Stability of Stable Areas

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Instrumentation and stability analysis of stable test areas are investigated in this paper. Seismometer output via conditioning electronics is monitored by a correlator and a spectrum analyzer. Outputs of these instruments are displayed as probability density functions and spectral densities, which are generated for three parameters; acceleration, velocity, and displacement. A tiltmeter system records signals to indicate small angular motions about the level axes of the test pad. A computer aided *x-y* plot reducer helps in analysis of these data. Seismic noise data generate integrated spectras for all three functions and tilt data show the peak diurnal angular motion. Final correlations of these results are hand calculated for comparison with accelerometer and gyro error state equations. As a result of the stability analysis, a grading system has been devised to give "stability merit" to tested pads.

Nomenclature

E_{rate} = rate error, deg/hr
E_{pos} = position error, arc-sec
E_{vert} vertical error vector magnitude, micro-g
E_{horz} = horizontal error vector magnitude, micro-g
Y = rms vertical displacement
$\dot{Y}$ = rms vertical velocity
$\ddot{Y}$ = rms vertical acceleration
X = rms vertical acceleration
X = rms horizontal displacement
$\dot{X}$ = rms horizontal velocity
$\ddot{X}$ = rms horizontal acceleration
n = number of integration periods, integral multiples
τ = integration period
θ_m = peak diurnal level axis motion, arc-sec
y = vertical component of Rayleigh wave
y_m = maximum value of y
$\dot{y}$ = vertical velocity
$\ddot{y}$ = vertical acceleration
θ = slope angle
$\dot{\theta}$ = angular rate
V = Rayleigh wave velocity in propagating medium
L = Rayleigh wave length
t = time
x = distance in the propagating medium

I. Introduction

FACTORS such as proximity to a high seismic noise area (Gulf of Mexico),[1] temperature changes, and mechanical isolation were known to play a major part in test pad motion, and so they were taken into account in the design of testing facilities. The physical make-up of the Honeywell Aerospace complex is aimed at eliminating and/or damping the main forcing functions which affect stable pad stability. The buildings are oriented along north-south east-west axes on about 115 acres in Pinellas County, Fla. Stable pads are located along the northern edges of three buildings to facilitate azimuth references by star fixes. The buildings are encircled by waterproof asphalt aprons, which drain into interception moats. The purpose of the moats is to decouple water-soaked subsoils from proximity to stable areas.

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The stable pads are reinforced concrete monoliths, which vary in thickness from 18 in. to 39 in. and in size from 17 ft by 22 ft to 40 by 50 ft (Fig. 1). For cataloging and identification, the pads have been indexed, starting in the northwest corner of each building and listed according to plant number, alphabetic stability merit, and location from the northwest corner.[2] Polystyrofoam insulation is placed around the edges of the preformed test pad prior to the concrete pour. It is subsequently etched away with solvents to provide mechanical isolation. Prior to construction, soil subgrade at prospective pad sites is undercut and replaced with washed sand to eliminate shifting resulting from decaying organic matter. Cultural perturbations are diminished by isolation of rotating machinery, control of room temperatures, and provision for buffer areas around pads to eliminate traffic and parking transients. But all these precautions "do not a stable pad make." Consequently, an ongoing program to monitor stability of pads was initiated.

II. Monitoring Systems

Rudimentary techniques once included the use of oil field geophones and bubble levles. A more sophisticated approach has since been realized with two monitoring systems. The frequency transition from noise measurements to level measurements is at best a nebulous area. In general, when instrumentation requirements were drawn up, a dividing line was established between the predictable results exhibited in level monitoring and the unpredictable noise (lateral acceleration) monitoring. Because of thermal lags found in our test pads, we suspected that motions with 10-sec periods or less would tend to resemble noise and the effects of true tile would dominate above 10 sec. With this division in mind, the noise monitoring system was designed to cover the dynamic range from 0.1 Hz to 100 Hz and the level monitoring system from d.c. levels to 0.1 Hz.

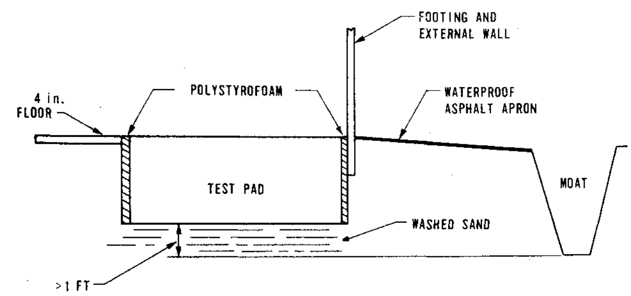


Fig. 1 Typical stable pad construction details.

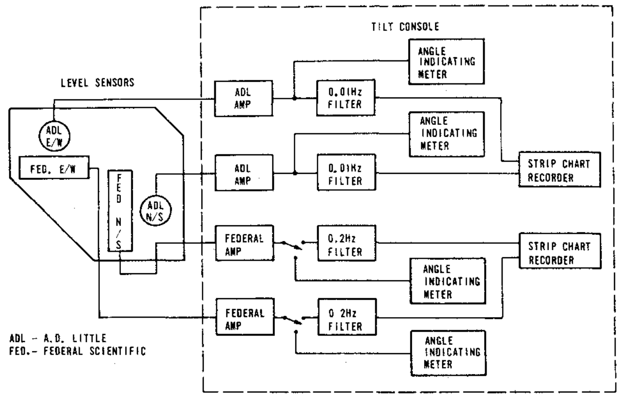


Fig. 2 Tilt monitoring system.

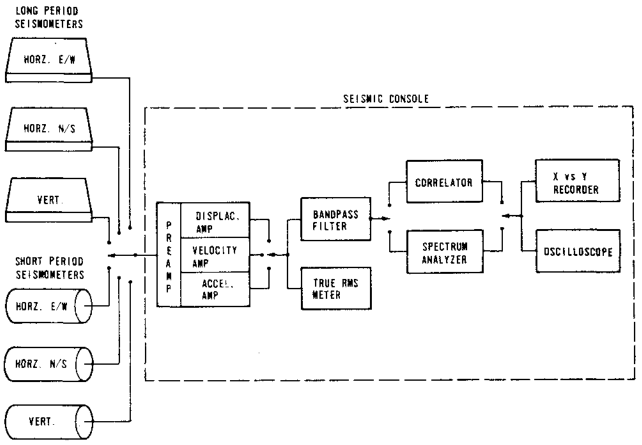


Fig. 3 Seismic noise measuring system.

The tiltmeter setup consists of two pairs of electronic levels‡ mounted on a three-legged fixture for leveling geometry. The level outputs are amplified for display on strip chart recorders (Fig. 2).

One set of level sensors provides wide range and sensitivities to the 1-arc-sec region. The other set provides sensitivities down to the 0.01-arc-sec region.

The second monitoring system is the seismic console. The analysis heart of the seismic console is a realtime correlator and a realtime spectrum analyzer. Six seismometers,§ one short period (5 -100 Hz) and one long period (0.2-20 Hz) for each of three axes, monitor random noise processes in the range 0.2-100 Hz for three parameters; acceleration, velocity, and displacement (Fig. 3). The output of the correlator is a probability density function (PDF) which indicates the type of amplitude distribution present in the pads over the measured frequency range. The output of the spectrum analyzer is a power spectral density (PSD) plot from which three things are generated; the total rms power in the frequency ranges, the integrated spectrum over any bandwidth down to 1/200 of the spectrum analyzed, and the predominant noise levels and their related frequencies.

Subsequent computer reduction of the PSD graphs provides these in rms values for acceleration (micro-g's), velocity (micro-in./sec), and displacement (micro-in.). Combination of analyzed results from level and seismic data through the use of gyro and accelerometer error state equations allows for the final stability grading of stable areas. A more comprehensive and thorough look at this monitoring setup will be made by following one pad from initial setup to final grading.

‡ Federal Scientific differential electronic levels, model 232P-68, 2 A/D Little electronic levels, model III-LP-2A.

§ Geotech short-period seismometers, model M-18300; 3 Geotech long-period seismometers, model M-8700C.

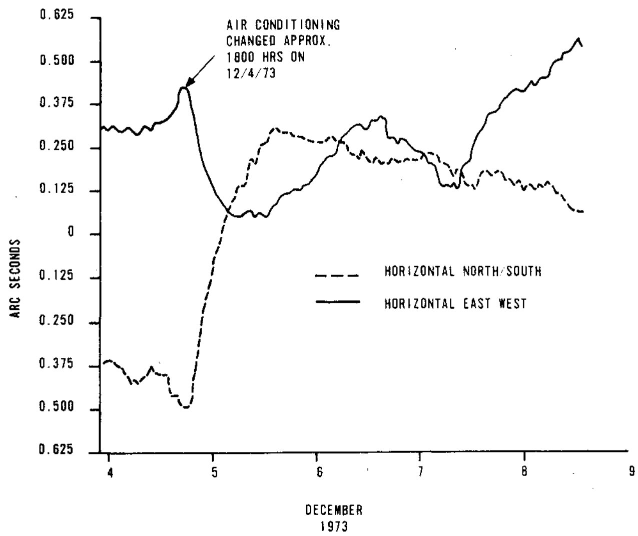


Fig. 4 Pad 4X03, ADL level output.

All data are taken over the c.g., since derivations of basic equations[3] of motion assume a reference frame at the center of gravity of a rigid test pad. Analytical models were developed to describe test pad motions based on external disturbing functions. Ground strata information[4] was incorporated in the derivation of these transfer functions.

III. Monitoring Pad 4X03

Pad 4X03 is located 100 ft east of the northwest corner of Plant 4. The pad is 38 in. thick and measures 40 by 50 ft. The northern edge of the pad is directly adjacent to the northern footing of the building. A false floor supported by jacks resting on the pad was installed to provide a draft-thermal shield. One of the floor sections is removed close to the c.g. of the pad (also center of the area). The removed section of flooring facilitates placing of the seismometers or the level monitoring fixture. For the first case, the level monitoring fixture and associated electronics will be described.

IV. Level Monitoring Setup

The fixture was fashioned from 1¼-in. thick aluminum plate approximately 12 in. square. Three leveling screws with fine threads allow for leveling. The concrete slab is carefully cleaned before placing the fixture relative to the orthogonal axes. Two electronic levels are mounted on each horizontal axis of the fixture. A thermal isolation enclosure was fabricated to fit snug over the monitoring fixture. The Federal electronic level head is basically a suspended pendulum. Its motion relative to its outer case causes an imbalance in the amount of flux passing through two secondary coils, which generates a signal proportional to pendulum displacement. Arc-seconds of motion about the level axes are displayed on a meter with ranges of ± 1000 arc-sec down to ± 10 arc-sec. A low-pass, 0.2-Hz filter cuts out unwanted noise and the amplifier provides 25 v per arc-sec on each scale when displayed on the two-pen, strip chart recorder.

The A/D Little (ADL) levels utilize a paramagnetic suspension with a "magnetic spring" restoring force. The spring constant is considerably larger than the "g spring" and the unit appears as an inverted pendulous accelerometer. The moving mass, relative to its case, is optically detected and an emf proportional to the motion is developed at the output. The amplifier was modified to act as a low-pass filter with a roll-off of -12 db per octave from 0.01 Hz. The output of the amplified signal provides 4 v per arc-sec when displayed on the other two-pen, strip chart recorder. Both recorders are run at low chart speeds (typically 1 in./hr). A coordinate system

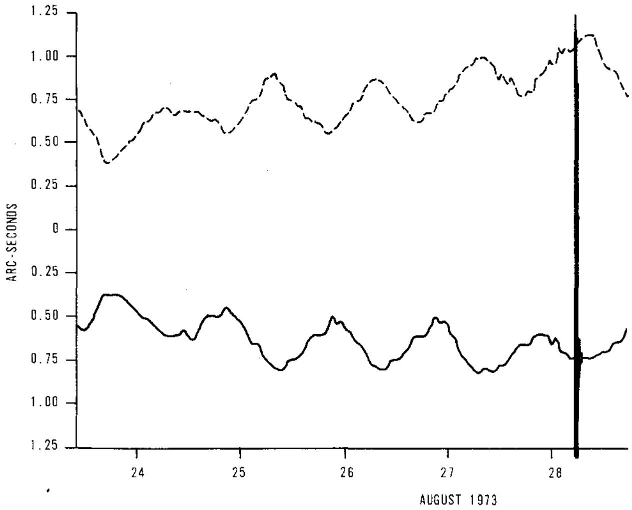
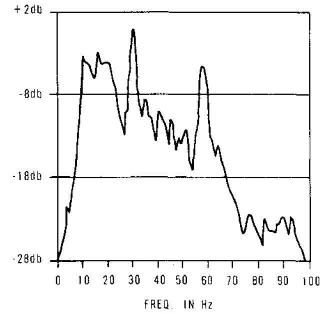
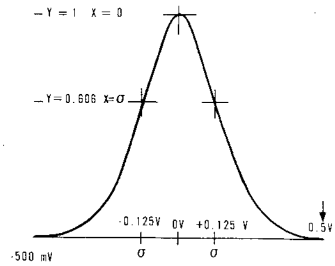


Fig. 5 Pad 4X03, ADL level outputs, earthquake event.



DATE	8 3 74
TIME	1027
TEST PAD	4X03
PLOT	PEAK PSD
FUNCTION	ACCELERATION
SEISMOMETER	VERTICAL S.P.
GEO-TECH SETTINGS	NORM
FILTER SETTINGS	5-100 Hz
INPUT SETTINGS	-12db
SAMPLING PERIOD	40 mSEC
NUMBER OF SAMPLES	16 SPB
MAGNIFICATION	+10db

Fig. 6 Power spectral density graph (left) and title block (right).



DATE	8-2-73
TIME	1450
TEST PAD	4 X 0³
PLOT	PDF
FUNCTION	ACC
SEISMOMETER	VERT S.P
GEO-TECH SETTINGS	NORM
FILTER SETTINGS	5.0 TO 100
INPUT SETTING	1 0V P-P
SAMPLING PERIOD	2 mSEC
NUMBER OF SAMPLES	2K X 10 (20960)
MAGNIFICATION	X64

Fig. 7 Probability density function (left) and title block (right).

has been adopted where X axis is north, Y axis is east, and Z axis is down along the gravity vector. Rotations are defined in terms of the right-hand rule. The finely threaded leveling screws are used to bring the fixture into an approximate zero level. The start time, date, chart speed, scale, test pad number, and initials of the operator are logged right on the start of the chart for future reference.

The Federal levels are typically monitored on the ±10-arc-sec full-scale setting while the ADL's are monitored on ± 0.625-arc-sec full-scale settings. When recording properly, the Federal units also provide a safeguard in case the ADL levels drive the recorder pens into stops due to motions greater than ±0.625 arc-sec. The fixture is allowed to stabilize for 3 hr and then data are recorded continuously for one week.

Figure 4 shows a five-day portion of one of the most sensitive tilt records on test pad 4X03. A significant change in levels is noted at approximately 1800 hr on Dec. 4, 1973 when the air conditioning cycled on.

Figure 5 shows a one-week record taken several months earlier at half the sensitivity. During the monitoring an earthquake event was recorded at 0545 on Aug. 28, 1973. The event corresponded to the Pueblo Earthquake, 150 miles southeast of Mexico City, as reported by the Smithsonian Institution for Short-Lived Phenomena.

The electronic levels are calibrated twice a year under strict conditions. Since the levels are measuring minute changes, calibration is accomplished on a Leitz dividing head employing the rotational-tilted plane method. This method is based on the fact that the angle of inclination θ is a sine function of the angle α from the nodal line of the tilted-rotational plane.

V. Seismic Noise Monitoring Setup

Seismic noise is monitored by two sets of seismometers. Two seismometers, a long-period (0.2-20 Hz) and a short period (5-100 Hz), are set in each of three axes directly over the center of gravity of the test pad. The use of the two seismometers allows measurements over the dynamic range of 0.2-100 Hz. Filtering the short-period seismometers with a bandpass filter from 5-100 Hz avoids the seismometer resonance at 0.93 Hz. The outputs of the seismometers were made to look alike by the addition of an amplifier to the long-period seismometer. Standard outputs allow the use of common scale factors. The function amplifiers were modified to provide 5 mv/unit and frequency range of 0.1 to 100 Hz. Scaling is as follows: acceleration: 5 mv = 1 μ-g; velocity: 5 mv = 1 μ in./sec; and displacement: 5 mv = 1 v in.

The seismometer outputs (the seismometers are velocity detectors) via function amplifiers, and a bandpass filter are analyzed by a correlator¶ and a spectrum analyzer.** The analyzer is a 200-line realtime spectrum analyzer having a resolution of 1/200 of full scale (0.2 Hz on the 0-20 Hz scale and 1 Hz on the 0-200-Hz scale). A linear mode or an integrated mode may be chosen. The integrated mode can average over a selected number of cyles or can be set to hold the peak value. After gain settings are made, the data run for the power spectral density (PSD) is begun. The PSD is stored in memory for output on the X-Y recorder. The output is recorded on 3-cycle semilog graph paper. Full scale on the graph is dependent upon the attenuation and gain settings, but a Y-axis scale of −10 db per section was used on all graphs. Figure 6 shows a typical PSD graph for vertical short-period acceleration. The output of the correlator is a probability density function (PDF) obtained in the same manner as the PSD's. The amplitude distributions are very nearly normal, even over different frequency ranges (Fig. 7). A first-order approximation of the standard deviation is used to obtain a value for the rms acceleration, velocity, or displacement from the PDF graphs.

VI. Azimuth Monitoring

To date we have not developed any short-term, realtime subsystem for azimuth monitoring. Long-term stability is based primarily on star fixes of azimuth references attached directly to the test pads. All indications are that almost all, if not all, azimuth changes are the result of thermal changes within the test pad. For that reason a detailed mapping of thermal changes within the test pad is being undertaken, as well as a detailed study of our ground water table, as this might affect thermal conditions as well as hydrostatic effects. With the mechanical isolation used, the azimuth "noise" terms might be expected to be low.

A survey[5] by the Air Force Cambridge Research Lab using seismometer arrays indicated that "estimates of slab rotation were formed by combining seismometer outputs in a manner that adds rotational inputs while canceling common linear motion and gravity component terms. Integrated spectra for rotation about the vertical are given in Fig. 8. Rms rotation

¶Federal Scientific Ubiquitous[R] correlator, model UC-201A.

**Honeywell Saicor spectrum analyzer/digital integrator, model SAI-57B.

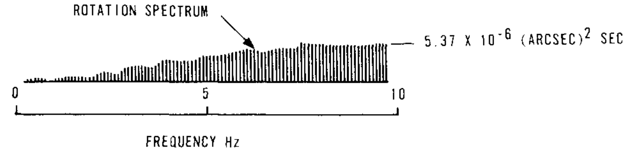


Fig. 8 Rotations about vertical.

Table 1 Spectrum and integrated spectrum title page-test pad 4X03

Test date: 8/3/73	Input attenuation, −db: 12
Start time: 1027	Output gain, db: 10
Period: normal	Frequency increments, Hz: 1
Test Pad: 4X03	Number of increments: 100
Plot mode: peak PSD	COS weighting: 0.676
Seismometer: vertical short period	ID No. S 85
Number of times sampled: 16	

Table 2 Spectrum and integrated spectrum data-test pad 4X03

	Plant: 4		Slab: 3	
Hz	db	UG↑2/Hz	Integral	Rms
0	−27.79	0.449785	0.449785	0.67066
1	−27.43	0.488658	0.938443	0.968733
2	−26.2	0.648642	1.58708	1.2598
3	−24.49	0.961623	2.54871	1.59647
4	−22.0	1.7061	4.25481	2.06272

amplitude level of 0.0023 arc-sec over the band 0.1-10 Hz as given in the figure is also typical of other component rotations." As a consequence of these data we have given this instrumentation low priority.

Since July 1969, the Geodetic Survey Squadron,†† with headquarters at the F. W. Warren AFB, Wyo., has been monitoring an azimuth reference located on test pad 4X03. Our own personnel has also continued observing this reference by means of astro star fixes using a first-order theodolite. Our data are sent to the Geodetic Survey Squadron and incorporated into their data base. Over this period of time, the azimuth reference has been estimated as having a standard error of less than 1.5 arc-sec. We believe this compares favorably with any of the azimuth references in our field.

VII. Data Reduction

Data reduction of the PSD graphs is a major task. Seventy-two graphs per test pad are recorded (36 during the normal period – 7:00 AM to 6:00 PM, and 36 during the quiet period – any other time, including weekends and holidays) and means to reduce the *X-Y* spectral density graphs is needed. A two-axis mechanical plot reducer‡‡ is used to introduce the data into a 16K computer programed in basic language (100 points per each graph). The PSD graph is db vs Hz, so it is necessary to convert the data to get the recorded values into the familiar $(\text{unit})^2/\text{Hz}$ of power spectral densitites. Scale factors and bias levels are read in, along with the other title block information. The printout has a title page with pertinent test pad information, including analyzer settings (Table 1).

The reduced data consist of five columns representing frequency, db, psd, integrated spectrum, and rms power (Table 2). A tabulation of the rms vibration levels is given in Table 3 for each of the three axes in both normal (7:30 AM to 5:00 PM weekdays) and quiet (5:00 PM to 7:30 AM weekdays and on weekends, holidays) periods.

††Now part of the Defense Mapping Agency, Aerospace Center. Actual data are gathered by the Fourth Detachment at ETR.

‡‡Gerber digital data reduction system, model GDDRS-3B.

Table 3 Vibration levels—test pad 4X03

	Normal period					
	Short period (5-100 Hz)			Long period (0.2-20 Hz)		
	H N/S	H E/W	Vert	H N/S	H E/W	Vert
Acceleration, micro-*g*	14.4	13.2	26.8	16.3	12.9	24.5
Displacement, micro-in.	1.03	1.08	1.22	6.98	5.69	5.56
Velocity,	64.3	53.7	93.0	152.7	117.9	113.0
	Quiet period					
	Short period (5-100 Hz)			Long period (0.2-20 Hz)		
	H N/S	H E/W	Vert	H N/S	H E/W	Vert
Acceleration, micro-*g*	11.9	3.83	20.9	15.6	10.5	21.4
Displacement, micro-in.	0.905	0.825	1.15	6.26	6.22	4.94
Velocity, micro-in./sec	46.4	50.6	89.4	83.4	69.1	82.2

A similar computer reduction program is available which reduces level axis data from the electronic levels. Data format is in the form of tilt about the two levels axes and respective delta angle. Data points are read off alternate axes for every half-hour period of data. A Fourier analysis of the tilt about either axis can then be checked for sine wave motion over a 24-hr period.

VIII. Comparison of Data with State Equations

Gyro and accelerometer state equations[6] were established by which comparison of actual data to theoretical postulates could be made. These equations are based on the following assumptions (derivation in Appendix):

1) Rayleigh waves (R-waves) are the prime energy source in ground motion disturbing our test pads.

2) The cutoff frequency for angular induced motions resulting from R-waves is twice the free-free resonance of the stable test pad.

3) Reset integrators or equivalents are used in gyro testing with integration period of τ sec and integer multiples of $\tau(n\tau)$. These multiples are treated as single-order, low-pass filters with 3 db points of $1/2n\tau$.

4) Pulse rebalance loops with second summations are used in accelerometer testing. These loops are treated as an accelerometer with a low-pass single-order filter with $1/2\ n\tau$ cutoff frequency.

5) R-waves are considered to have a random spatial distribution so that rotations about level axes for vertical test pad motions will incorporate a $1/\sqrt{2}$ term from rms levels.

Thus, for rate mode gyro testing, the following equations were developed for a cutoff of $1/2\,n\tau$

$$[E_{\text{rate}}\text{rms}]^2 = [(4.30/2\ n\tau\sqrt{2}) \times 10^{-5}]\ \dot{Y}^2 + (1.65\times 10^{-2}\ddot{Y})^2/2 \tag{1}$$

When evaluated for a 5-min filter or integration time (300 sec) Eq. (1) becomes

$$E_{\text{rate}} = [(4.9/n)\times 10^{-8} Y]^2 + (1.17\times 10^{-2}\dot{Y})^2]^{1/2} \tag{2}$$

And for position mode gyro testing:

$$E_{\text{pos}} = \frac{[\theta_m{}^2(1-\cos\pi\frac{\tau}{12})]^{1/2}}{2(\pi\frac{\tau}{12})^2} + \frac{1}{4\tau^2}\ (4.3\times 10^{-5}Y)^2 \tag{3}$$

Table 4 Error introduction—test pad 4X03

Errors	Normal period	Quiet period
Gyro error		
E_{rate}, deg/hr	1.613×10^{-5}	1.654×10^{-5}
E_{pos}, arc-sec	3.184×10^{-3}	3.182×10^{-3}
Accel error		
E_{vert} μ-g	1.554×10^{-2}	1.529×10^{-2}
$E_{horz} E/W$, μ-g	8.84×10^{-1}	8.84×10^{-2}
E_{horz} N/S, μ-g	5.30×10^{-1}	5.30×10^{-1}

For accelerometer testing, the vertical error vector magnitude is:

$$E_{\rm vert} = \left[\left(\frac{1}{n2\tau} \dot{Y} \right)^2 + (\ddot{Y})^2 \right]^{1/2} \tag{4}$$

And the horizontal error vector magnitude is:

$$E_{\rm horz} = \left[\left(\frac{\dot{X}}{n2\tau} \right)^2 + \ddot{X}^2 + 0.5\times10^{-8} \left(\frac{Y^2}{(2n\tau)^2} + Y^2 \right) + \frac{25\theta_m{}^2}{2} \right]^{1/2} \tag{5}$$

IX. Grade Label for Test Pad 4X03

From level data taken the week of 12/3/73 to 12/10/73 and seismic data taken 8/2 and 8/3/73, the values in Table 4 were reached through Eqs. (2-5).[7]

Based on the preliminary data base and guidelines, test pad 4X03, along with seven other test pads rated last year, was given a label. In the case of test pad 4X03, the label became 4AX03. The rating letter is founded on general conditions and rationale involved in gyro and accelerometer testing and only holds true if the user properly ties into the test pad and "house-keeping" practices are not ignored. The choise of τ-$=300$ sec for the integration period is indicative of most test conditions for gyro testing. For a gyro running in the position mode, a total error buildup could be specified; in effect, the drift rate or maximum change over any time interval would be known. Since the primary concern would be over the test interval, the maximum position deviations are rated over 24-hr, 7-day, and 30-day periods. In addition, a "noise" term is included, based on a 6-hr readout.

The basic criteria used is the point where the signal to noise ratio has gone to one. A grade A label was chosen for the following test parameters (all values are rms): angular rate floor—10^{-5} degs/hr; position criteria—1 arc-sec (over any period up to 30 days); "noise" term—0.3 arc-sec; vertical error vector magnitude—1 μ-g; and horizontal error vector magnitude—1 μ-g.

A "10-db" criterion is then applied to these conditions to generate successive grade labels. Therefore, an A grade label test pad is 3.16 times better than a grade B, 10 times better than a grade C, etc. Since this was the first go-around for the grading criterion and as new data became available, these labels really represent the ultimate potential capacity of the test pad. The second grade label in the identification number has been reserved to indicate the test pads capability for dynamic tests such as spectrum analysis of gyro drift rates. As of yet, our test pad monitoring program has not defined the type of instrumentation and testing to assign the label.

Appendix

Derivation of sample error state equation for gyro rate testing with reset integrator on the rate signal: the Rayleigh waves (R-wave) vertical component can be written as

$$y \doteq y_m \sin\left[(2\pi/L)(x - Vt) \right]$$

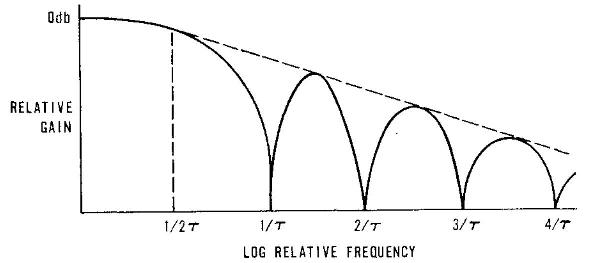


Fig. 9 Characteristic response of reset integrator.

The first derivative of this with respect to x is the tangent of the slope angle of the tangent to the point. For small motions this is approximately the angle. Therefore

$$dy/dx = \theta = y_m (2\pi/L) \cos\left[(2\pi/L)(x - Vt) \right] \tag{A1}$$

The derivative of θ with respect to time yields the associated angular rate

$$\dot{\theta} = y_m V (2\pi/L)^2 \sin\left[(2\pi/L)(x - Vt) \right] \tag{A2}$$

Expressions can be obtained for y_m in terms of $\dot{y}$, the vertical velocity, and $\ddot{y}$, the vertical acceleration. If this is done and the necessary substitutions made, one gets

$$\theta = -\dot{y}/V \text{ and } \dot{\theta} = -\ddot{y}/V \tag{A3}$$

Thus, from vertical velocity and acceleration terms we can estimate the angular motion and rates. This strictly applies to points or wavelengths very large compared to the test pad size. Any sampled data system, reset integrator, or sequential sum has a characteristic response, as shown in Fig. 9. The dashed line represents a low-pass, single-order system with a roll-off of $1/2\tau$. τ is the interval over which the sums, integrations, or sampling occurs. For frequencies above $1/2\tau$, the low-pass system is an integrator and is always higher gain than our sampled system. Thus, if we use the low-pass system to predict error effects, we will err on the conservative side (that is, the prediction will be worse than the actual effect).

If one now has an angular rate sensor under test on a test pad, the pad inputs would be $\dot{\theta} = -\ddot{y}/V$. When this is run through the sampled data system, all frequencies above the roll-off point will, in effect, go through an integrator or the response will be the same as the angular motion θ. Therefore, we can predict the error term at the output as

$$E = \dot{\theta}_0 + \theta_{2\tau} = -(\dot{y}_0 + \ddot{y}_{2\tau})/V \tag{A4}$$

where $\dot{y}$ is vertical velocity in the frequency range from 0 to the roll-off point and $\ddot{y}$ is vertical acceleration from the roll-off point on up.

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