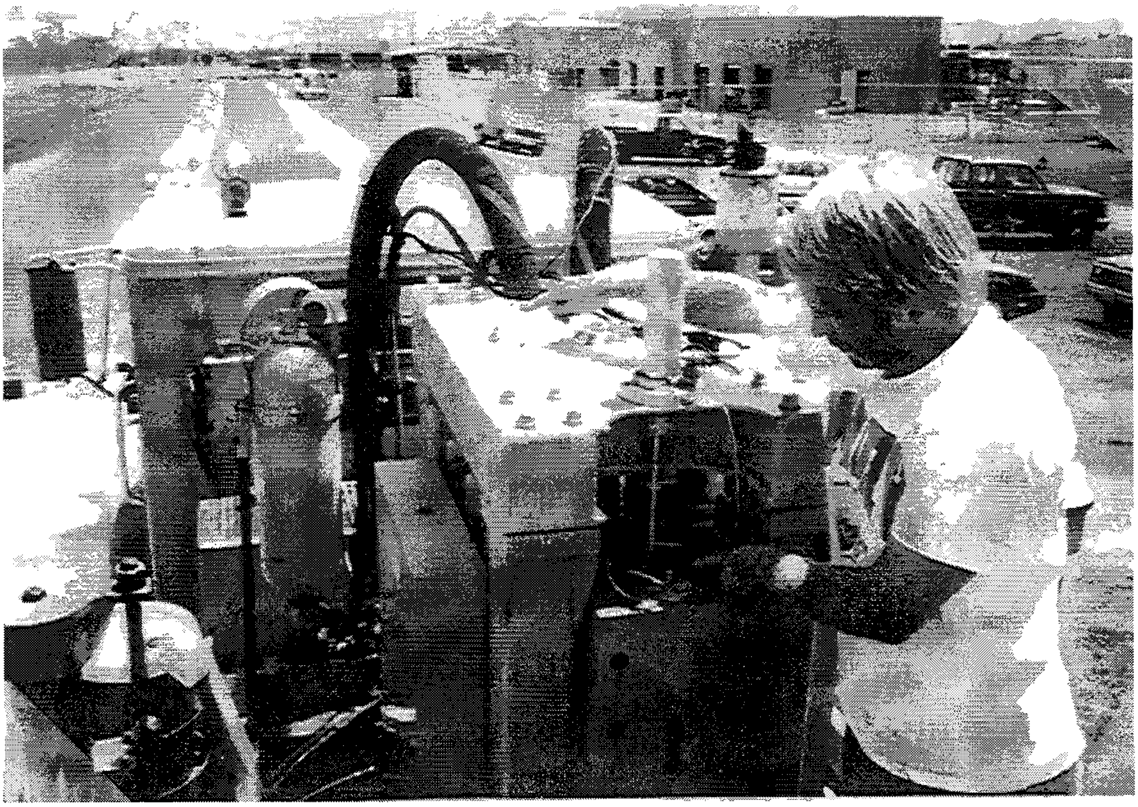


Fig. 3.3 Accelerometers Mounted on Top of Stilt Structure and on the Load Frame Used to Measure Dynamic Force Applied by the Rolling Dynamic Deflectometer

applied to the pavement through the loading wheels, F_d, is equal to the sum of the accelerations of these two parts (the reaction mass and loading frame plus the stilt structure) times their masses as:

$$F_d = A_1 \times M_1 + A_2 \times M_2 \tag{3.1}$$

where A_1 and M_1 are the acceleration and mass of the reaction mass, respectively, and A_2 and M_2 are the acceleration and mass of the combined loading frame and wheels, respectively. To measure the dynamic force, the signals from each accelerometer were amplified with a gain proportional to the mass of the respective system, one signal was inverted, and the two signals were summed with a differential amplifier. To generate a calibration curve, the combined output of the two accelerometers was divided by the dynamic force measured with the load cells, as the RDD was driven at various frequencies. This calibration curve is shown in Figure 3.4. The calibration curve is quite uniform from 1 to 47 Hz. At frequencies below 10 Hz the measurement is still robust because accelerations are so large. At frequencies above 47 Hz, the performance of the system could not be evaluated due to resonances in the WIM load cells. Further work using dynamic load cells with a wider frequecy range is required to calibrate the RDD at higher frequencies. However, the frequency range shown in Figure 3.4 was satisfactory to perform the initial studies presented herein.

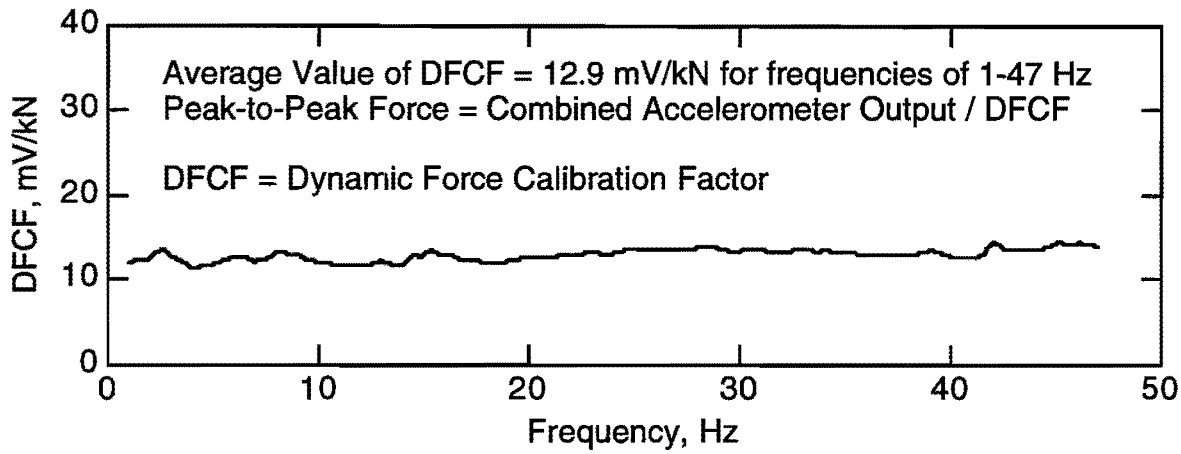


Fig. 3.4 Variation of Dynamic Force Calibration Factor (DFCF) with Loading Frequency for Applied Dynamic Load

3.3 RECEIVER WHEEL CALIBRATION

Dynamic displacements created by the RDD are measured on the pavement surface with an accelerometer mounted on the axle of the two rigid receiver wheels shown in Fig. 2.9. This system acts like a single-degree-of-freedom damped spring-mass system, with the urethane coating on the wheels acting as the damped spring. Therefore, it is expected that the response of this system will vary with frequency and have a single resonant peak. To measure this response, a velocity transducer with a known calibration was secured to the pavement surface between the receiver wheels, and the pavement was driven at a series of frequencies with the RDD while it was stationary. The output of the geophone and accelerometer were both measured. In the frequency domain, the output of the geophone was converted from velocity to acceleration in g's (1 g = 9.81 m/sec^2) using the following equation:

$$\text{Acceleration} = \frac{\text{Geophone Output} \times \text{Calibration factor} \times i\,2\pi f}{9.81\ \text{m/sec}^2/\text{g}} \tag{3.2}$$

The above result was divided by the output of the accelerometer to determine the calibration curve. This resulting curve is shown in Fig. 3.5. Below 10 Hz, the accelerometer output becomes unstable because of the very small accelerations. However, over the range of frequencies of interest in most pavement testing, the receiver wheel assembly is quite well behaved and acts as a single-degree-of-freedom system with a resonance around 44 Hz. The calibration curve shown in Fig. 3.5 was applied to all displacement measurements in the frequency domain.

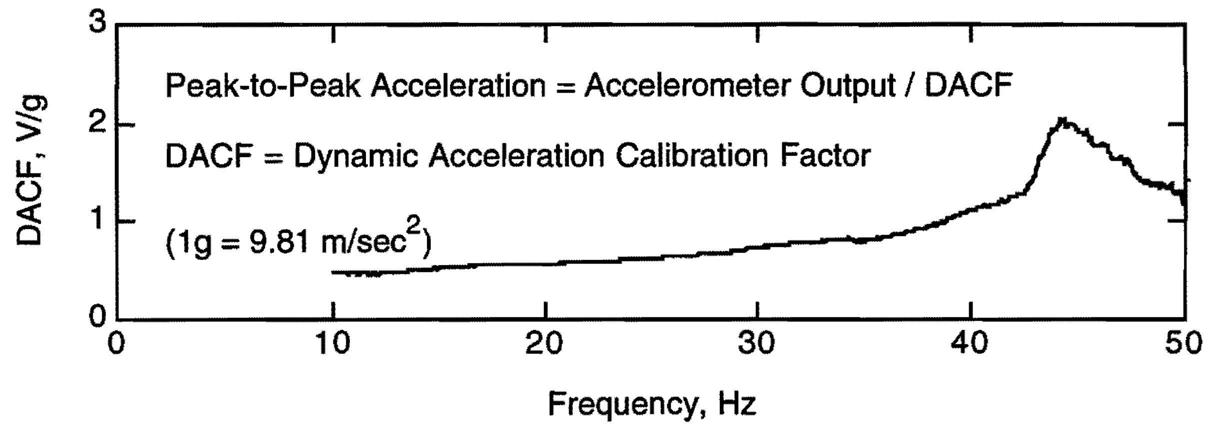


Fig. 3.5 Variation of Dynamic Acceleration Calibration Factor (DACF) with Loading Frequency for the Receiver Wheel

CHAPTER 4 TESTING AND ANALYSIS PROCEDURES

4.1 TESTING PROCEDURE

The RDD is designed to move along a pavement at velocities of 3 to 6 km/h (2 to 4 mph) while generating large dynamic loads with the servo-hydraulic system and applying them to the pavement through the loading wheels. The pavement motions are measured at the isolated receiver wheel assembly, which rolls along the pavement at the mid-point between the loading wheels. Currently, the position of the RDD along the testing axis is determined by knowing the velocity of the truck and the elapsed time. This is only suitable for continuously profiling over short sections of pavement (less than about 30 m). Very long sections of pavement could be profiled continuously by incorporating a distance measuring device which is contemplated for future adaptations.

In the present configuration, the operator must control four parameters when profiling with the RDD. The first parameter is the velocity of the truck. Currently, this is very important because it is used to determine the testing location with time. However, the vehicle velocity also controls the magnitude of the noise generated by the loading and receiver wheels rolling on the rough pavement surface. Initial experience indicates that velocities of 5 km/h (3 mph) or less provide adequate signal-to-noise ratios for the reasonably heavy loads and the close measurement point employed. The second parameter is the static force, F_s, applied to the loading wheels. As discussed previously, the static force cannot be set at less than 67 kN (15 kips) until further modifications to the hydraulic system are completed. With the modifications, the static force can be varied from 13 to 180 kN (3,000 to 40,000 lb). Considerations in selecting a static force involve the third parameter, the dynamic force, F_d. This force is controlled by regulating the flow of hydraulic fluid through the servo-valve. The possible range of dynamic force is 9 to 310 kN (2,000 to 70,000 lb) peak-to-peak.

There are three criteria that must be met in selecting the static and dynamic forces. First, one must satisfy:

$$F_s - \frac{F_d}{2} > 4.5 \text{ kN} \tag{4.1}$$

This criterion insures that the loading wheels will be in constant contact with the pavement. The second criterion is:

$$F_S + \frac{F_d}{2} \leq 150 \text{ kN} \qquad (4.2)$$

which insures that the capacity of the loading wheels will not exceeded. And the third criterion is:

$$F_S + \frac{F_d}{2} < \text{Pavement Capacity} \qquad (4.3)$$

This criterion insures that the pavement will not fail under testing. Unfortunately, the writers have not always been successful with this criterion in their initial tests. One reason is that higher dynamic forces provide larger pavement motions which result in higher signal-to-noise ratios. The desire to create very large signals resulted in overloading one flexible pavement.

The last parameter that the operator must select is the operating frequency of the RDD. The RDD as currently configured is capable of generating and measuring frequencies from 10 to 47 Hz. The choice of an operating frequency is not a simple one. Considerations in selecting an operating frequency include: site resonances due to shallow bedrock, frequency dependencies in the pavement materials, desired depth of sampling, and the frequency content of rolling and vehicle vibrations. Site resonances and frequency dependencies can be identified by exciting the RDD with broad-band excitation (transients, swept-sines or chirps) while stationary and measuring the response spectra. Up to this point, frequencies around the 30-Hz predominant frequency often found in FWD measurements have been used.

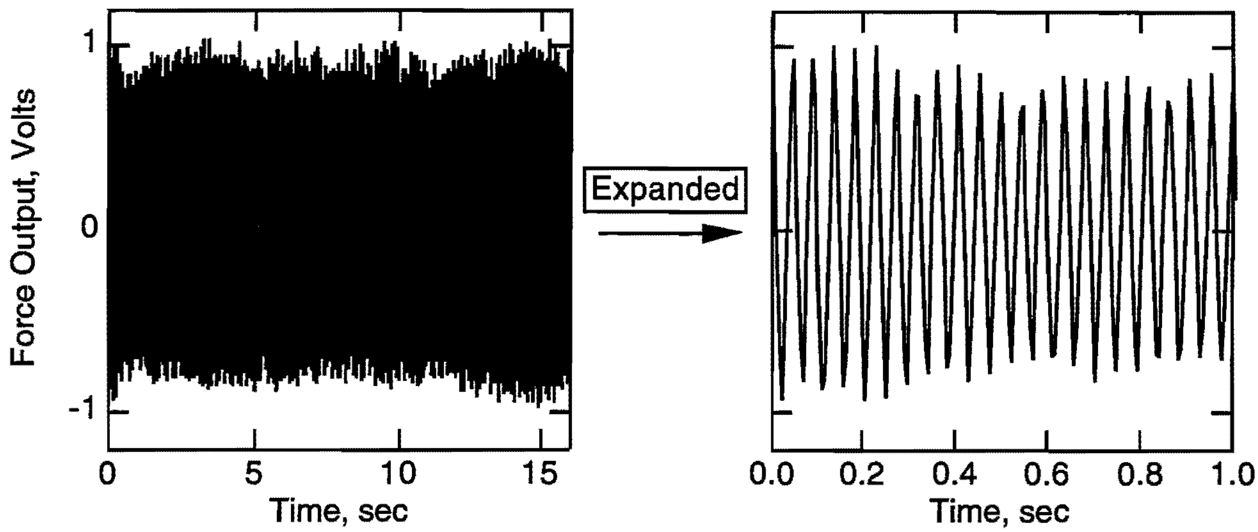
4.2 ANALYSIS PROCEDURE

The procedure used to analyze RDD data is illustrated by stepping through the procedure for a typical measurement. The example measurement is from tests at the Texas Transportation Institute (TTI) testing facility at Texas A&M University. The pavement used in this example is designated as Section 10. Details about this flexible pavement and the other ones tested at TTI are provided in Chapter 5.

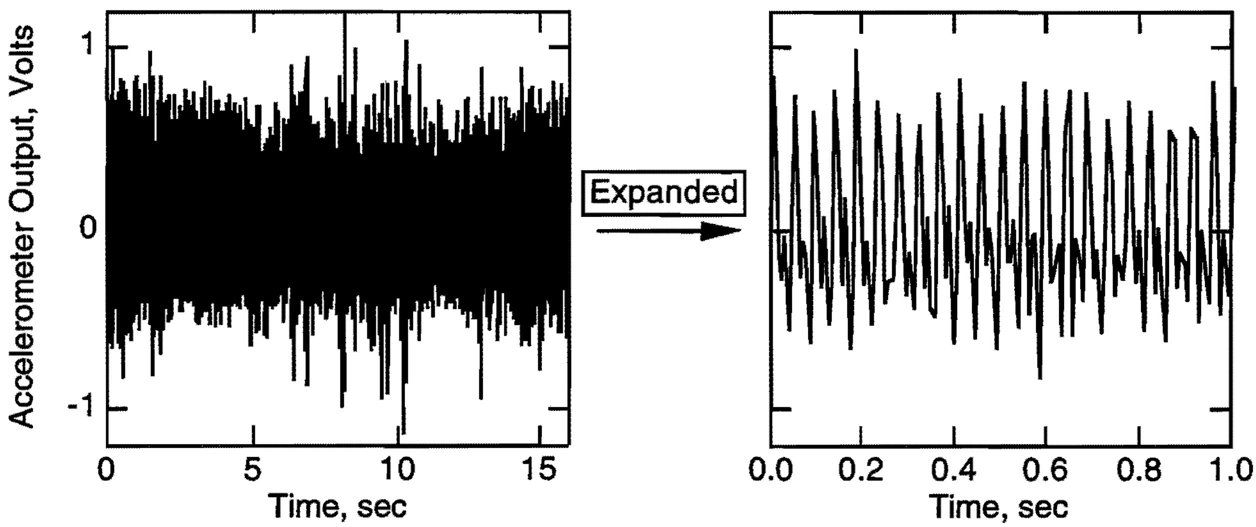
Fig. 4.1 contains time records of force and acceleration that were measured while rolling across Section 10 and operating the RDD at 22 Hz. The complete time record for a 7-m long, continuous profile is shown along with an expanded portion. The force output is quite monochromatic, with little harmonic distortion or rolling noise. The accelerometer output exhibits significant amounts of harmonic distortion and rolling noise. However, the effects of this distortion and noise are greatly reduced in the process of converting the acceleration measurement to a displacement measurement as discussed below.

To analyze the data, it is necessary to isolate the components of force and displacement at the operating frequency (22 Hz). This can be done in several ways. One method would have been to filter the signals through a notch-pass analog filter. Another method would be to use digital filters. Each of these methods has limitations. The method that was finally employed was spectral analysis using the Fast Fourier Transform (FFT). Using the FFT, the data were separated into the frequency components, and measurements were made not only at the operating frequency but also at frequencies around the operating frequency. Measurements at these additional frequencies permitted quantification of the noise level and allowed evaluation of measurement quality.

The spectral analysis procedure applied to the excitation force is illustrated in Fig. 4.2. The force output shown in Fig. 4.2a is the same record shown in Fig. 4.1. The time record is divided into a number of sections. Each section is determined by multiplying the time record by the weighting function shown in Fig. 4.2b. This function is a Hanning window that is commonly used in spectral analysis. The effect of using the Hanning window (weighting function) is to average the measurement over a region in which more weight is applied to the center of that region. Using the window shown and the velocity that the RDD was moving, the data were effectively averaged over about a 0.6-m (2-ft) interval. Successive measurements are analyzed using overlapping weighting functions so that all data are utilized equally. The weighted force output for one section is shown in Fig. 4.2c. An FFT is performed on this time record, transforming it into the frequency domain. The magnitude of the resulting frequency function is shown in Fig. 4.2d. At this point, the Dynamic Force Calibration Factor (DFCF) shown in Fig. 3.4 is applied to the data to convert from units of voltage to units of peak-to-peak force. This conversion is shown in Fig. 4.2e, and a peak-to-peak loading force of 69.0 kN (15,500 lb) is measured at 22 Hz. To analyze the noise level, the same spectrum shown in Fig. 4.2e is plotted in Fig. 4.2f using a



a) Dynamic Force Applied to Pavement Surface



b) Motion of Pavement Surface Measured with Receiver Wheels

Fig. 4.1 Typical Time Records from the Rolling Dynamic Deflectometer Operating at 22 Hz on Flexible Pavement Section 10 at the TTI Test Facility

vertical log scale. The average noise level measured at frequencies ± 5 Hz from the operating frequency was found to be 0.36 kN (80 lb). Therefore, the actual driven force would be 69.0 kN ± 0.36 kN (15,500 ± 80 lb).

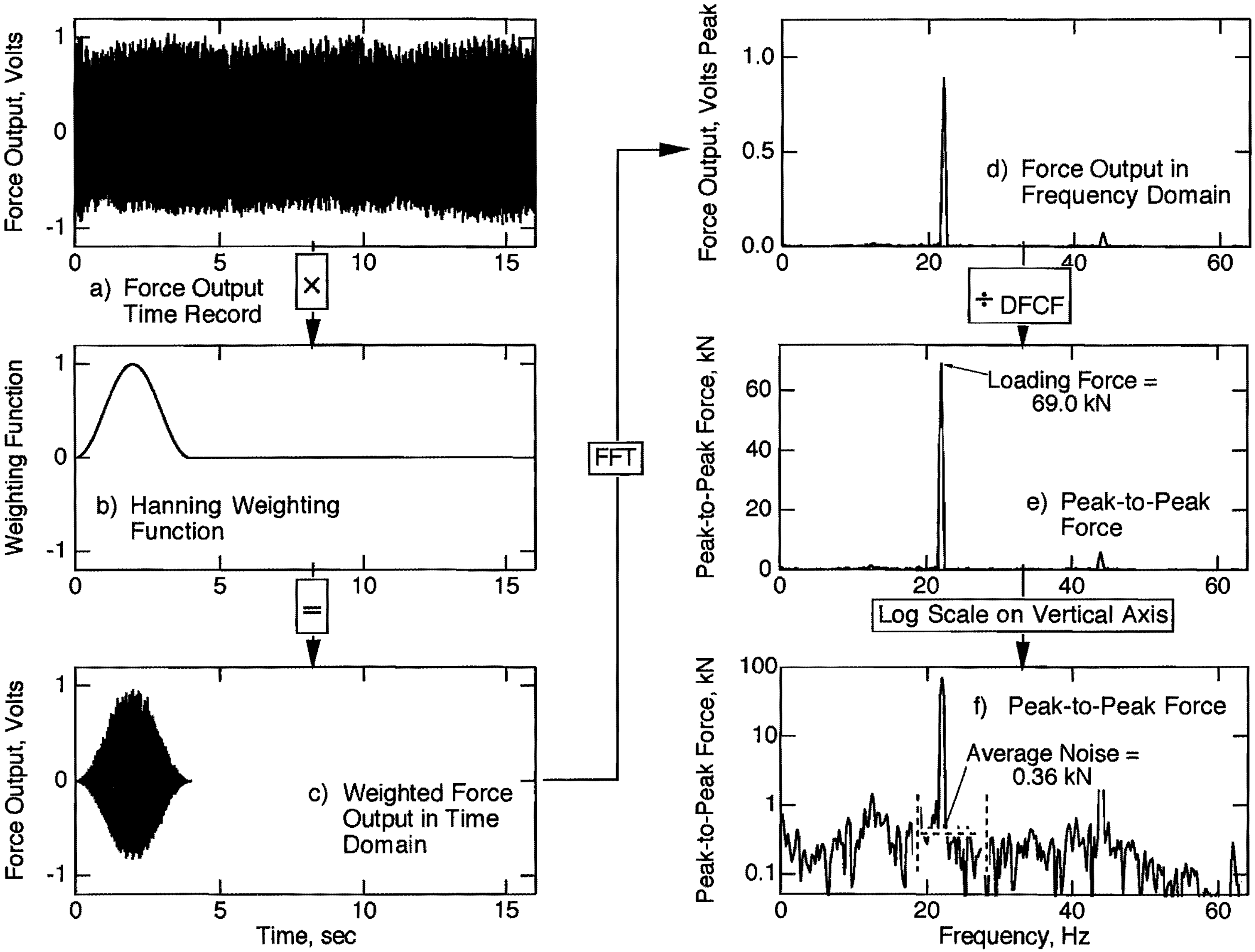


Fig. 4.2 Schematic Showing Sample Calculation of Dynamic Force Applied by the Heavy-Load Profilometer

The same procedure is shown in Fig. 4.3 for the displacement measurement. The procedure is identical, except when converting from units of volts in the frequency domain to units of displacement in meters. In this case, the displacement was found to be 0.365 mm (0.0144 in.), with an average noise level of 0.0061 mm (0.00024 in.) The rolling noise has much more effect on the displacement measurement than the force measurement. However, both measurements are high-quality measurements as shown by signal-to-noise ratios in excess of 50.

To quantify a property of the pavement system, the flexibility is calculated next. Flexibility is the inverse of stiffness. Therefore, higher flexibility indicates a softer pavement system and lower flexibility indicates a stiffer system. Flexibility is defined as:

$$\text{Flexibility} = \frac{\text{Dynamic Displacement}}{\text{Dynamic Force}} \tag{4.4}$$

Using 25 successive Hanning weighting functions with the records in Fig. 4.1, successive values of force, displacement, flexibility and average noise levels were calculated for 25 points along the measured length of Section 10. These values are plotted in Fig. 4.4. The flexibility profile shown at the bottom of Fig. 4.4 reveals that the section is quite uniform longitudinally.

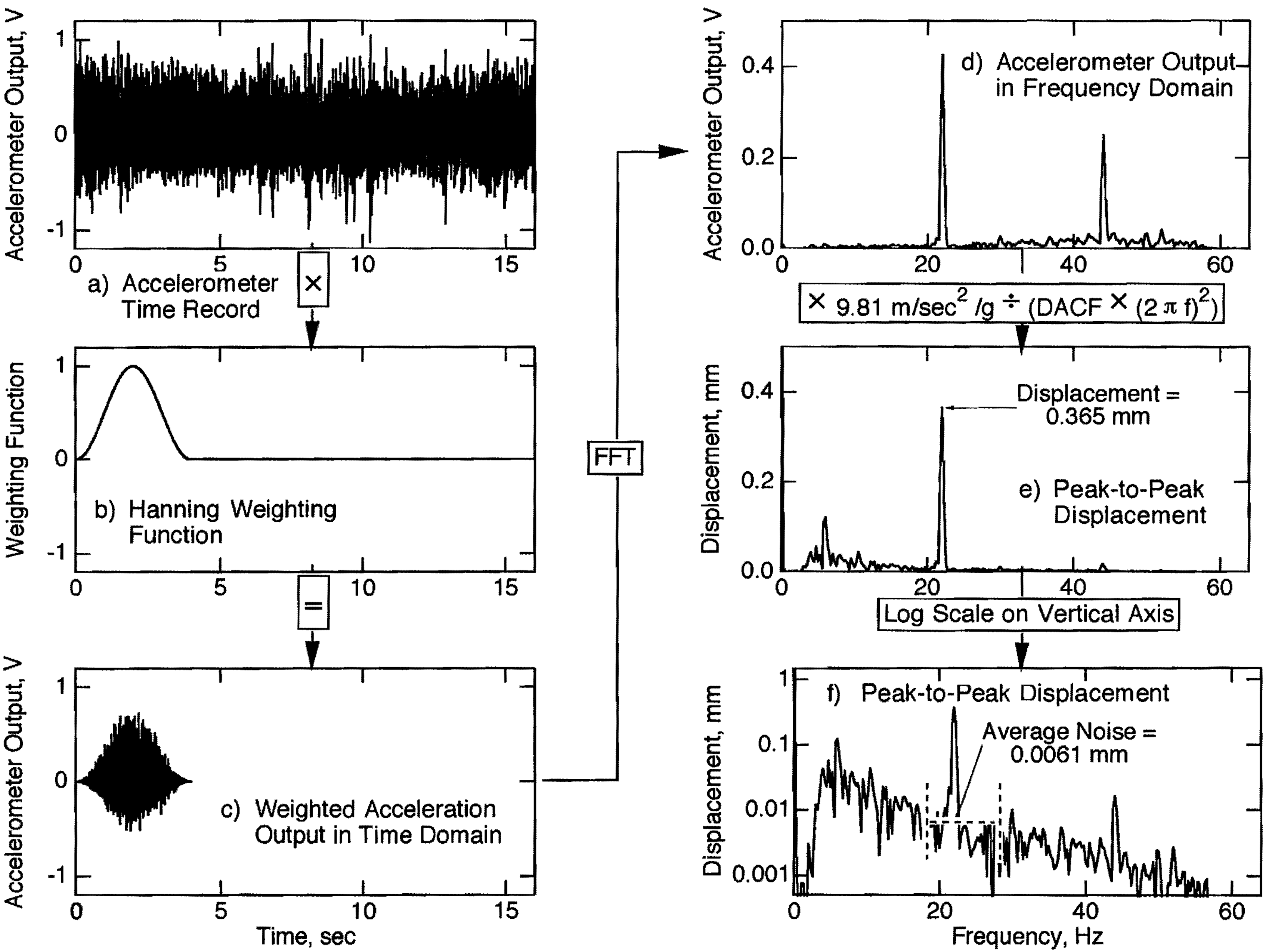


Fig. 4.3 Schematic Showing Sample Calculation of Dynamic Displacement Measured with Receiver Wheels

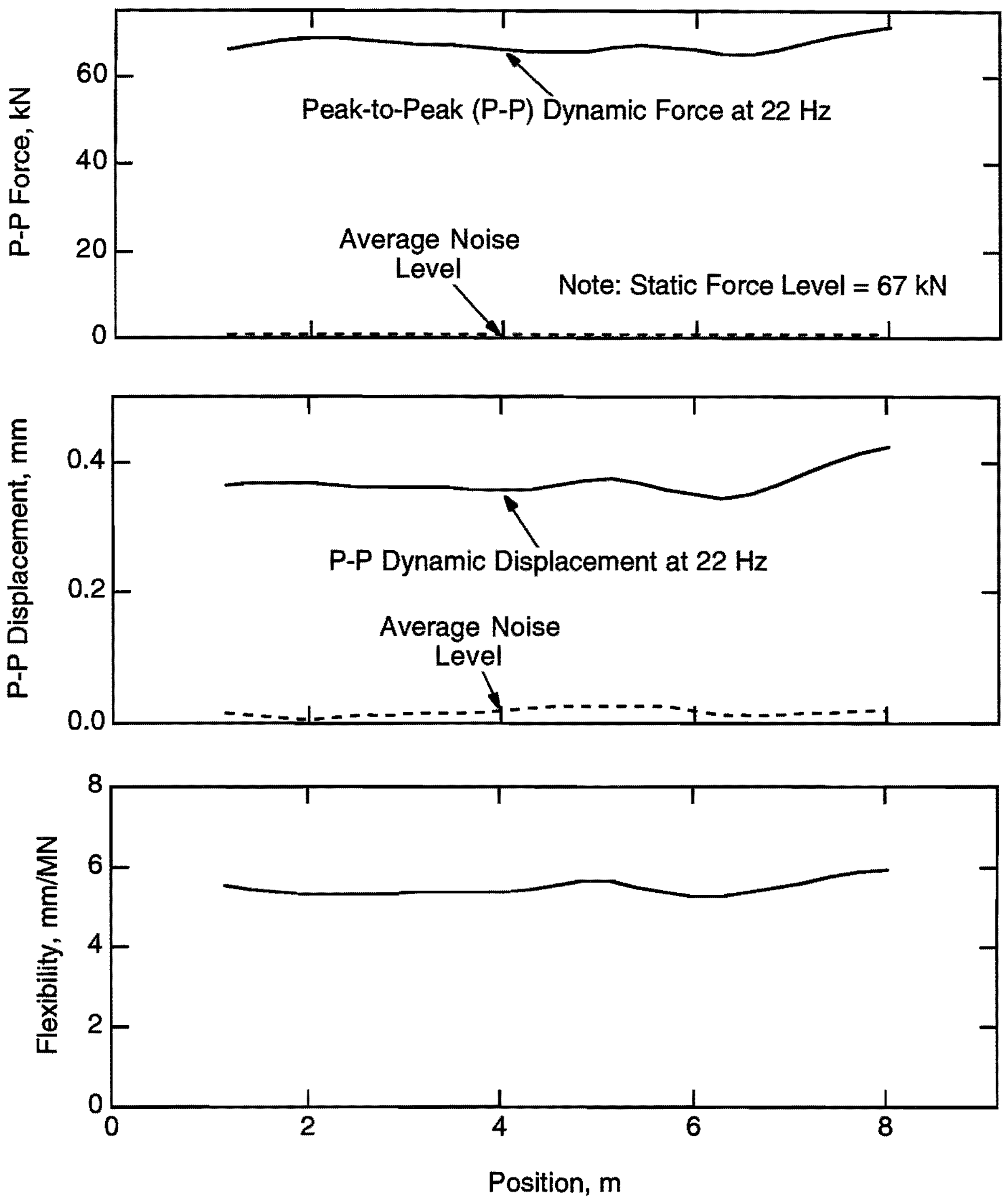


Fig. 4.4 Continuous Force, Displacement and Flexibility Profiles at Pavement Section 10 at the TTI Test Facility Determined with the RDD Operating at 22 Hz with a High Dynamic Force Level

CHAPTER 5 RDD RESULTS AT TTI FLEXIBLE PAVEMENT TEST SECTIONS

A series of tests was performed using the RDD at the Texas Transportation Institue (TTI) pavement test facility. At this facility, a number of flexible pavement sections have been constructed using different materials and thicknesses of pavement, base and subgrade. RDD profiling was performed at eight of these test sections. Fig. 5.1 shows part of the TTI pavement test facility with the RDD in the background. Fig. 5.2 shows the RDD's loading wheels and receiver wheels lowered to the ground, ready to begin profiling pavement. Table 5.1 contains the materials and layer thicknesses of the sections where tests were performed. The objectives of the testing were: 1) to determine uniformity along the longitudinal centerline of each section, 2) to observe differences in average flexibility between the different sections, and 3) to observe nonlinearities in the pavement sections. Falling Weight Deflectometer (FWD) tests were also performed concurrently at some of the pavement sections to compare with the RDD results. Most RDD tests were performed at an operating frequency of 22 Hz. However, a few tests were performed at 40 Hz to observe the effect of frequency. All testing was performed with a static force of 67 kN (15,000 lb)

5.1 VARIABILITY WITHIN PAVEMENT SECTIONS

One of the major benefits of the RDD is that continuous measurements of pavement flexibility can be performed. This makes the RDD especially well suited for studying the variability (longitudinally or laterally) of pavement systems. This benefit is demonstrated by the continuous profile of Section 10 shown in Fig 4.4. Another approach that can be used to observe longitudinal variability is to normalize the flexibility measured continuously by dividing by the average flexibility determined over the entire section at the measured load level. This was done for tests performed at a high load level (approximately 70 kN) at Sections 9, 10 and 16 at the TTI test facility. These normalized profiles are shown in Fig 5.3. Sections 9 and 10 are quite uniform, with less than 5% variation along the longitudinal axis. On the other hand, Section 16

Fig. 5.1 Part of TTI Flexible Pavement Test Facility Determined with the Rolling Dynamic Deflectometer in the Background

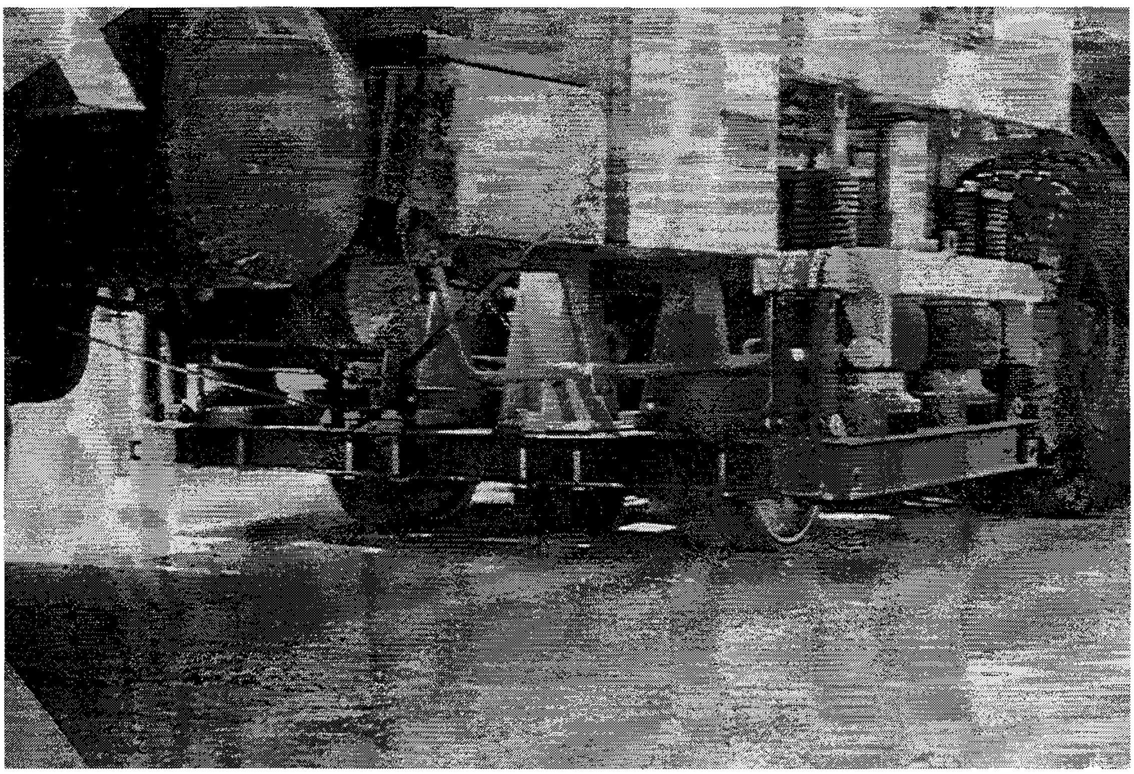


Fig. 5.2 Rolling Dynamic Deflectometer Loading Wheels and Receiver Wheels Lowered to the Ground, Ready to Profile

Table 5.1 Layer Thicknesses and Materials of the Flexible Pavements at the TTI Facility That Were Tested with the Rolling dynamic Deflectometer

Section Number	Layer Thickness (mm)			Material Type		
	Surface	Base	Subbase	Base	Subbase	Subgrade
9	127	102	102	Crushed Limestone	Crushed Limestone	Sandy Gravel
10	25	305	102	Crushed Limestone	Crushed Limestone	Sandy Gravel
11	25	102	305	Crushed Limestone	Crushed Limestone	Sandy Gravel
12	127	305	305	Crushed Limestone	Crushed Limestone	Sandy Gravel
14	25	305	102	Crushed Limestone with 4% Cement	Crushed Limestone with 4% Cement	Sandy Gravel
15	25	102	305	Crushed Limestone with 4% Cement	Crushed Limestone with 4% Cement	Sandy Gravel
16	127	305	305	Crushed Limestone with 4% Cement	Crushed Limestone with 4% Cement	Sandy Gravel
29	76	203	203	Crushed Limestone with 2% Lime	Crushed Limestone with 2% Lime	Sandy Gravel

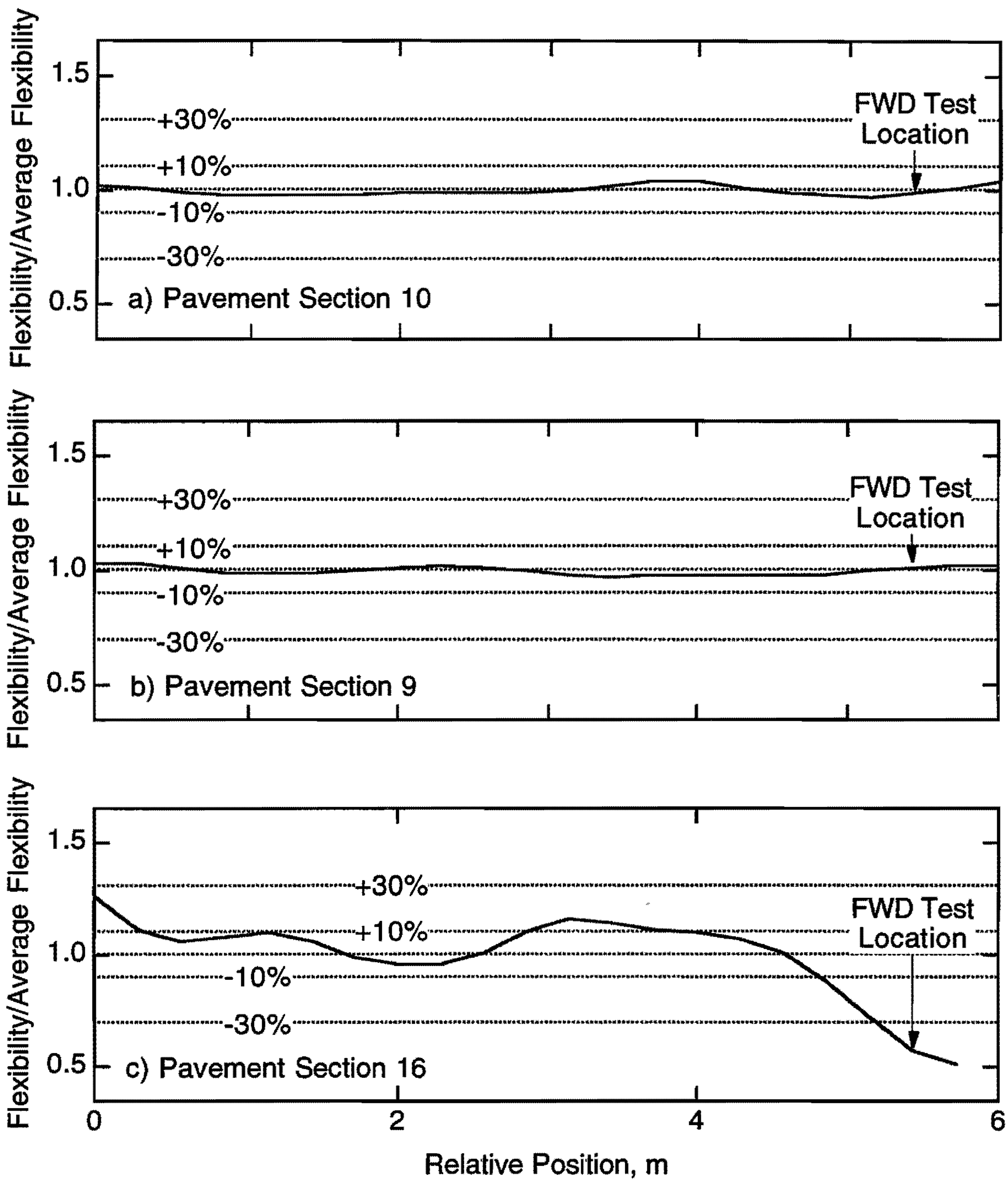


Fig. 5.3 Continuous Profiles of Normalized Flexibility for Three Flexible Pavement Sections at the TTI Test Facility Determined with the RDD Operating at 22 Hz with a High Dynamic Force Level

exhibits a high degree of variation in the longitudinal direction, with more than a 60% variation in the 6-m long section.

FWD measurements were also performed on Sections 9, 10 and 16 at the locations noted is Fig. 5.3. These test locations were selected before the RDD profiles were determined. The FWD results from Sections 9 and 10 should properly characterize the whole section as shown by the continuous profiles. However, the average stiffness of Section 16 would be grossly overestimated by using only the FWD results at the location tested, because that location is not representative of the entire section. This result clearly demonstrates the powerful tool that RDD testing represents in determining bounds in pavement characterization and the limitations of using discrete tests. Comparisons of RDD and FWD results are presented below.

5.2 COMPARISON BETWEEN FLEXIBILITY PROFILES OF DIFFERENT PAVEMENT SECTIONS

RDD profiling was performed at two different dynamic force levels on eight different pavement sections. Testing was nominally performed at peak-to-peak force levels of 33.5 and 67 kN (7,500 and 15,000 lb). However, in practice, higher and lower force levels were generated at some pavements due to the lack of experience with the equipment. To compare flexibilities of the pavements at one force level, interpolation was used to determine a flexibility representative of a dynamic force level of 67 kN (15,000 lb). These results, along with a graphical representation of the pavement layers, are shown in Fig. 5.4. These results are very consistent, with thicker and stiffer pavement materials yielding lower flexibilities and with the flexibilities of similarly constructed sections being similar. Of course, plotting at the horizontal scale shown accentuates longitudinal variations in these sections.

5.3 EFFECT OF DYNAMIC FORCE LEVEL

Another benefit of the RDD is that testing can be performed using heavy loads. Profiles of dynamic force level and flexibility are shown in Fig. 5.5 for three pavement sections at TTI.

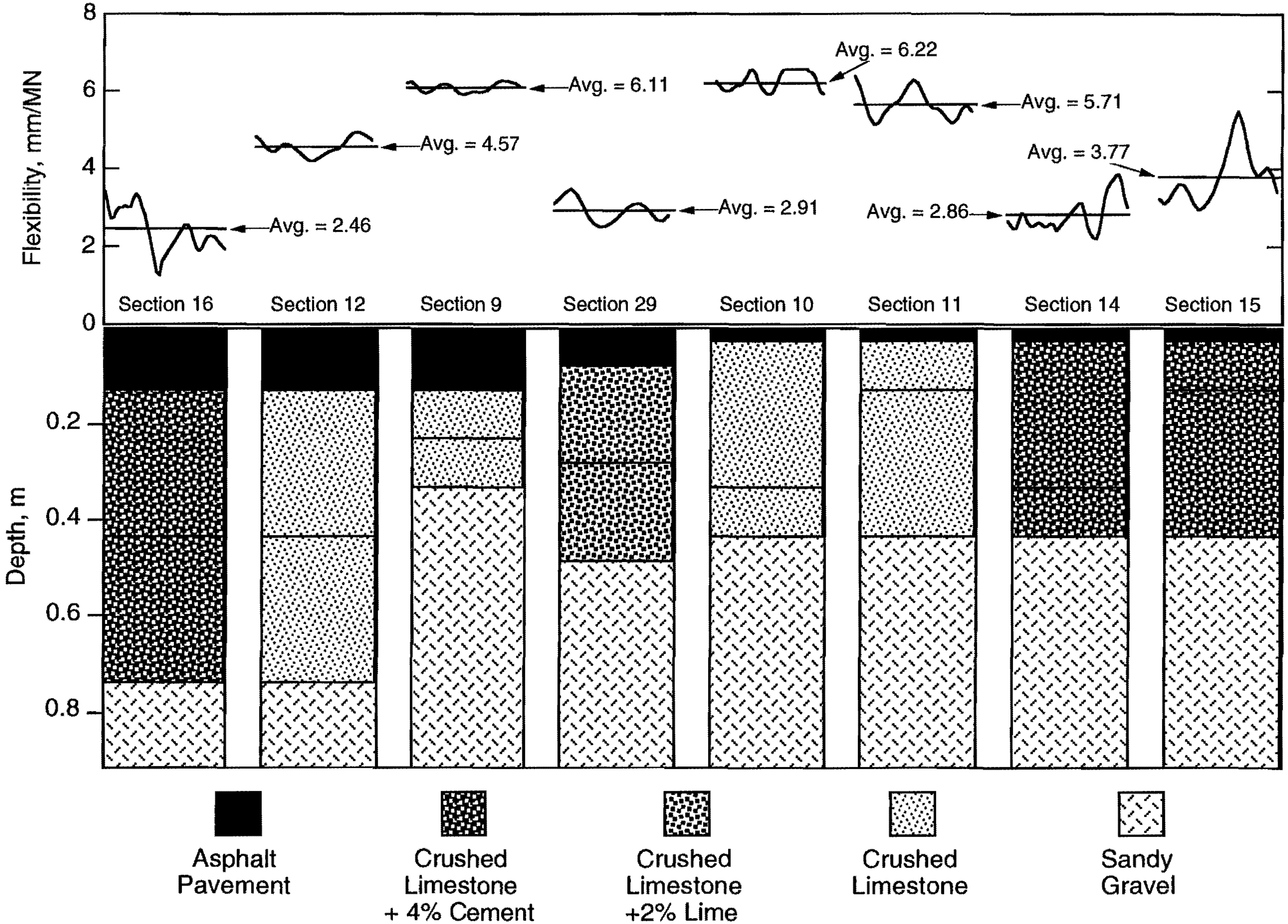


Fig. 5.4 Flexibility and Pavement Profiles of Eight Flexible Pavement Sections at TTI Test Facility Determined with the Rolling Dynamic Deflectometer Operating at 22 Hz

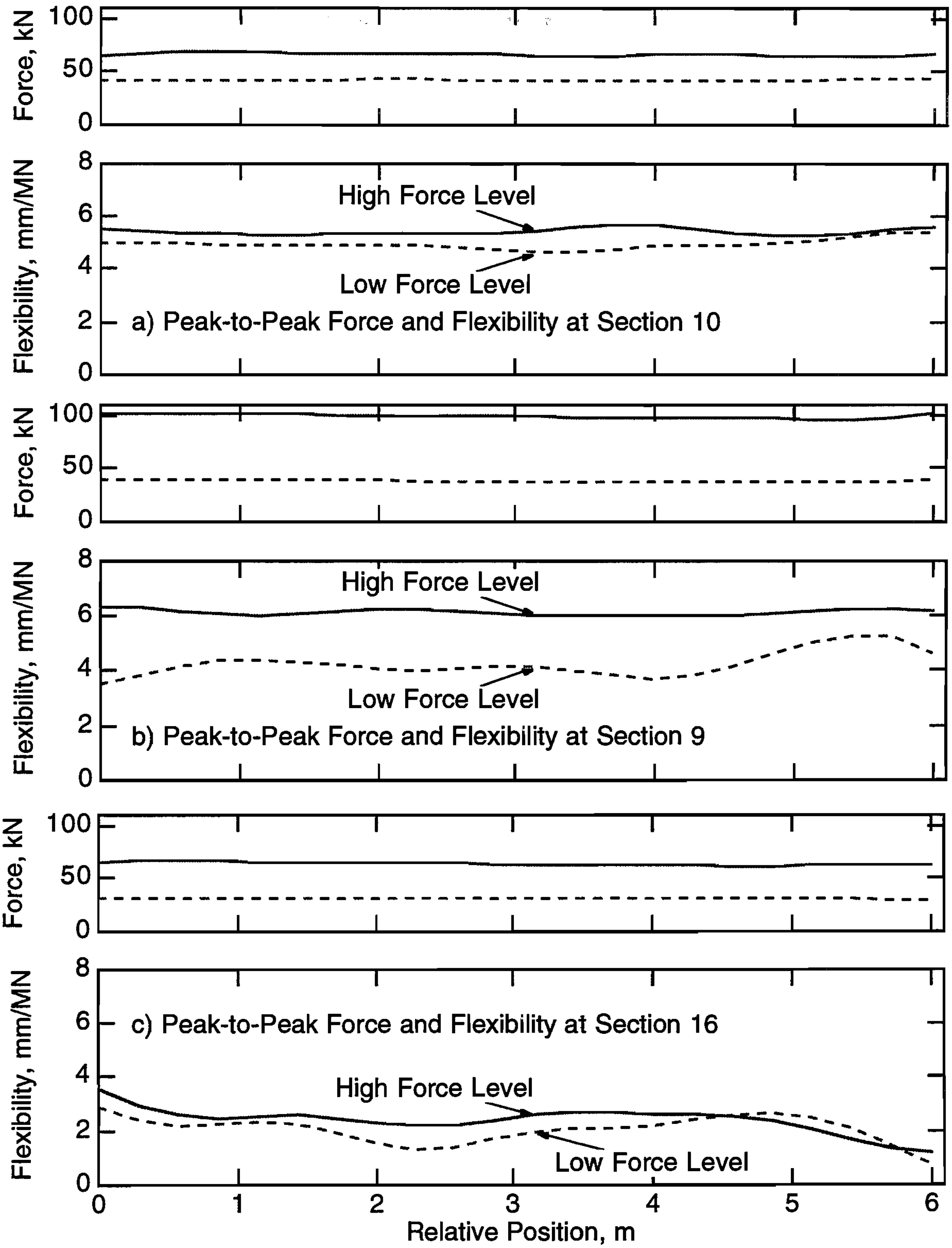


Fig. 5.5 Continuous Profiles of Force Level and Flexibility for Three Flexible Pavement Sections at the TTI Test Facility Measured at Two Dynamic Force Levels with the RDD Operating at 22 Hz with a High Dynamic Force Level

Tests were performed at two different dynamic force levels at each pavement section, with the upper level near or above nominal allowable loads. These profiles clearly show some nonlinear effect, with higher force levels yielding higher flexibilities. This effect is especially pronounced in Section 9. However, the high force level at this section was inadvertently applied at a much higher dynamic force level than at the other sections. This level probably caused the excessive nonlinearity. However, the ability to study this characteristic of pavements with the RDD is clearly shown.

5.4 COMPARISON BETWEEN RDD AND FWD RESULTS

FWD tests were performed at three load levels at several of the TTI test sections within one hour of the RDD testing. The distance from the center of the receiver wheel to the center of the loading wheels is nearly 0.6 m (2 ft) in the RDD. Therefore, comparisons were made between deflections measured with the RDD and deflections with the FWD at measurement station 3 at a distance of 0.6 m (2 ft) from the center of the loaded area. Comparisons of FWD and RDD flexibilities for a range of dynamic loads are shown in Fig. 5.6. The flexibility measured with the FWD is consistently lower than the flexibility measured with the RDD operating at 22 Hz. However, both tests show the same basic nonlinearity with dynamic load level. A few RDD tests were performed at an operating frequency of 40 Hz. These results are also plotted in Fig. 5.6. There is substantial difference between the results of the 22 and 40 Hz tests, indicating a significant effect of frequency on the measurements. The FWD applies a broad-band, transient loading function, with the frequency content depending upon the mass being dropped and the properties of the pavement. With the RDD, a single monochromatic frequency is being applied. In view of the effect of frequency observed in 22- and 40-Hz tests, it should not be expected that the RDD and FWD would give the same results. More work is needed to study this issue, but these preliminary results are very consistent.

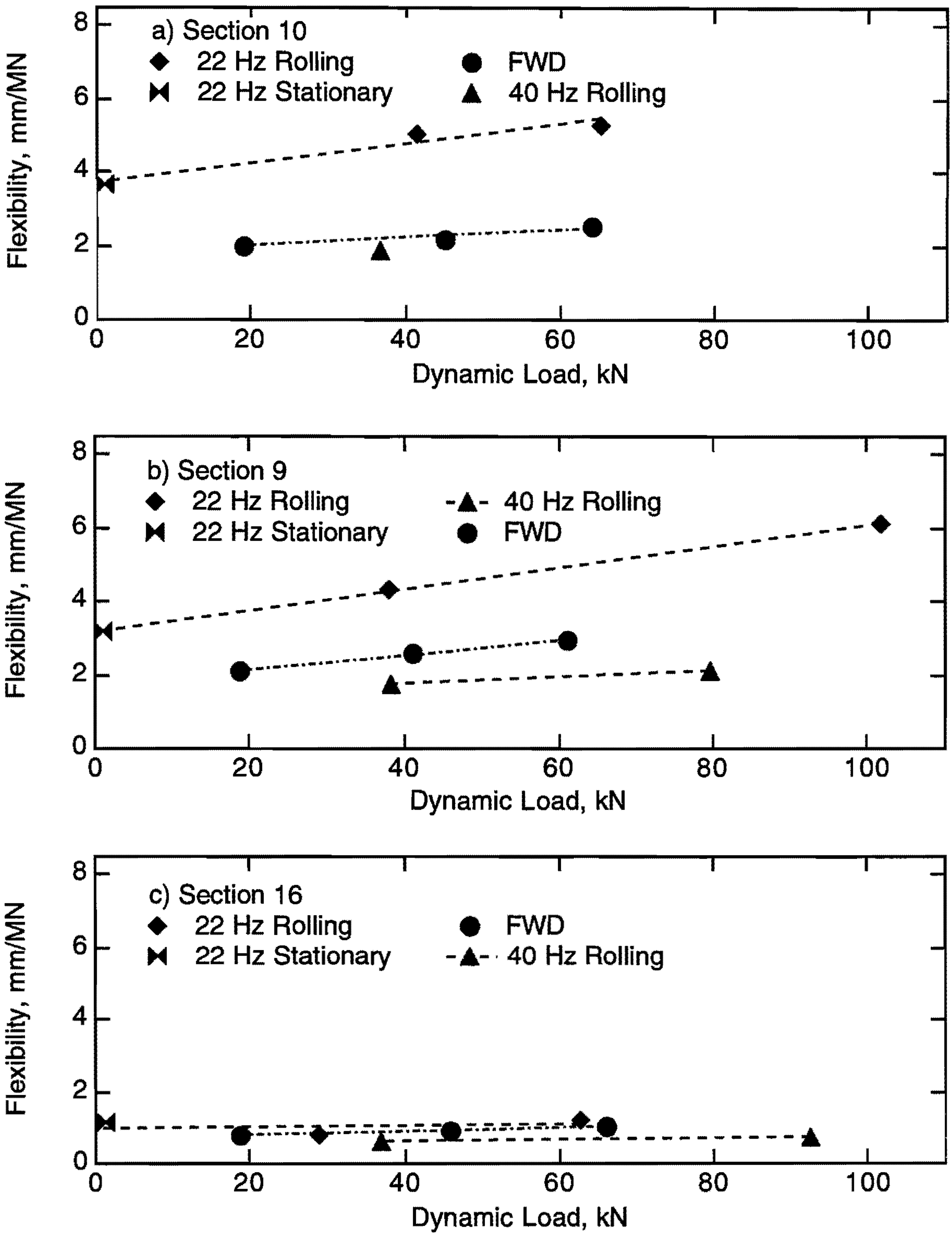


Fig. 5.6 Comparison of Flexibilities Determined at Several Dynamic Force Levels Using the Falling Weight Deflectometer and the Rolling Dynamic Deflectometer Operating at Two different Frequencies on Three Flexible Pavement Sections at the TTI Test Facility

CHAPTER SIX. SUMMARY AND CONCLUSIONS

A Rolling Dynamic Deflectometer (RDD) has been developed by making modifications to a vibroseis truck. The RDD measures continuous profiles of pavement flexibility or stiffness under heavy loads. The RDD employs a servo-hydraulic vibrator to apply static hold-down and vertical dynamic forces to two sets of dual loading wheels. A total force (static plus dynamic) of 150 kN (33,000 lb) can be applied to the pavement surface while the RDD is moving at velocities of 3 to 6 km/h (2 to 4 mph). Dynamic deflections of the surface are continuously recorded with an accelerometer located on a set of receiver wheels positioned mid-way between the loading wheels.

The loading and monitoring systems of the RDD have been calibrated, and initial testing has been performed at the Texas Transportation Institute (TTI) pavement test facility. Eight flexible pavement sections, covering a range in flexibility, have been successfully tested. Loading frequencies of 22 and 40 Hz have been used with a wide range in dynamic loads. With the RDD, it was possible to measure the: longitudinal variability within each section, differences in flexibility between sections, and nonlinearities in flexibility at several sections. A comparison between RDD and FWD measurements show the flexibilities measured by both methods are consistent with each other, and closely related. Finally, it was demonstrated that the RDD can also be used to investigate the effect of loading frequency on pavement response.

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5. Lee, C. E., Izadmehr, B., and Machemehl, R. B. (1985), "Demonstration of Weigh-in-Motion Systems for Data Collection and Enforcement," Center for Transportation Report 557-1F, Study No. IAC (84-85)-1024, The University of Texas at Austin, December.

APPENDIX A

MACHINE DRAWINGS FOR RDD PARTS

Units on all drawings are in inches so parts will fit on vibroseis truck
(1 inch=2.54 cm)

4 Longitudinal Beams

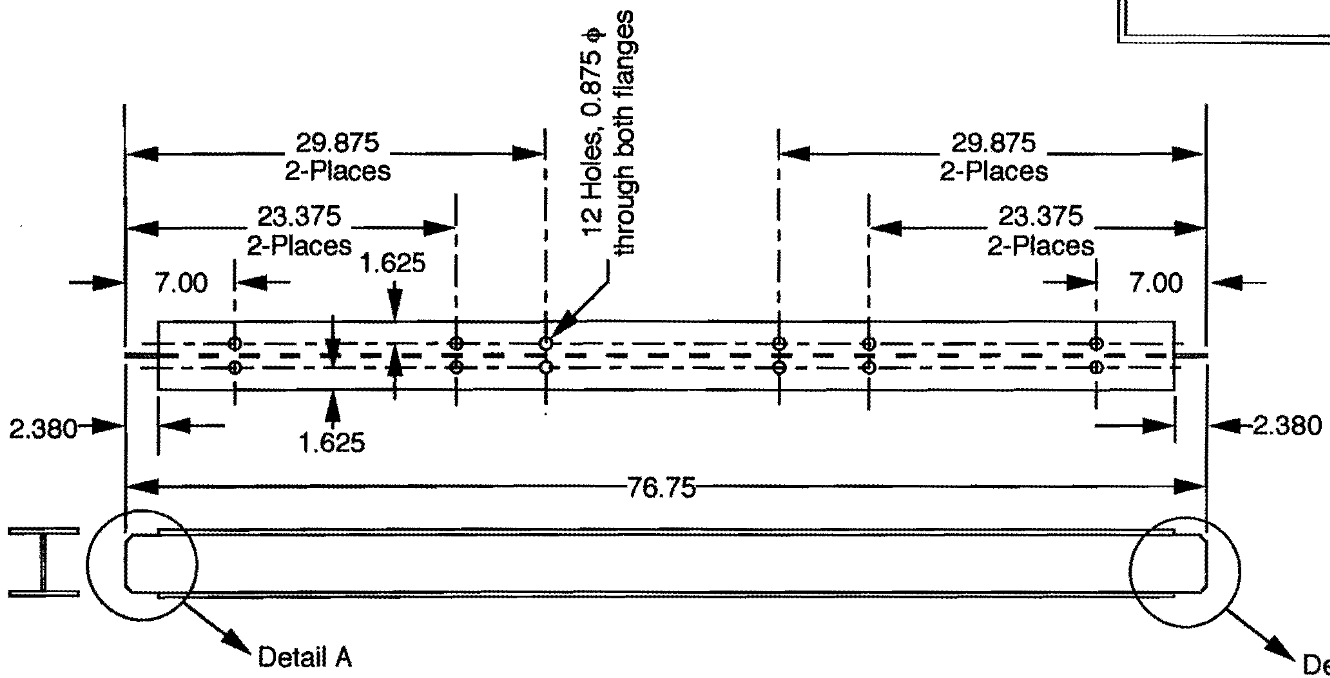
Wide Flange Section W 5 × 16

all dimensions are inches

Tolerances: all parts

3-Place Decimals ± 0.005
2-Place Decimals ± 0.030
1-Place Decimals ± 0.100

Hole Tolerances + 0.008
- 0.001



Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 1

Fig. A.1 Drawings for Longitudinal Beams Rolling Dynamic Deflectometer Load Frame

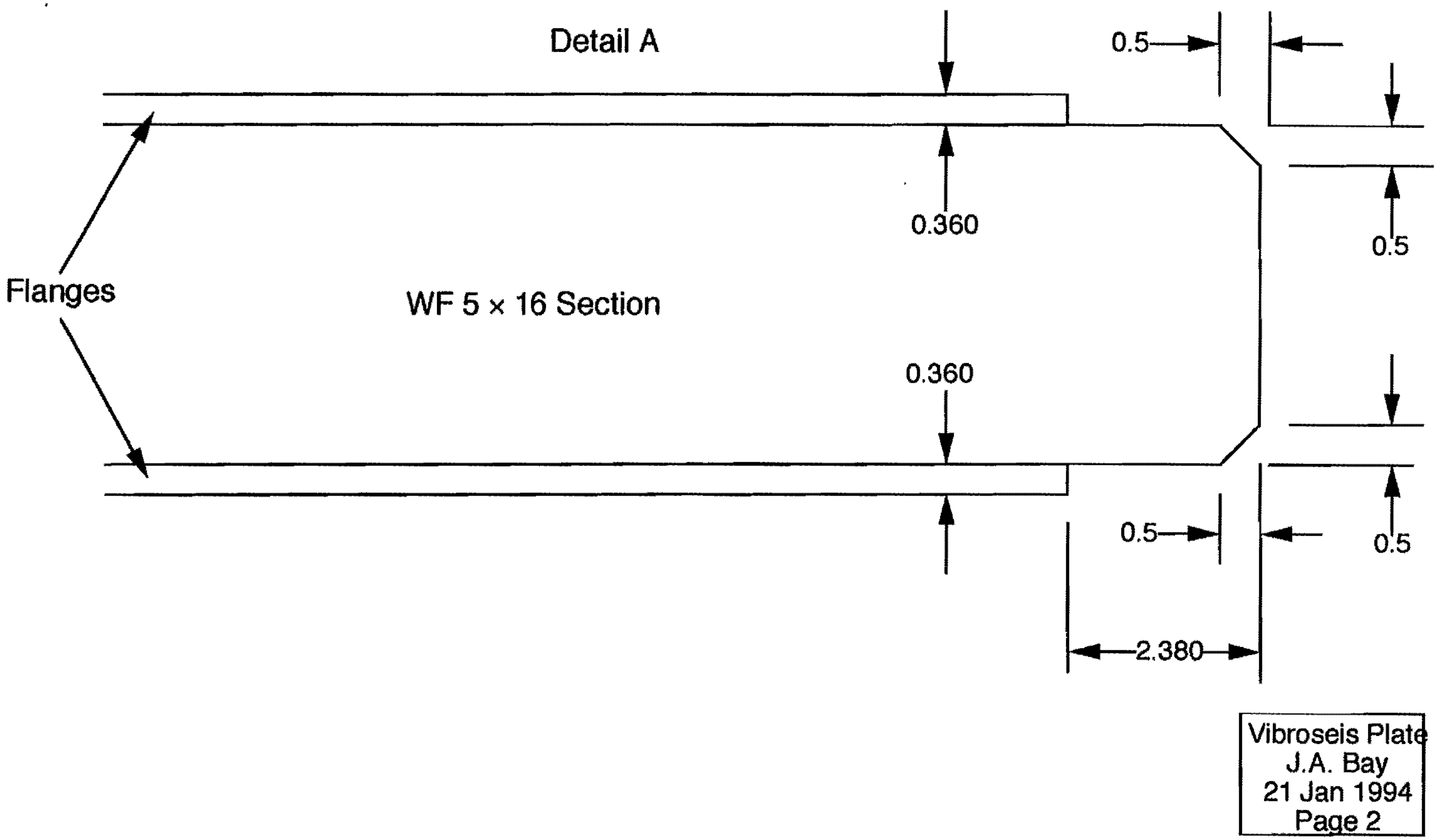


Fig. A.2 Drawings for Longitudinal Beam Detail Rolling Dynamic Deflectometer Load Frame

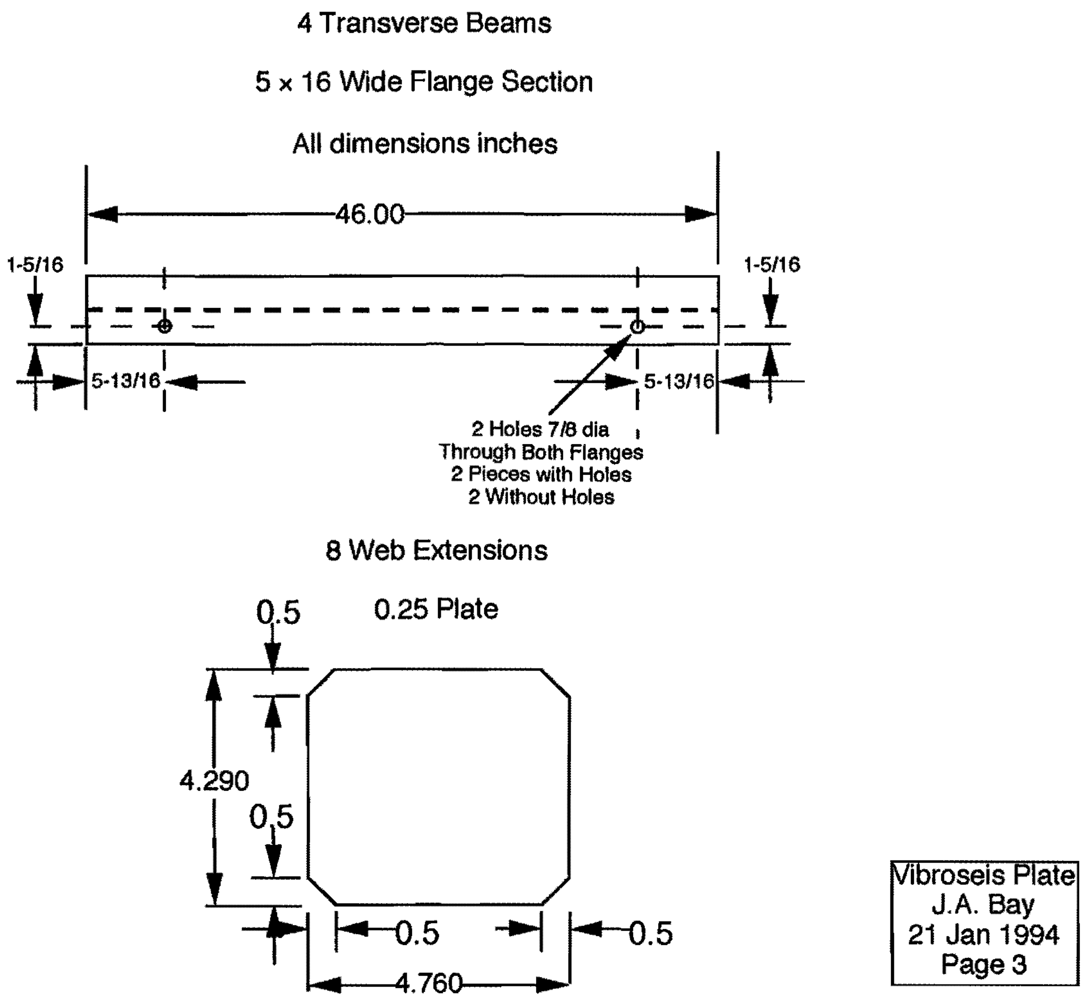


Fig. A.3 Drawings for Transverse Beams and Web Extenders Rolling Dynamic Deflectometer Load Frame

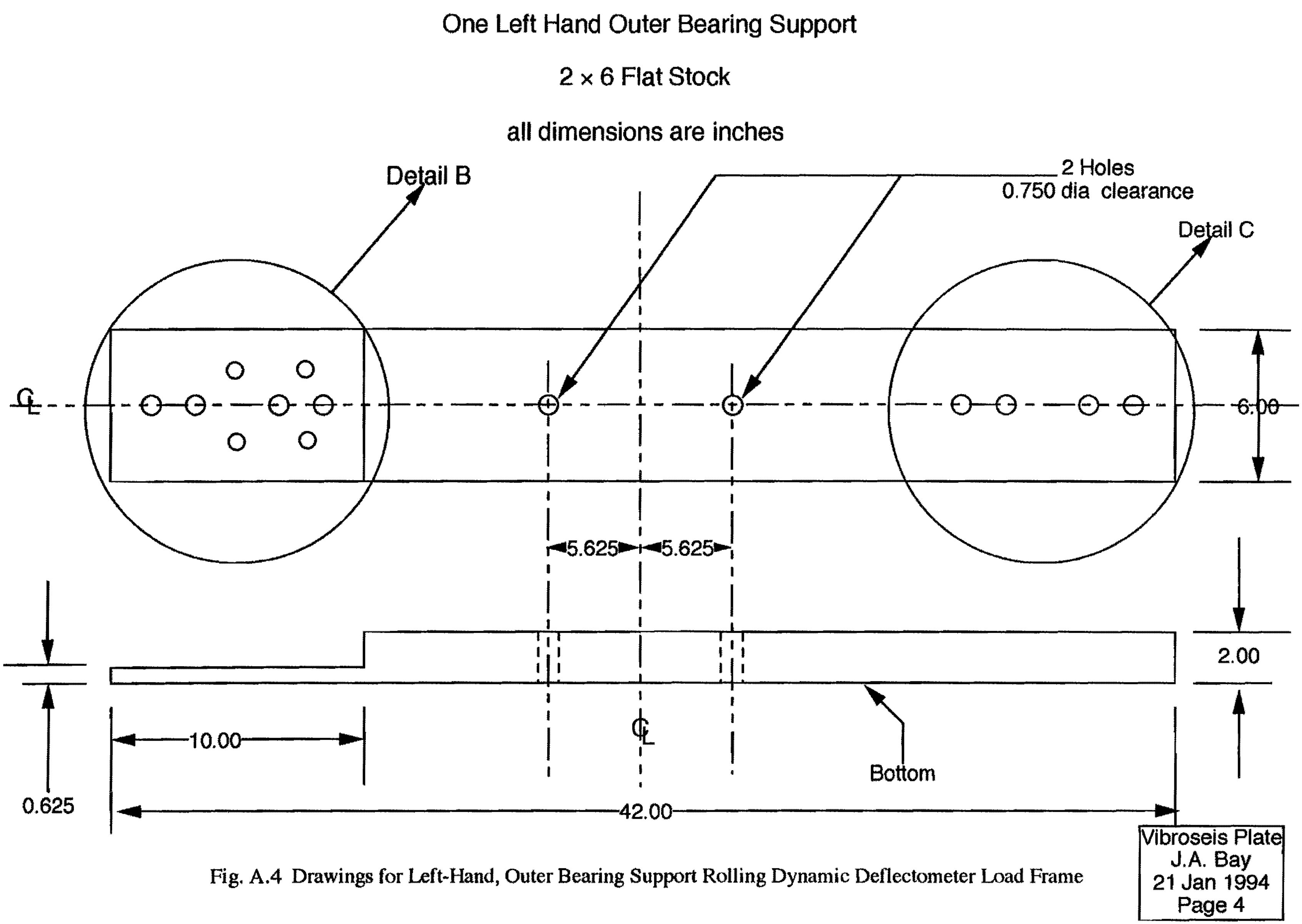


Fig. A.4 Drawings for Left-Hand, Outer Bearing Support Rolling Dynamic Deflectometer Load Frame

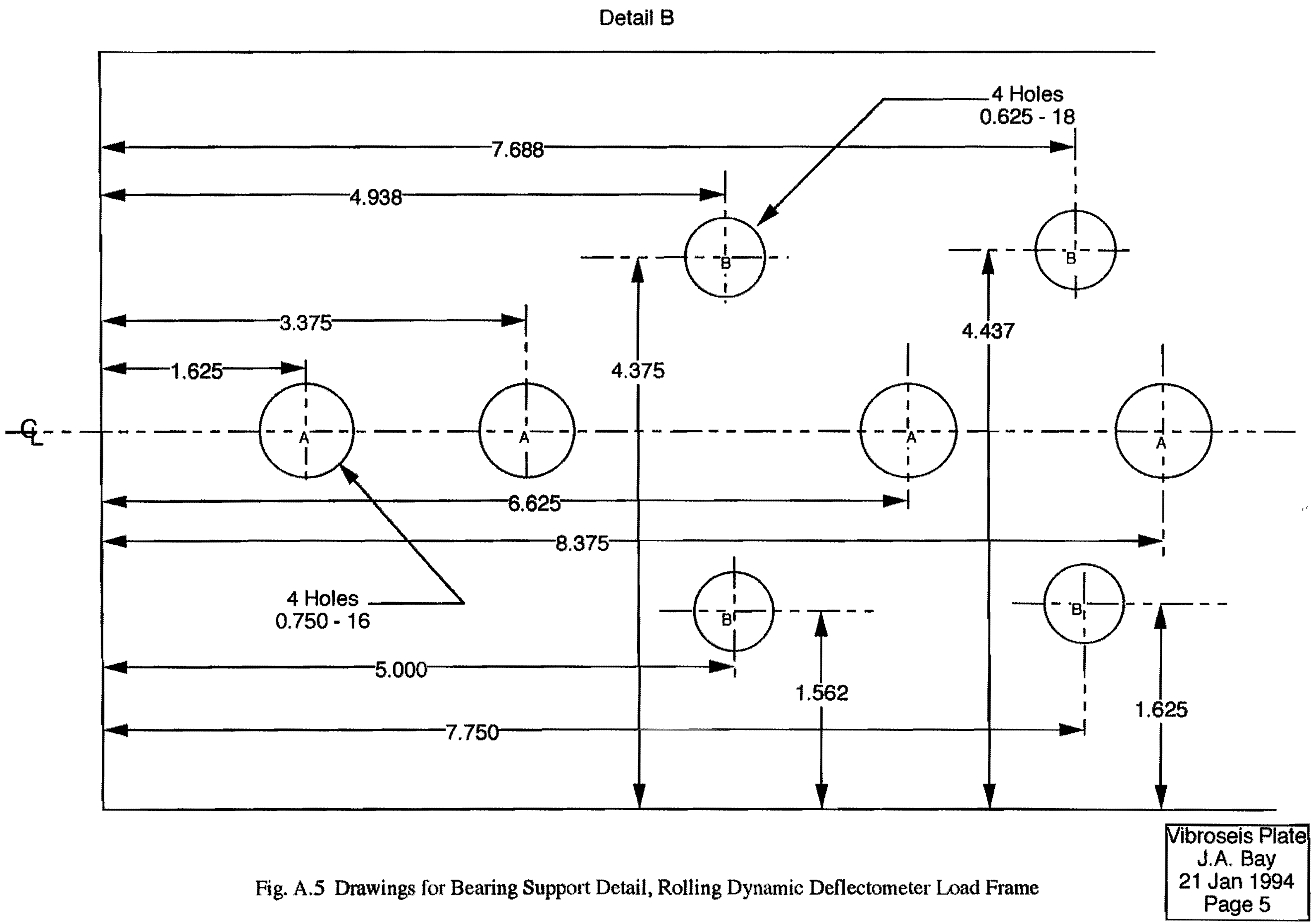


Fig. A.5 Drawings for Bearing Support Detail, Rolling Dynamic Deflectometer Load Frame

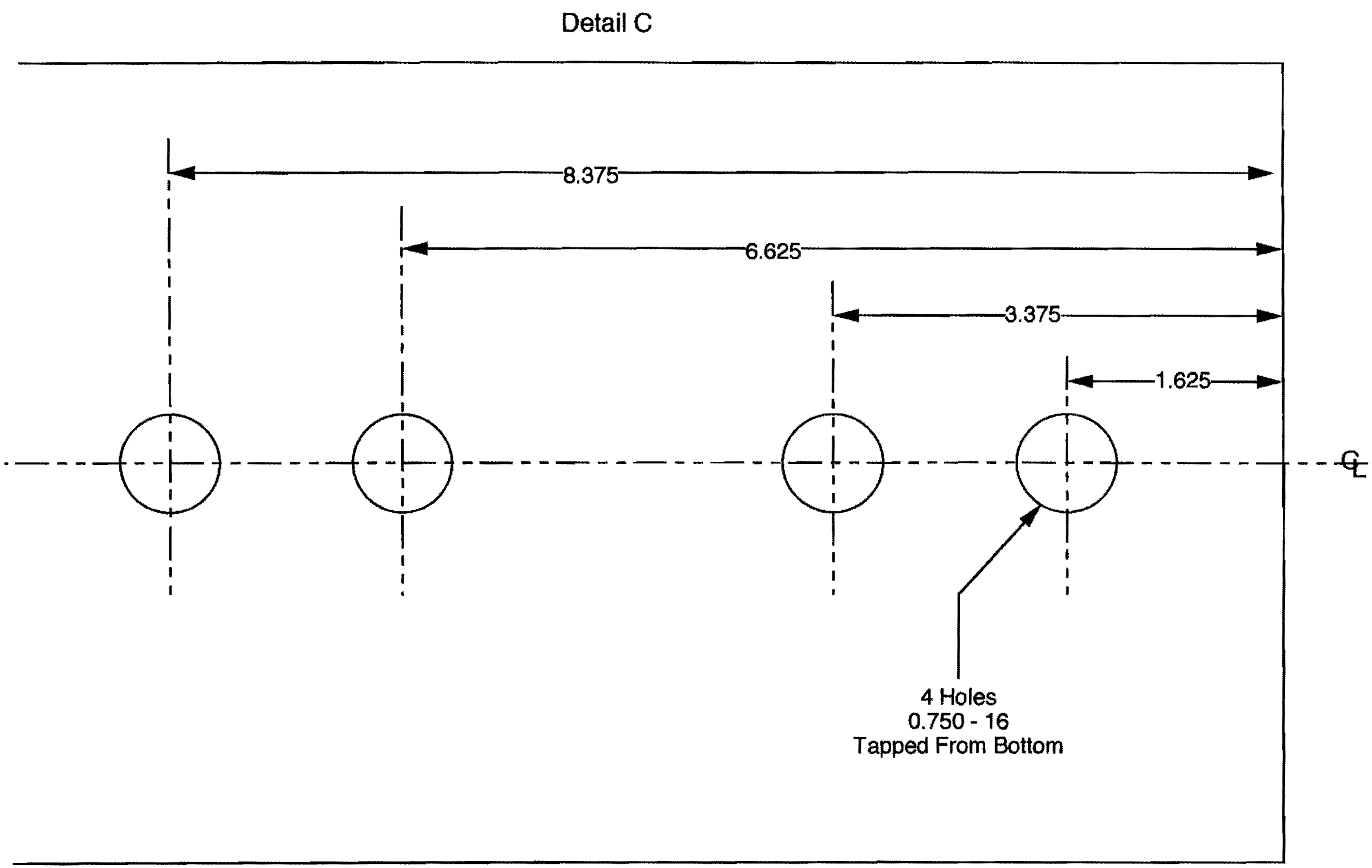


Fig. A.6 Drawings for Bearing Support Detail, Rolling Dynamic Deflectometer Load Frame

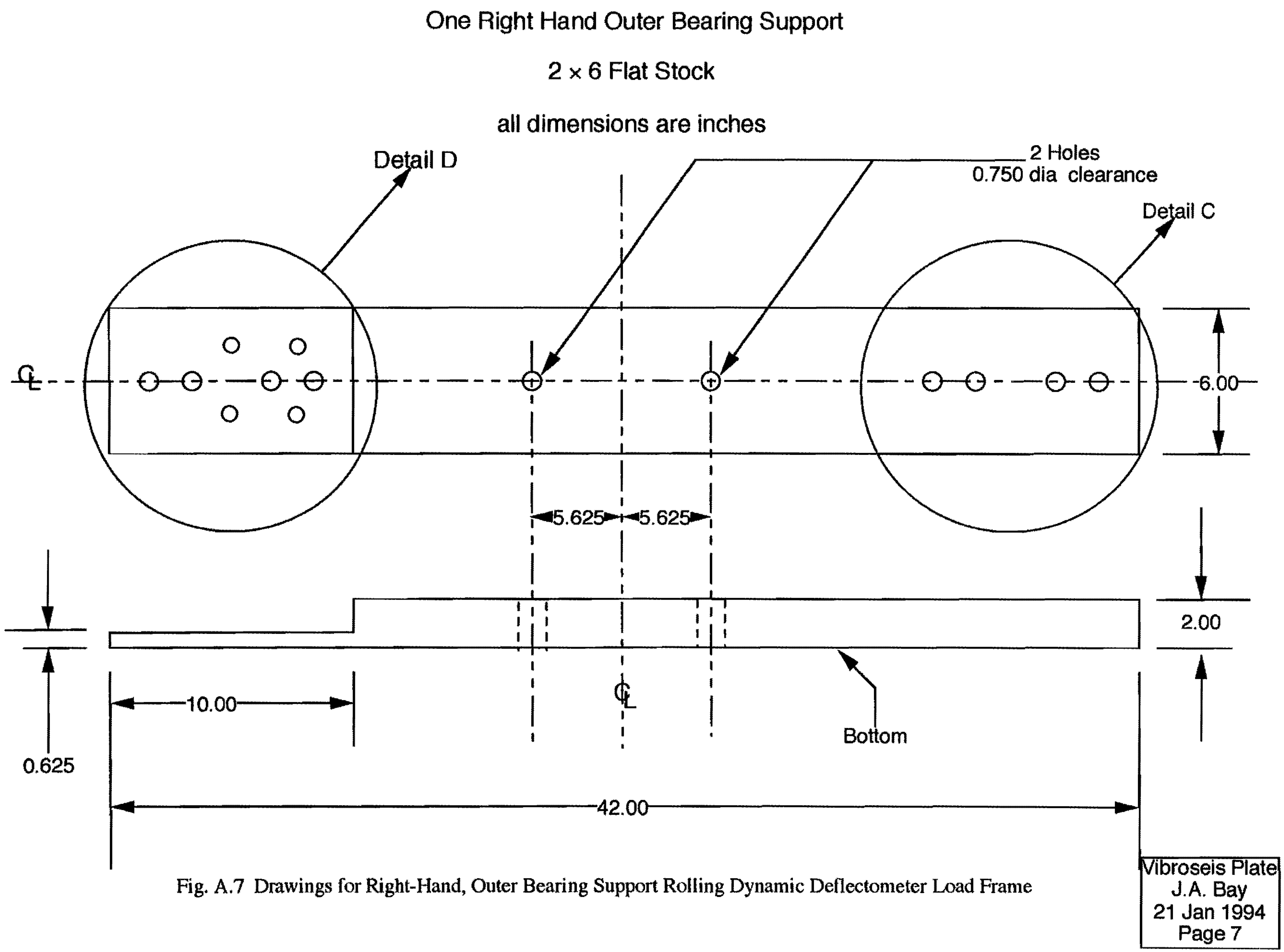


Fig. A.7 Drawings for Right-Hand, Outer Bearing Support Rolling Dynamic Deflectometer Load Frame

Detail

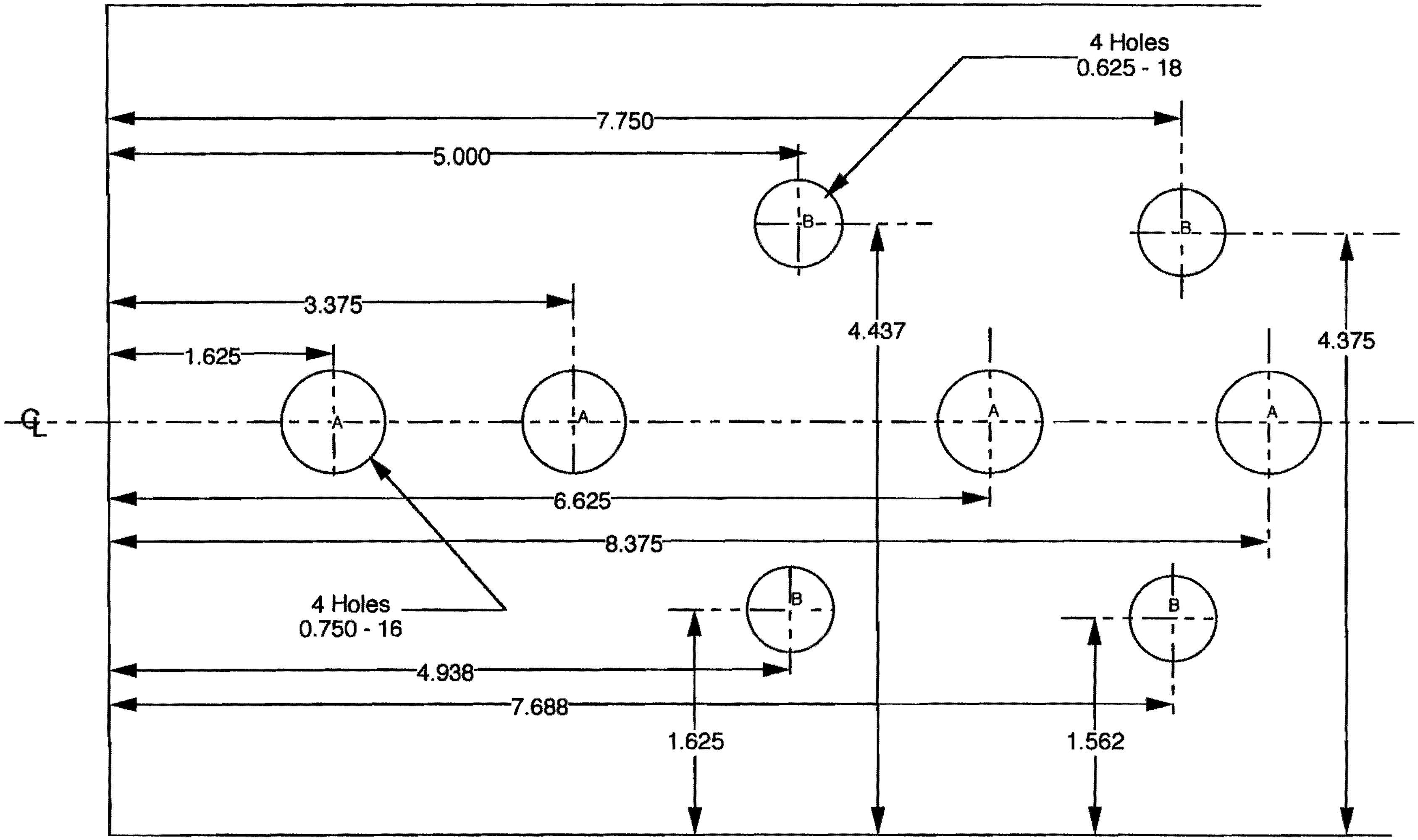


Fig. A.8 Drawings for Bearing Support Detail, Rolling Dynamic Deflectometer Load Frame

Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 8

2 Inner Bearing Supports

2 × 6 Flat Stock

all dimensions are inches

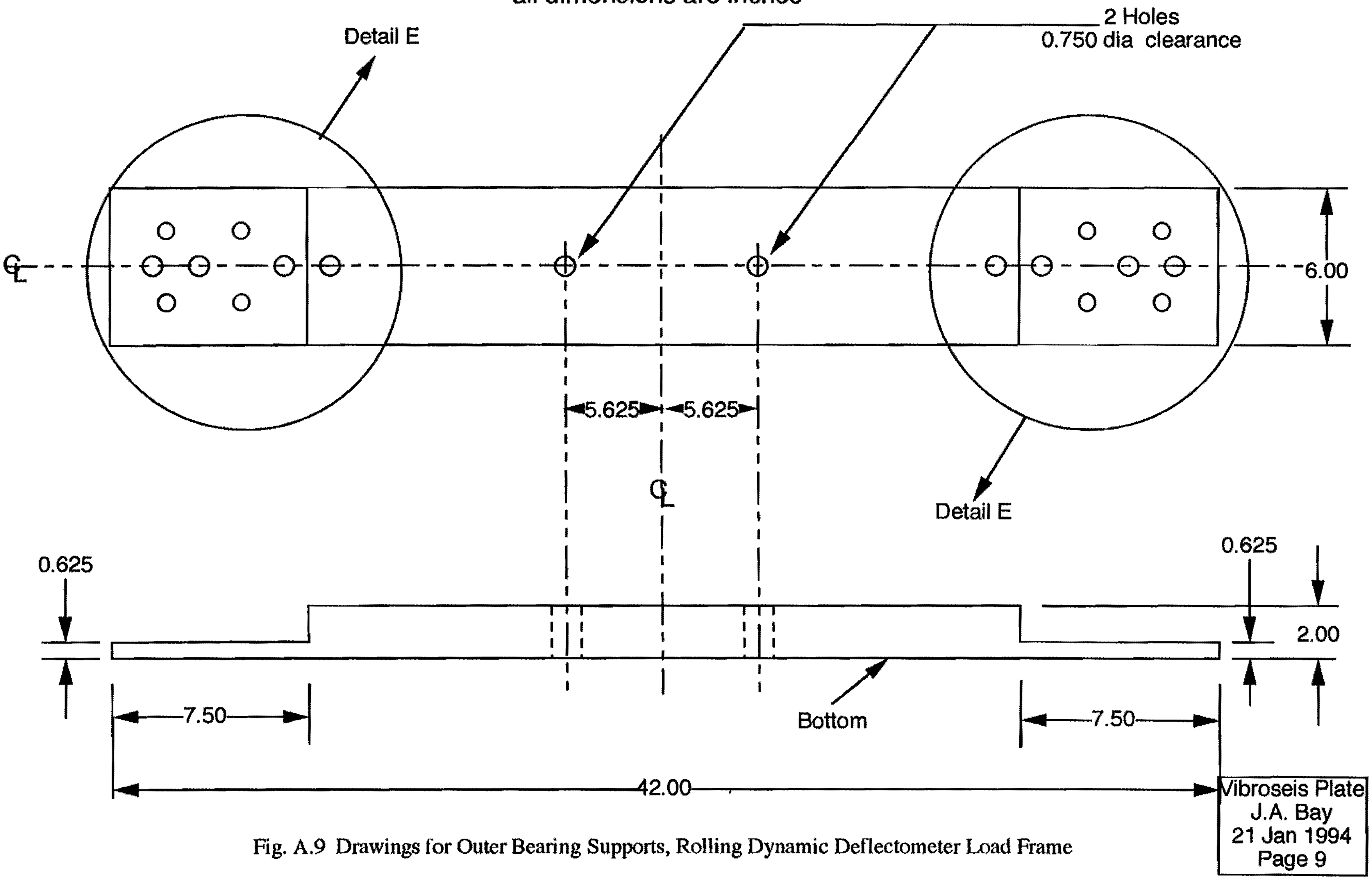
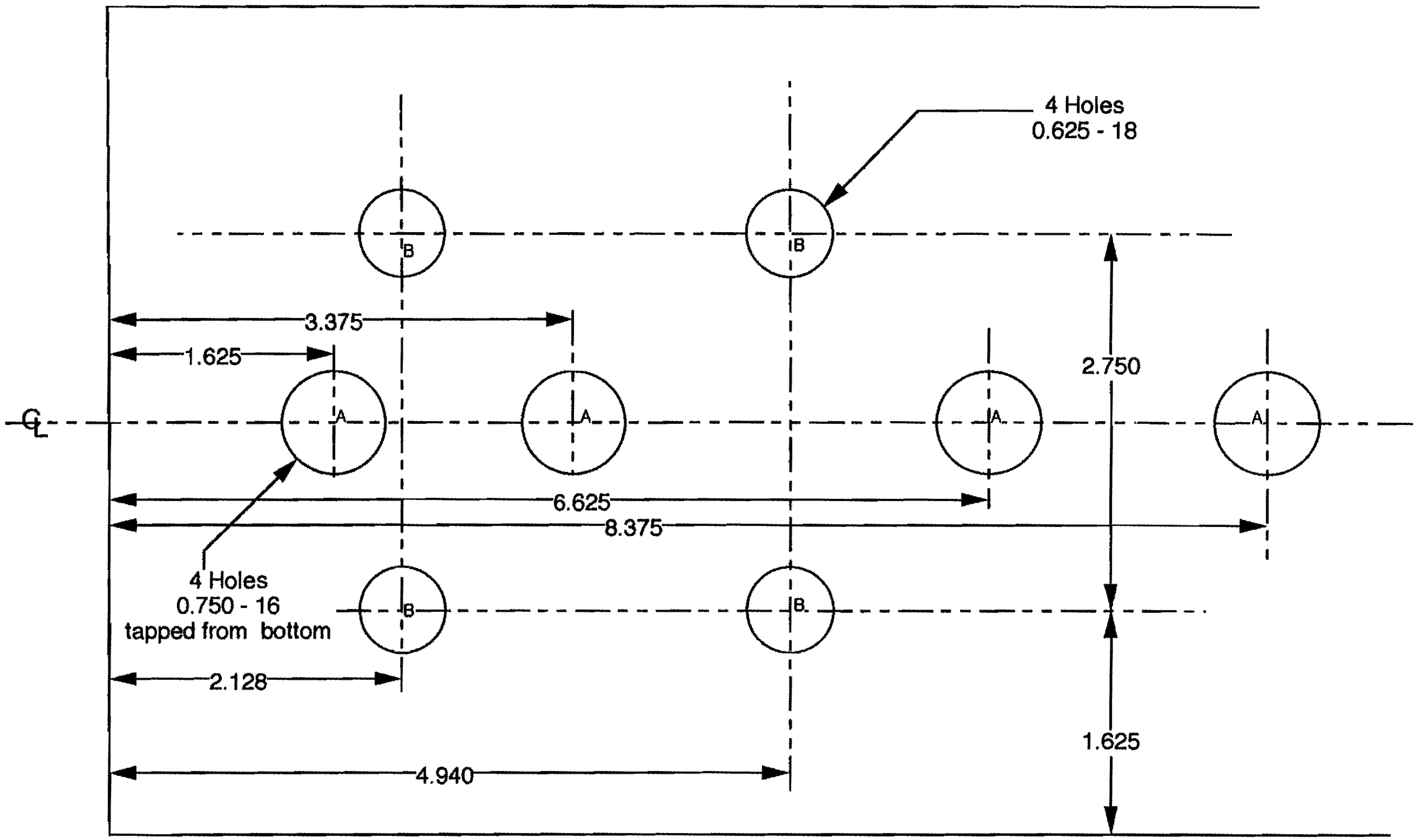


Fig. A.9 Drawings for Outer Bearing Supports, Rolling Dynamic Deflectometer Load Frame

I E



Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 10

Fig. A.10 Drawings for Outer Bearing Support Detail, Rolling Dynamic Deflectometer Load Frame

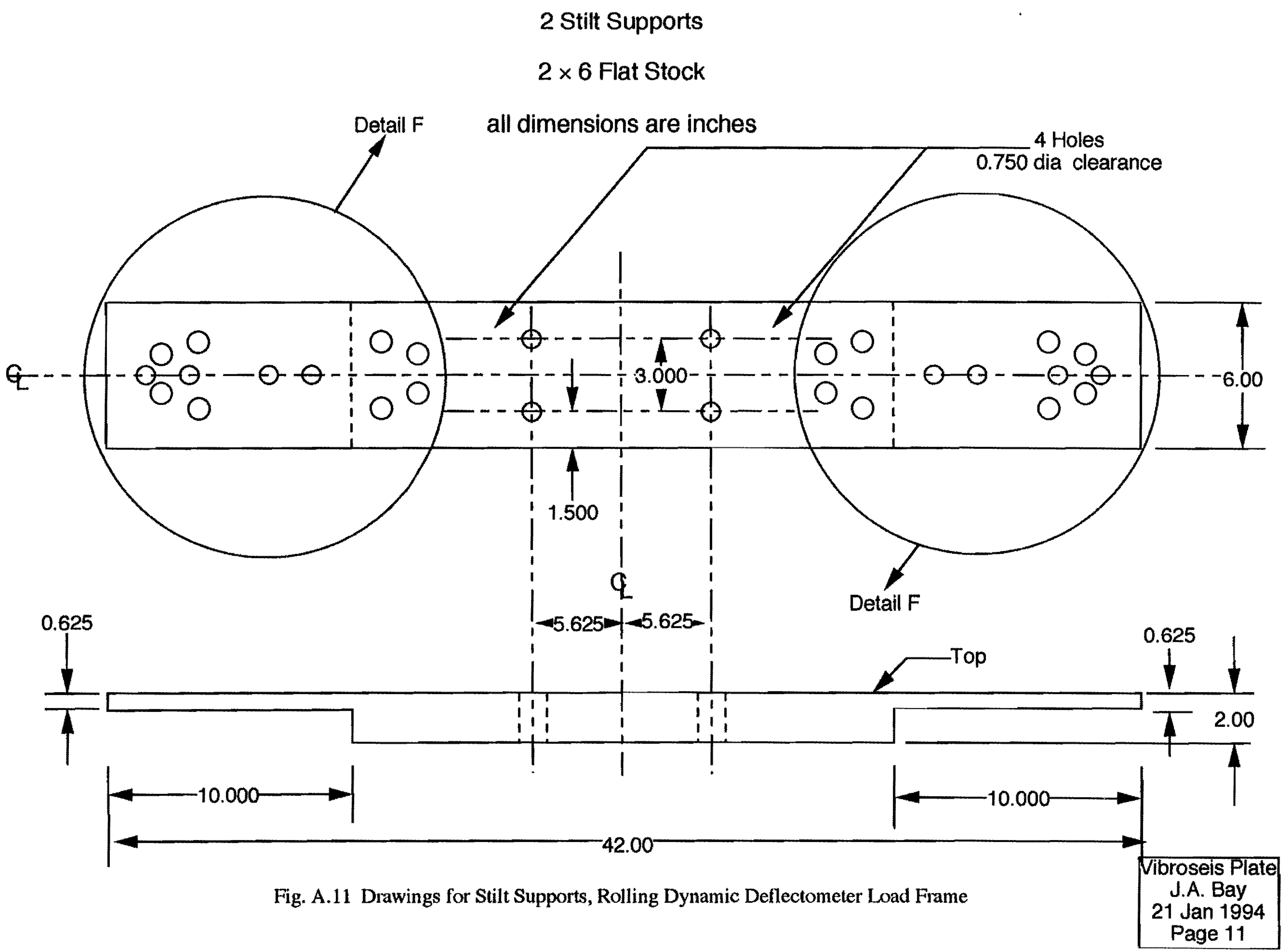


Fig. A.11 Drawings for Stilt Supports, Rolling Dynamic Deflectometer Load Frame

Detail F

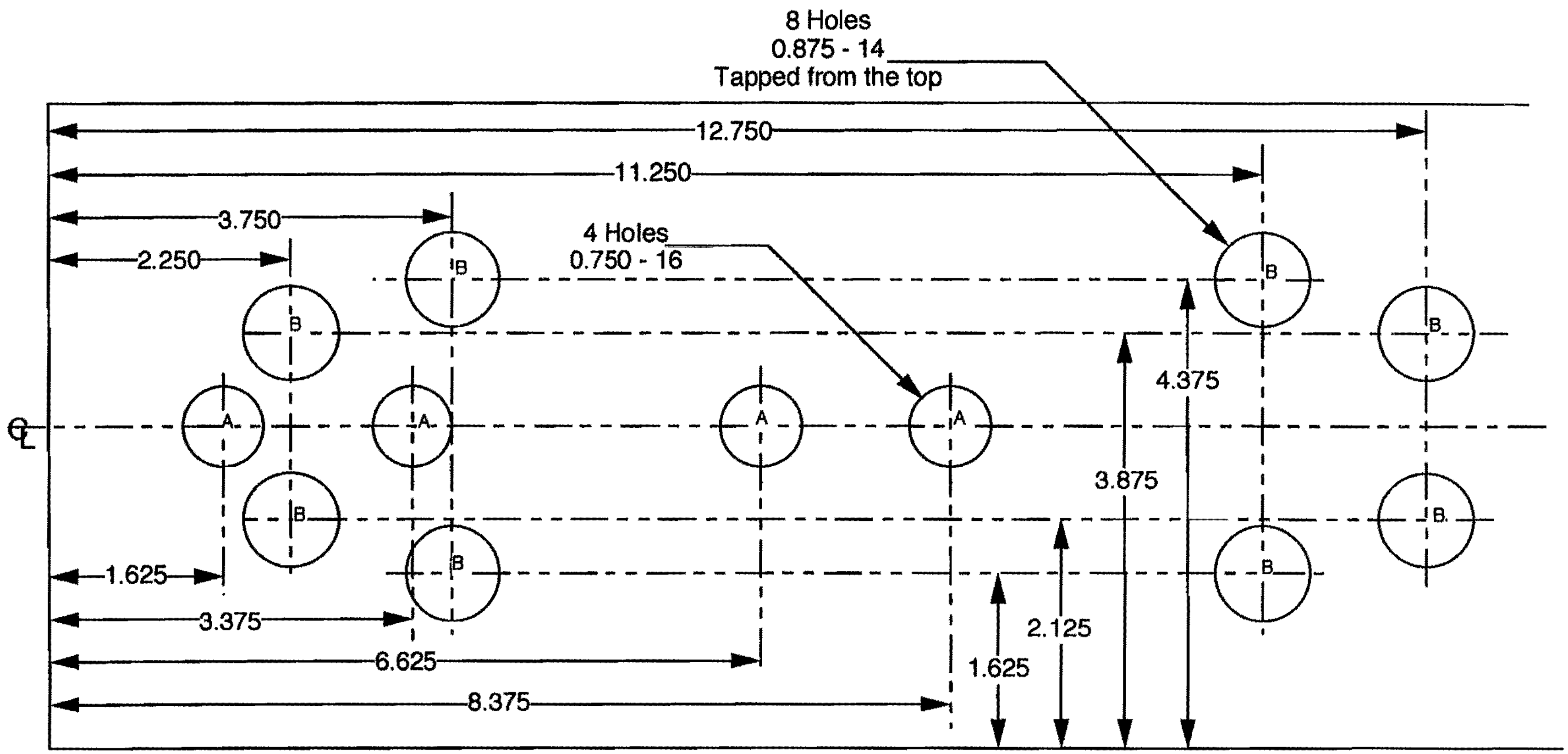


Fig. A.12 Drawings for Stilt Support Detail, Rolling Dynamic Deflectometer Load Frame

Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 12

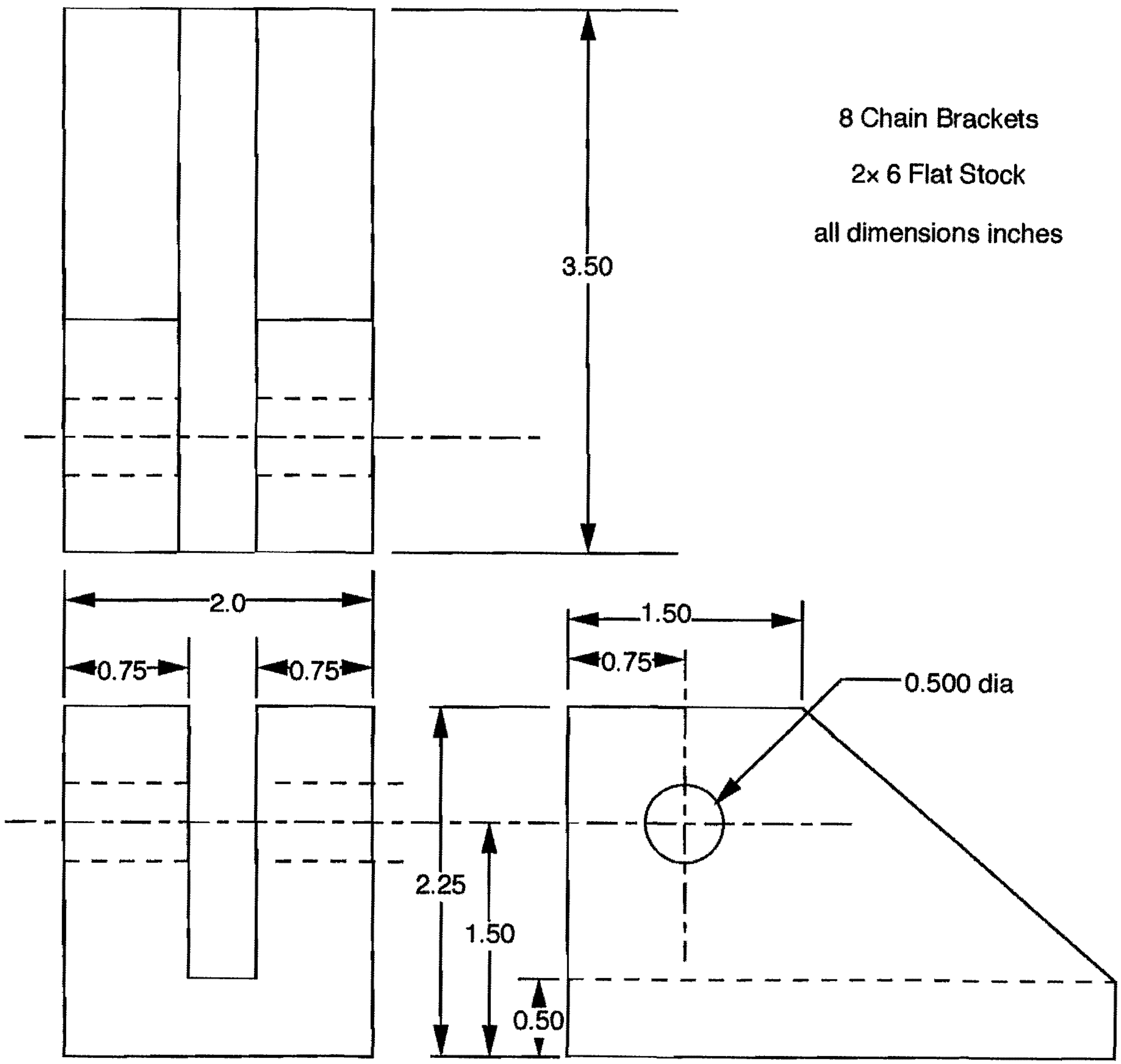


Fig. A.13 Drawings for Chain Brackets, Rolling Dynamic Deflectometer Load Frame

Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 13

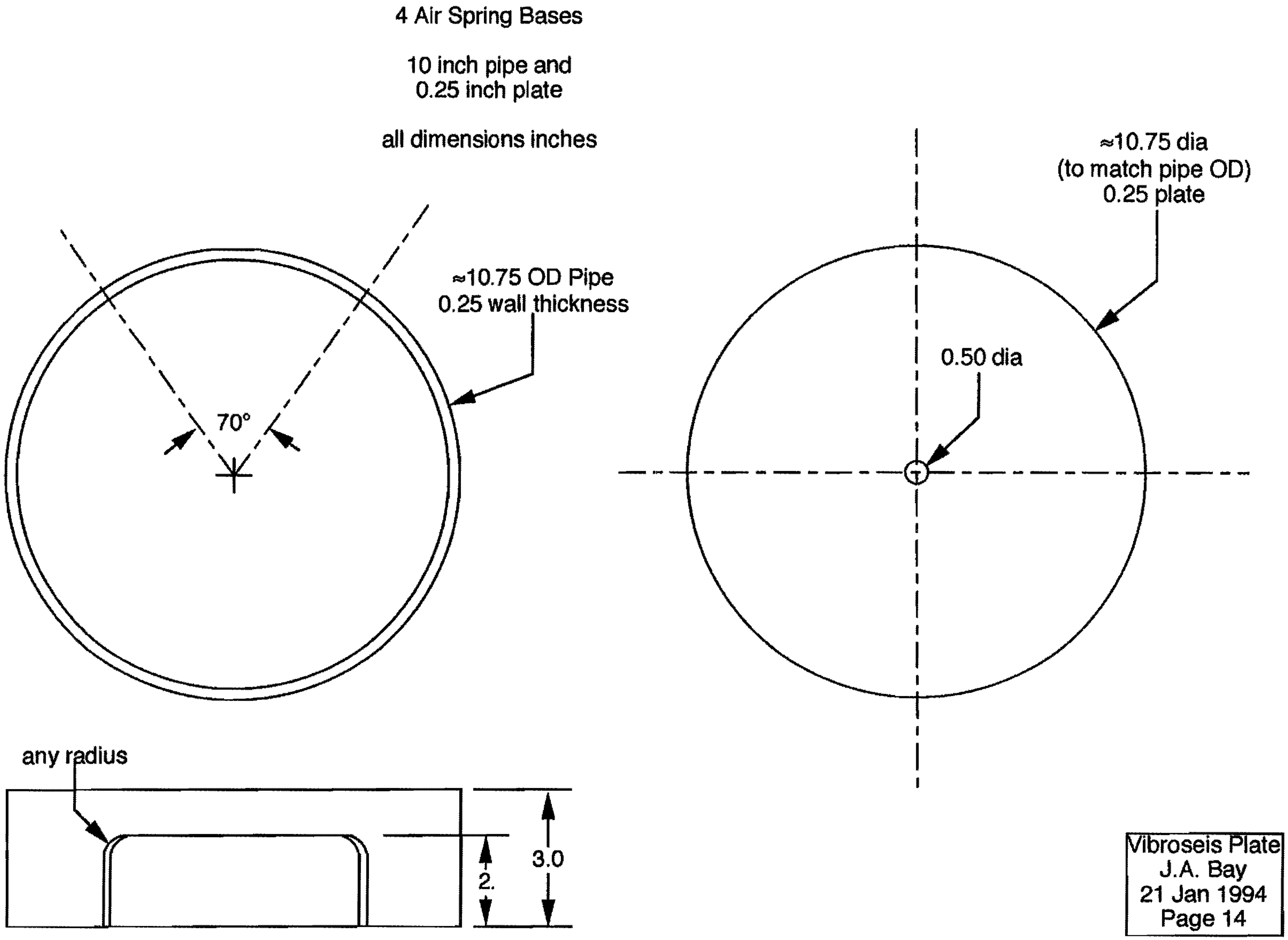
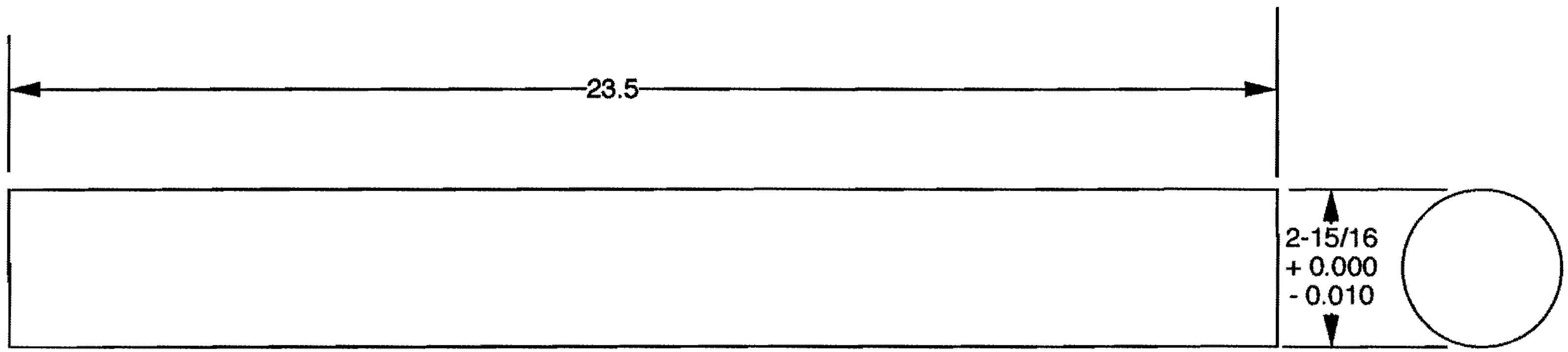


Fig. A.14 Drawings for Air Spring Bases, Rolling Dynamic Deflectometer Load Frame

2 Axles

3 dia rod

all dimensions inches



The axles will need dimples drilled radially to line up with set screws in wheels and bearings after assembly

Vibroseis Plate
J.A. Bay
21 Jan 1994
Page 15

Fig. A.15 Drawings for Loading Wheel Axles, Rolling Dynamic Deflectometer Load Frame

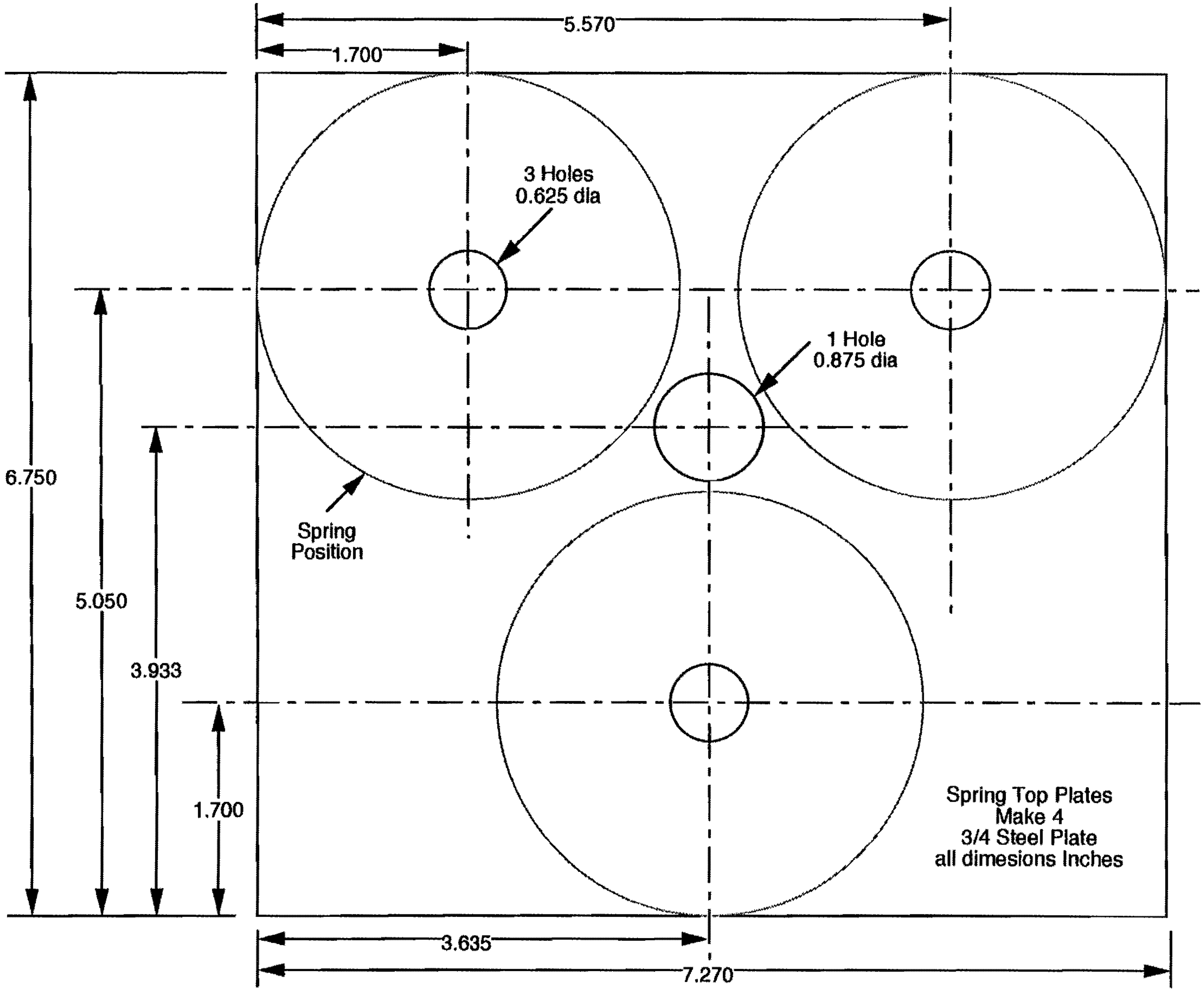


Fig. A.16 Drawings for Top Plates, Coil Spring Suspension, Rolling Dynamic Deflectometer

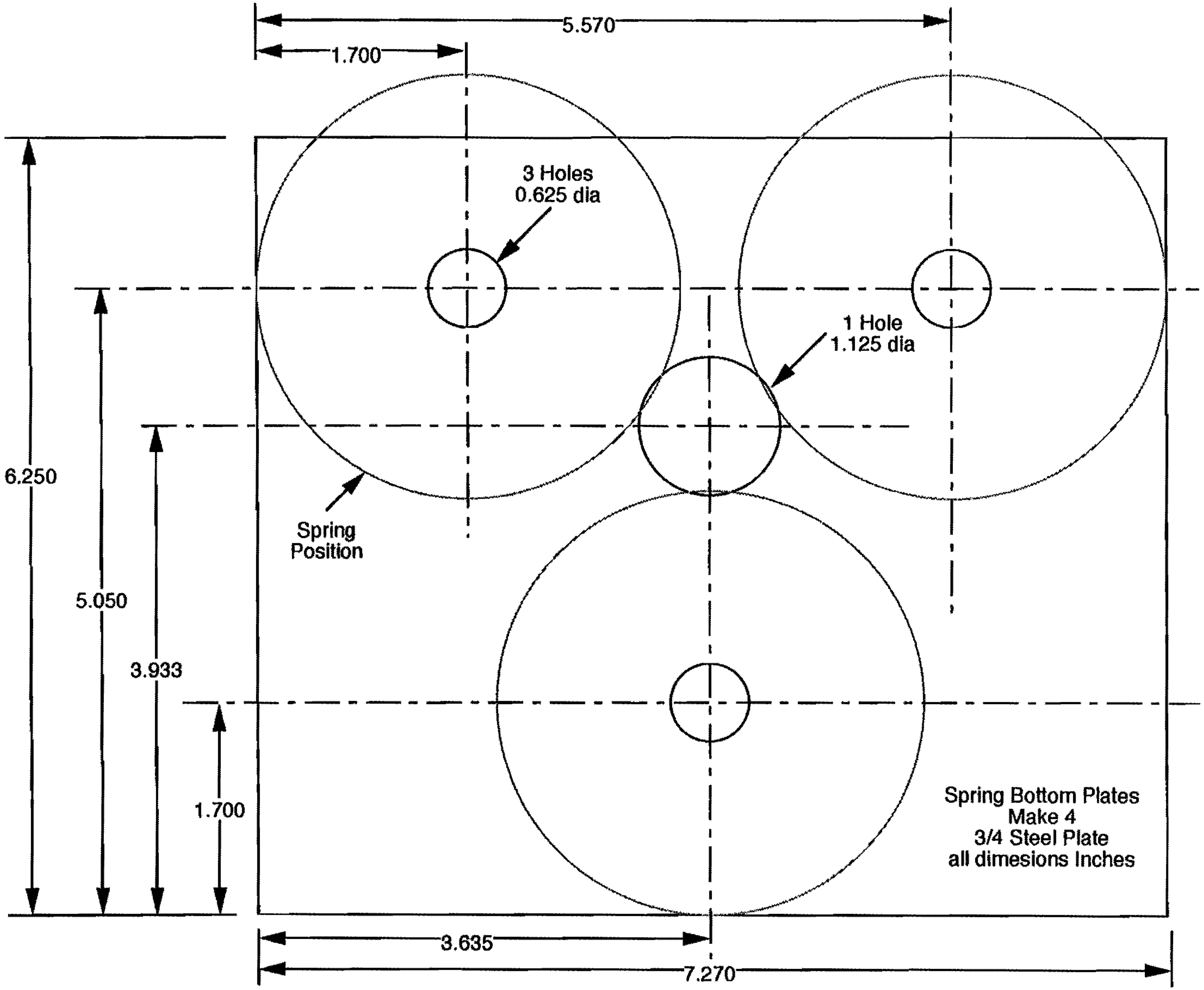
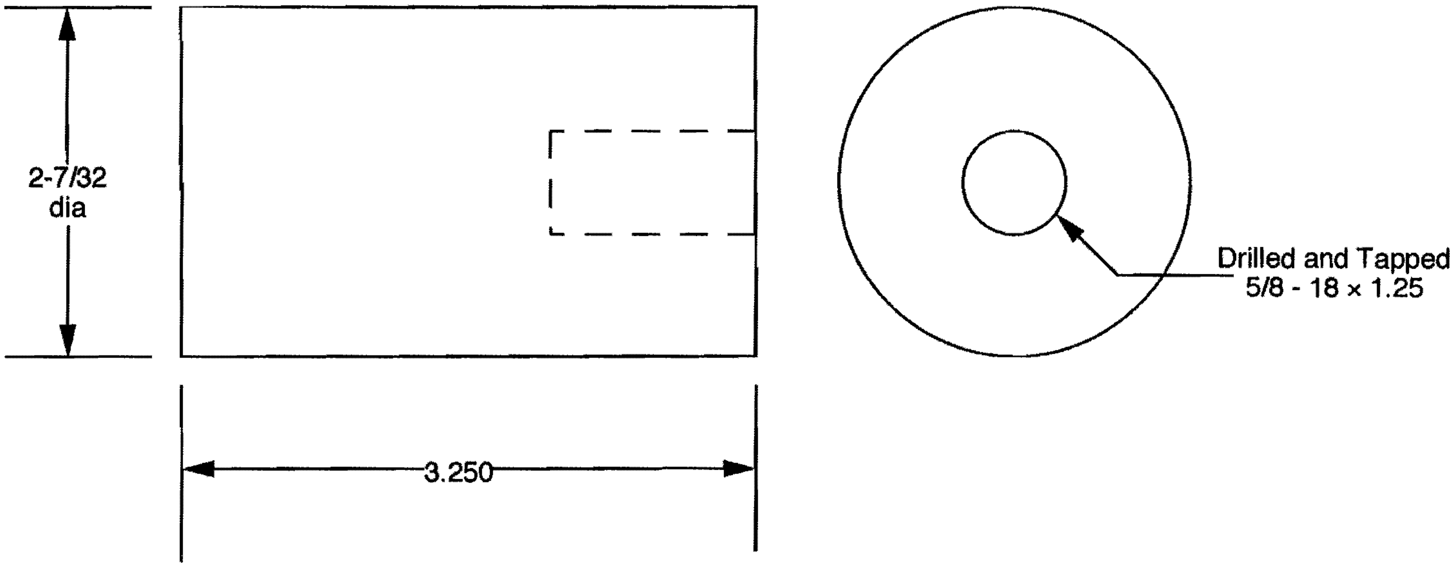


Fig. A.17 Drawings for Bottom Plates, Coil Spring Suspension, Rolling Dynamic Deflectometer

Spring Center Posts
Make 24
2-1/2 diaAluminum
Rod
all dimensions inches



Also Cut 4 Pieces of 7/8 All Thread
to a length of 21-3/8 inches

Fig. A.18 Drawings for Spring Center Posts, Coil Spring Suspension, Rolling Dynamic Deflectometer

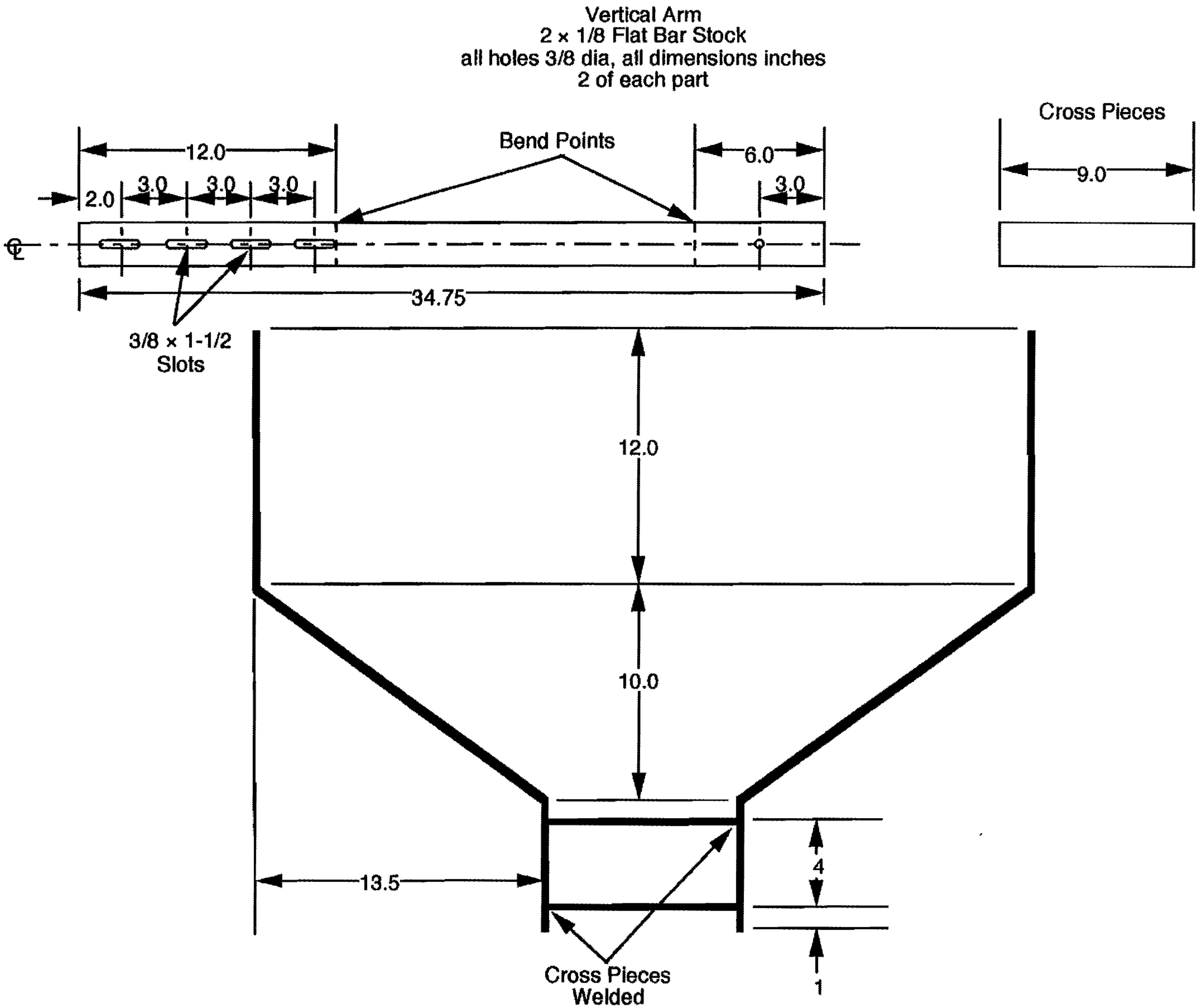


Fig. A.19 Drawing for Vertical Arm, Receiver Wheel Support, Rolling Dynamic Deflectometer

Inner Arm
2 × 1/8 Flat Bar Stock
all holes 3/8 dia, all dimensions inches
2 long pieces, 3 cross pieces

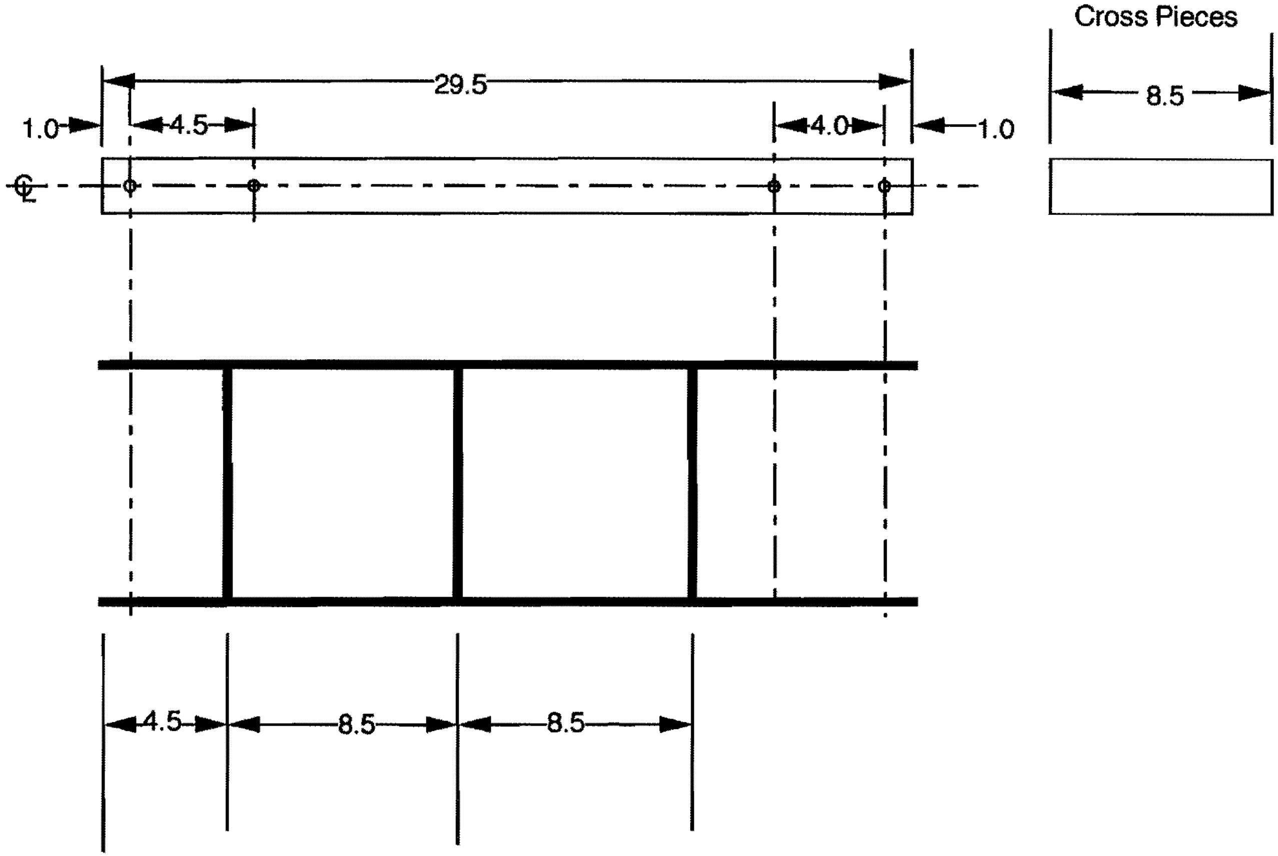


Fig. A.20 Drawing for Inner Arm, Receiver Wheel Support, Rolling Dynamic Deflectometer

1/8 x 2 Flat Bar Stock
2 of each

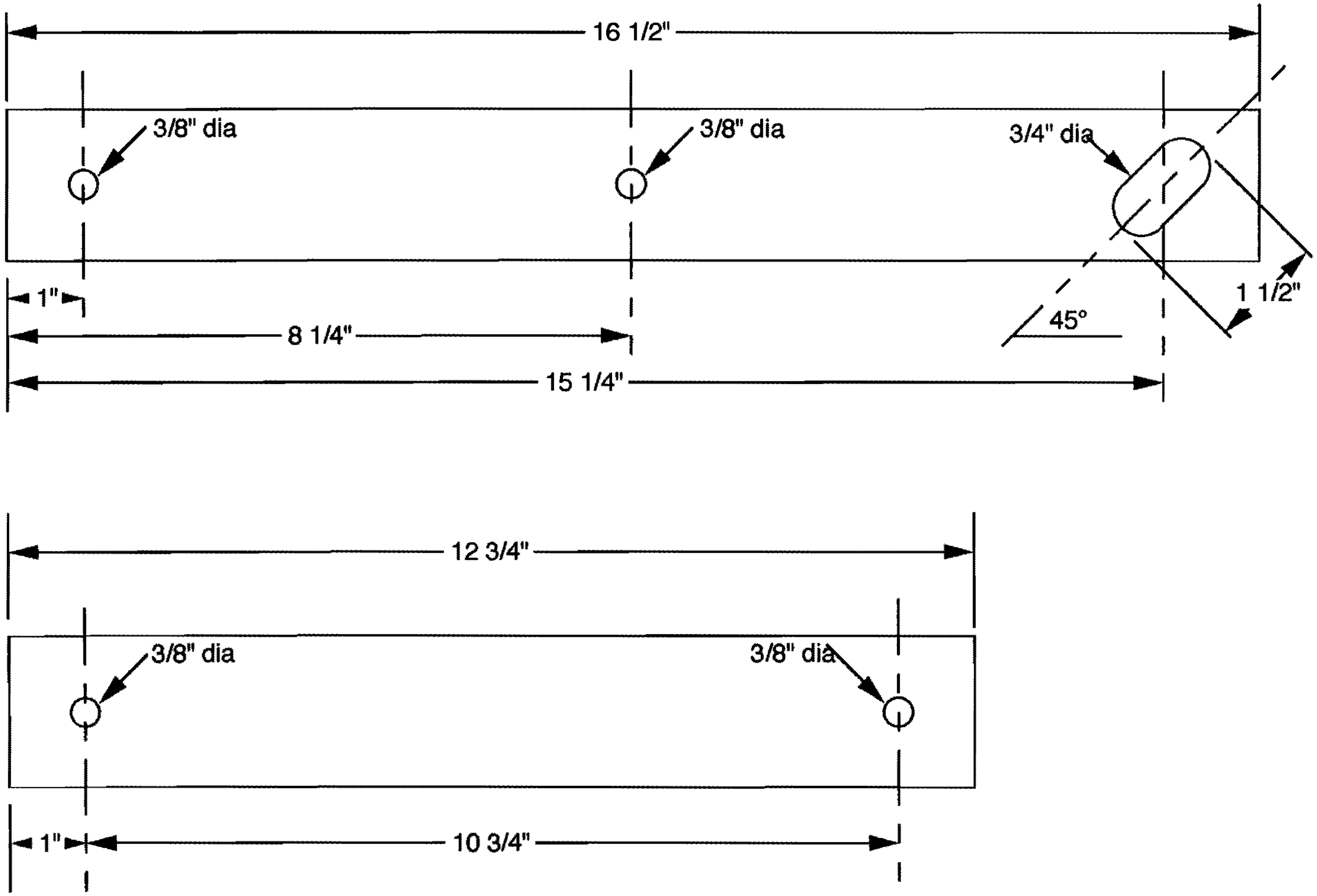


Fig. A.21 Drawing for Outer Arm, Receiver Wheel Support, Rolling Dynamic Deflectometer

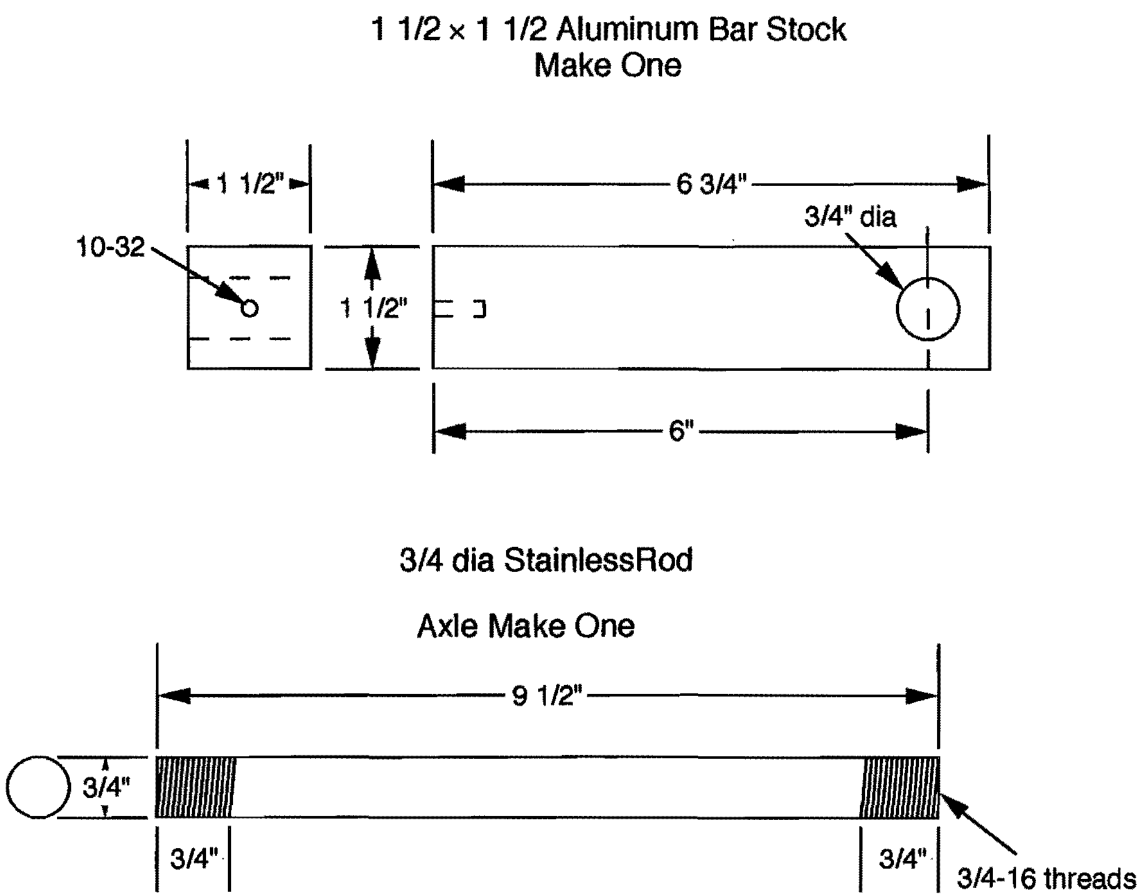


Fig. A.22 Drawings for Accelerometer Support and Axle, Receiver Wheel Support, Rolling Dynamic Deflectometer