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SOME OBSERVATIONS ON STRONG-MOTION EARTHQUAKE MEASUREMENT USING A DIGITAL ACCELEROGRAPH

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ABSTRACT

This paper presents results of a study of some of the characteristics of a PDR-1 digital strong-motion accelerograph. Results are presented for laboratory tests of the background noise level of the instrument, and these results are compared with previously reported observations for optical instruments. Noise levels for the digital instrument are found to be one or two orders of magnitude lower than for an analog optimal instrument. The paper discusses determination of displacement from acceleration data, and results of laboratory tests are presented. An instrument anomaly in the FBA-13 transducer is identified, a simple data correction algorithm proposed, and examples given. The paper also presents detailed results of a comparison of earthquake records obtained from side-by-side digital and optical analog instruments during an aftershock of the 1983 Coalinga earthquake.

INTRODUCTION

The development of reliable, digital strong-motion accelerographs is having a significant impact on the measurement of strong ground motion. Digital instruments electrically convert the transducer output from analog to digital form and then record the digital data on magnetic tape or a core memory in a computer-readable form. This bypasses the errors associated with the recording of analog data and subsequent conversion to digital format which are inherent with optimal analog accelerographs. The digital instruments have the advantages of lower noise and greater ease of data processing. Timing is also considerably more accurate in digital recorders being derived from an accurate data rate of 100 to 200 sps rather than from a timing pulse with a 2-Hz rate as is typical of optical analog instruments.

The resolution and dynamic range of a digital instrument generally exceed those of an analog instrument, and the transducers used with digital instruments normally have a greater bandwidth than their analog counterparts. In addition, digital instruments commonly have a preevent memory so that the entire history of the motion is recorded along with initial conditions.

Due to their many advantages, the use of digital instruments will probably become widespread throughout the world in the years to come. However, since these instruments have only recently been put into service, their characteristics are not yet well known. The purpose of this paper is to present results of a study of the recording characteristics of a typical strong-motion recorder/transducer instrument, the Kinemetrics PDR-1/FBA-13. This paper is an extended version of material presented in one of the references (Iwan, 1984).

NOISE LEVEL OF DIGITAL INSTRUMENT

A great deal of laboratory and field experience has been gained with optical strong-motion recorders. The limitations of these instruments are fairly well un-

derstood and substantial effort has been expended to maximize the data return from such instruments using various filtering and correction algorithms. An excellent review of the considerable work done in this area has been presented by Hudson (1979). Noise enters into the optical recording from a number of sources including transducer drift, recording medium lateral drift and speed variation, trace density variations, and the digitization process. This noise limits the range of ground motion for which useful data can be obtained. Generally speaking, the optical instruments will have difficulty providing useful data for earthquakes of $M = 4$ or smaller even in the epicentral region and for earthquakes of magnitude $M = 6.5$ if further than 200 km from the source.

Digital instruments have inherently lower noise than analog instruments. Noise associated with media drift, transport speed variation, and trace density variation is virtually eliminated with the digital format. Furthermore, digitization error is greatly reduced by eliminating the intermediate step of optical recording.

In order to obtain quantitative data on the background noise of a typical digital strong-motion recorder, a Kinemetrics PDR-1/FBA-13 instrument was tested. The PDR-1 is a gain ranging recorder with 12-bit resolution and a 102dB dynamic range. The FBA-13 is a triaxial "force balance"-type accelerometer. In a true force balance accelerometer, the mass element is held in dynamic "equilibrium" by means of an electrically generated feedback force which balances the acceleration induced force. The FBA-13 is not a force balance transducer in the strictest sense since the mass element is allowed to move with respect to its support. Indeed, it is this movement of the mass element on its flexures that is sensed as the output of the transducer. Feedback is used primarily to control the stiffness and damping of the system (Amini and Trifunac, 1985). The natural frequency and damping of the FBA-13 are nominally 50 Hz and 70 per cent, respectively.

For the noise tests, the FBA-13 transducer was mounted on an air suspension optical table in a relatively quiet laboratory environment. Samples of instrument noise were recorded for a duration of 20 sec using the PDR-1 "run" mode. The recorded data was subsequently processed to obtain the time history of the noise and the pseudovelocity response spectrum. Care was taken in balancing the transducer so that maximum system gain was obtained. No data was obtained at lower gains. The input low-pass filter of the recorder was set at its maximum value of 50 Hz, and the sample rate was 200 sps. No correction was introduced into the processing except for a uniform baseline shift obtained by subtracting the average of the entire accelerogram. It was impossible to determine the absolute motion of the test table with any greater accuracy than that of the transducer measurement itself. Therefore, the results reported may contain some background environment noise as well as instrument noise. In this regard, the results may be viewed as conservative estimates of the instrument noise.

Figure 1 shows the superimposed zero-damped response spectra for four different test runs. Also shown in Figure 1 is the band of average digitization noise plus one standard deviation for a typical hand digitized optical record as reported in the literature (Hudson, 1977, 1979). In addition, the figure shows the 20 per cent damped average digitization noise spectrum which is claimed for the automatic digitization system employed by the California Division of Mines and Geology.

It is seen from Figure 1 that there is a very striking difference in noise level between the analog and digital systems. The difference varies from more than one order of magnitude at short periods (high frequency) to about two orders of magnitude at long periods (low frequency). It is clear from the figure that the digital instrument is capable of accurately measuring the acceleration from much smaller

events than the analog instrument. It is also clear that the digital instrument should give superior results for integrals of the acceleration, i.e., velocity and displacement. The digitization noise in the displacement at a period of 10 sec is of the order of two inches for the optical instrument but is closer to 0.02 inches for the digital instrument. It would therefore be anticipated that the digital instrument could be used to extract significantly more information about displacement than the analog instrument. This possibility is examined in the next section.

COMPUTATION OF DISPLACEMENT FROM ACCELERATION

In principle, velocity and displacement time histories could be obtained directly from an acceleration time history by numerical integration. However, for optically

FIG. 1. Noise response spectrum.

recorded data, this usually results in errors which are unacceptably large. This is partly due to the fact that digitization and other errors increase with period as indicated in Figure 1 and therefore become effectively amplified when the acceleration time history is integrated. In addition, an initial portion of the acceleration time history is lost in the analog instrument due to the absence of a preevent memory and the finite time required to trigger the instrument. The digital instrument has much lower noise than the analog instrument and the preevent memory eliminates the ambiguity in the initial conditions of the data.

In order to examine the nature of the errors associated with integration of acceleration time histories obtained from digital instruments, a series of laboratory tests were conducted using the PDR-1/FBA-13 instrument. The transducer was moved horizontally in a straight line on a very flat, level surface through a known displacement. The recorder was triggered from the output of the accelerometer oriented in the direction of motion. The acceleration data was then integrated to obtain the time histories of velocity and displacement. The input low-pass filter of the PDR-1 was set at 50 Hz, and the sample rate was 200 sps.

A typical result for a test with a relatively smooth displacement is shown in Figure 2. For the test results shown, the actual permanent displacement of the transducer was 25.4 ± 0.3 cm (10 ± 0.1 inches). It is seen that the integrated acceleration time history gives a fairly accurate measure of this permanent displacement. The only correction applied to the data was to adjust the zero offset of the accelerogram by the average value of the preevent data (the first 1.0 sec of the record was used for this average) and apply an instrument correction to remove transducer distortion. The PDR-1 does *not* have a high-pass filter, so the dc output from the accelerometers is retained. This is a necessary feature of the instrument if true permanent displacement information is desired.

FIG. 2. Displacement test—no data correction.

It would not be possible to generate a displacement time history like that shown in Figure 2 from an optical recording instrument due to absence of preevent data and the presence of significant long-period noise. In an attempt to minimize the effects of these factors, optically recorded data are typically subjected to various forms of baseline correction and low- and high-pass filtering. In order to obtain a better understanding of the effect of these corrections, the acceleration time history of Figure 2 was processed using the standard correction algorithms employed in the report series entitled "Corrected Accelerograms" published by the California Insti-

tute of Technology (Trifunac and Lee, 1973). The results are shown in Figure 3. It is seen that the effect of the correction algorithm is to "level out" the displacement time history thus eliminating any permanent displacement and simultaneously reducing the magnitude of the dynamic displacement.

AN ANOMALY OF THE TEST INSTRUMENT

Unfortunately, the excellent results of double integration of the acceleration indicated in Figure 2 are not altogether typical of those obtained. Rather extensive

FIG. 3. Displacement test of Figure 2 with standard CIT Volume II correction.

laboratory testing and field use of the FBA-13 transducer has revealed an anomaly which has a significant effect on data analysis. Figure 4 shows the result of direct numerical integration for a permanent displacement test in which the transducer was moved in an oscillating fashion having associated high peaks of acceleration. In this case, a very noticeable drift is observed in the displacement time history which completely overshadows the actual test permanent displacement which was again 25.4 cm.

Through further testing, it was determined that the baseline output of the FBA-13/PDR-1 would shift by a very small amount whenever a sufficiently large input acceleration pulse was applied. This shift appears to be the result of minute

mechanical or electrical hysteresis within the transducer system. The cause of this hysteretic-like behavior is not fully understood and is currently being investigated by the manufacturer. Although, the anomaly produces only a small acceleration offset, it can have a noticeable effect on the double integral of the acceleration data.

An attempt has been made to develop a correction algorithm which can compensate for the observed anomaly without having an adverse effect on the ability of the instrument to predict permanent displacement. The proposed correction algorithm is quite simple and based on the perceived hysteretic nature of the anomaly. The

FIG. 4. Displacement test showing effects of instrument anomaly.

acceleration data is first corrected for the dc offset observed in the preevent data. Typically, this is accomplished by performing a time average on only the first one-half of the preevent data in order to eliminate the possibility of including any actual earthquake data.

Next, the final offset of the acceleration is determined. If there were no instrument anomaly, this offset should be zero since the preevent and final offsets should be equal. However, due to transducer hysteresis, these two offsets will not, in general, be the same. If the dynamic or oscillatory component of the acceleration at the end of the record is smaller than the final offset of the record, as in Figure 2, the acceleration record may be used directly to determine the final offset. However, it

has been found that it is usually more accurate to estimate the final acceleration offset from the final slope of the velocity record since it has a relatively smaller oscillatory component. Normally, a strong-motion recorder will continue to operate for at least 15 sec after the major motion. This will generally be adequate to determine the final acceleration offset.

The cumulative effect of the transducer anomaly during the time of strong shaking is estimated by simply assuming that the individual intermediate baseline shifts associated with movement hysteresis can be replaced by a single rectangular

FIG. 5. Simple correction algorithm for instrument anomaly.

acceleration correction which occurs only during the strongest portion of the acceleration time history. The value of the intermediate acceleration correction is selected so as to make the velocity correction continuous over the entire record. The overall correction for the instrument anomaly is shown schematically in Figure 5.

The times t_1 and t_2 may be selected in a number of different ways, and it has been observed that the final results are generally fairly insensitive to this selection. Experiments have shown that very little transducer hysteresis occurs for accelerations less than 50 cm/sec^2 . Therefore, one possible approach is to select t_1 and t_2 as respectively the times of first and last occurrence of accelerations $a(t) \geq$

50 cm/sec². This approach (Option One) has been found to work well when there is known to be a real final net displacement. Another approach would be to select t_1 as the time of the first significant acceleration pulse and then select t_2 so as to minimize the computed final displacement. This approach (Option Two) is useful when the existence of a final displacement is not known *a priori*. If there is in fact a real final displacement, Option Two will normally yield a value of t_2 which is less than t_1 , signifying that Option One is more appropriate.

FIG. 6. Displacement test of Figure 4 with proposed correction algorithm.

The correction for the final offset is most easily determined by a least-squares fit of the final portion of the velocity data. This correction will have the form

$$v_c(t) = v_0 + a_f t.$$

Then, the value of the intermediate range correction acceleration will be

$$a_m = \frac{v_c(t_2)}{(t_2 - t_1)}.$$

The result of applying the correction algorithm to the acceleration time history of Figure 4 is shown in Figure 6. Option One was used in the selection of t_1 and t_2 . The corrected displacement results show good agreement with the actual permanent displacement of 25.4 cm. Very little low frequency (long-period) information seems to have been lost from the data by the correction algorithm. Indeed, this was one of the goals in the development of the algorithm.

Additional examples of the results of prescribed displacement tests using the proposed correction algorithm are given in a California Institute of Technology

FIG. 7. Digital accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; 35°.

report (Iwan *et al.*, 1984). It has been observed that the numerical values of the corrections a_f and a_m are generally quite small, being of the order of 2 per cent or less of the maximum acceleration. The displacement results have been observed to be fairly insensitive to the selection of the threshold acceleration level which defines t_1 and t_2 .

It is believed that the simplified correction algorithm is adequate for most short-duration earthquake-like time histories of motion. In this case, the time duration over which the central correction is applied will generally be smaller than for the

high level acceleration tests presented herein, and the permanent ground displacement will also take place over a shorter time interval. This will be illustrated by examples which follow.

It should be emphasized that the suggested correction algorithm has been introduced only to eliminate an observed anomaly in the instrument. It is anticipated that the source of this anomalous behavior will soon be eliminated so that correction of the digital accelerogram will no longer be necessary.

FIG. 8. Digital accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; up.

COMPARISON OF ANALOG AND DIGITAL RECORDS

Following the Coalinga earthquake of 2 May 1983, an SMA-1 optical analog recording accelerograph and PDR-1/FBA-13 digital accelerograph were installed side-by-side in a residential garage near the center of the city to record aftershocks. On 8 May 1983, an aftershock of $M_L = 5.5$ with an epicenter approximately 11 km to the north of the city was recorded simultaneously by both instruments. The results obtained represent a unique opportunity for a direct comparison between the optical analog and digital recording instruments.

The time histories of the ground acceleration, velocity, and displacement for the

digital instrument are shown in Figures 7 to 9. The time histories shown were corrected using the algorithm described herein with t_1 and t_2 selected according to Option Two. The sampling rate was 100 sps.

The time histories obtained from the analog instrument are presented in Figures 10 to 12. These results were obtained from accelerograms which were digitized and corrected by the California Division of Mines and Geology. This data was band-pass filtered with a low-frequency cut-off of 0.2 to 0.4 Hz (2.5 to 5 sec) and a high-

FIG. 9. Digital accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; 125°.

frequency cut-off of 23 to 25 Hz. The maximum acceleration, velocity, and displacement obtained from the two different instruments are compared in Table 1.

In general, there is rather close agreement between the results obtained from the analog and digital instruments. The greatest difference is, as expected, in the displacement. The results obtained from the digital instrument show the presence of a long-period displacement which is filtered out of the results from the optical analog instrument. The use of Option Two to correct the digital data in this case minimizes the final displacement. However, a small but significant long-period displacement with a rise time of the order of 2 to 3 sec is clearly evident. The

potential of the digital instrument to provide long-period information would appear to be supported by this data.

In order to obtain a more complete understanding of the difference between the analog and digital records, a correlation analysis was performed. The cross-correlation coefficient between each pair of records was computed and the time difference for maximum correlation determined. The analog record was shifted by

FIG. 10. Analog accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; 35°.

this time difference and then subtracted from the digital record to obtain the time history of the difference acceleration. The results are shown in Figures 13 to 15.

The difference acceleration shown in Figures 13 to 15 is somewhat larger than might have been anticipated from the relatively high correlation of the analog and digital records. The most satisfactory explanation for this seems to be that there is a slowly varying phase shift with time between the two records. Whether this is associated with speed and therefore time variations in the analog instrument, the digitization process or the instrument correction is uncertain.

In Table 2, the maximum correlation time difference for each pair of records is compared to the time difference between the largest acceleration peak of the records.

In general, there is fairly close agreement between the two measures of time difference. This agreement holds as well for the difference between the largest velocity peak but not for the peak displacement.

The Fourier amplitude spectra of the digital, analog, and difference acceleration time histories are shown in Figures 16 to 18. It is noteworthy that the Fourier amplitude spectrum associated with the difference acceleration is generally signifi-

FIG. 11. Analog accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; up.

cantly larger than the difference between the Fourier amplitude spectra of the digital and analog time histories. This is another indication of the presence of phase differences in the records that are not accounted for by a time shift corresponding to the maximum correlation time. Although not shown herein, a significant phase variation was also observed in the cross-spectrum of the digital and analog records even after the records were shifted. The range of frequency is limited to 25 Hz which is the natural frequency of the SMA-1.

The zero-damped response spectra for the three components of this aftershock are shown in Figure 19–21. The solid lines denote the spectra obtained from the digital instrument, and the dashed lines denote the spectra obtained from the analog

FIG. 12. Analog accelerogram with integrated velocity and displacement. Coalinga aftershock of 8 May 1983; 125°.

TABLE 1
COMPARISON OF OPTICAL AND DIGITAL VALUES OF PEAK ACCELERATION, VELOCITY, AND
DISPLACEMENT—COALINGA AFTERSHOCK OF 8 MAY 1983

	Component	Digital Records	Optical Records
Maximum acceleration (cm/sec ²)	N35E	99.5	95.7
	Up	73.3	-72.7
	S55E	117.3	114.6
Maximum velocity (cm/sec)	N35E	7.37	6.75
	Up	2.17	2.20
	S55E	4.46	4.11
Maximum displacement (cm)	N35E	0.97	-0.39
	Up	0.4	-0.17
	S55E	0.63	0.36

instrument. Two spectra are shown for each analog record. The higher response spectrum values were obtained using corrected accelerograms which were high-pass filtered with a corner frequency of 0.07 Hz (14.3-sec period). The lower values were obtained using the accelerograms filtered with a corner frequency of 0.4 Hz (2.5-sec

FIG. 13. Correlation coefficient and difference between digital and analog accelerograms. Coalinga aftershock of 8 May 1983; 35°.

FIG. 14. Correlation coefficient and difference between digital and analog accelerograms. Coalinga aftershock of 8 May 1983; up.

period) which are reproduced in Figures 10 to 12. It is understood that the corner frequency of 0.4 Hz was selected by the California Division of Mines and Geology to correspond approximately to the intersection of the 20 per cent damped earthquake response spectrum and the nominal noise response spectrum (see Figure 1). There is very close agreement between the optical and digital response spectra for periods less than 1 sec. However, there are some very significant differences in the

FIG. 15. Correlation coefficient and difference between digital and analog accelerograms. Coalinga aftershock of 8 May 1983; 125°.

TABLE 2
COMPARISON OF TIME DIFFERENCE BETWEEN ANALOG AND DIGITAL RECORDS—COALINGA
AFTERSHOCK OF 8 MAY 1983

Component	Time Difference (sec, ± 0.01 sec)	
	From Max. Correlation	From Max. Accel. Peak
35°	4.06	4.05
Up	4.06	4.01
125°	4.05	4.04

range of periods greater than 1 sec. The difference can be as large as an order of magnitude depending on the filtering used and the period considered. In this particular case, the optical instrument results are conservative compared to those of the digital instrument but this cannot be assured in general.

The spectral differences observed are believed to be caused by the presence of low-frequency noise in the analog records which is not eliminated by the baseline and filtering corrections applied to this data. This conclusion is supported by the background noise level results presented in Figure 1. The absence of preevent data

alone cannot account for the observed differences. The fact that the accelerograms filtered at 0.4 Hz have nearly the correct displacement asymptote appears to be coincidental.

From an engineering point of view, the comparison of the response spectra

FIG. 16. Fourier amplitude spectra of analog and digital accelerograms and difference. Coalinga aftershock of 8 May 1983; 35°.

suggests that for an earthquake with this level of shaking, the optical instrument is capable of providing quite adequate estimates of the response of structures with periods less than 1 sec. However, the optical instrument data may lead to significant errors in estimates of the response of structures with longer periods even when the

FIG. 17. Fourier amplitude spectra of analog and digital accelerograms and difference. Coalinga aftershock of 8 May 1983; up.

FIG. 18. Fourier amplitude spectra of analog and digital accelerograms and difference. Coalinga aftershock of 8 May 1983; 125°.

FIG. 19. Zero-damped response spectra of analog and digital accelerograms. Coalinga aftershock of 8 May 1983; 35°

FIG. 20. Zero-damped response spectra of analog and digital accelerograms. Coalinga aftershock of 8 May 1983; up.

FIG. 21. Zero-damped response spectra of analog and digital accelerograms. Coalinga aftershock of 8 May 1983; 125°.

data is filtered according to accepted techniques. Additional data from side-by-side comparisons would be useful in extending these observations.

CONCLUSIONS

Based on the observations reported herein, it is believed that the digital accelerograph will eventually become the standard for instrument strong-motion measurement. Even allowing for anomalies which may exist in some current instruments, it appears that the digital instrument is capable of providing accurate data over a much wider range of amplitude and frequency than was previously thought possible. Expanded use of digital instruments could have a beneficial impact on source modeling and wave propagation studies as well as structural response studies.

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