An Implementation of the ANSI Standard C37.98.

Abstract

A description is given of one way of fulfilling the requirements of the ANSI standard C37.98 by using a biaxial computer aided servohydraulic test rig. The test rig, excitation signal generation, measurement, analyses and presentation of results are described.

1. Introduction

In power plants and other processing industries it is necessary to ensure safe shutdowns in case of a serious disturbance, as an earthquake. It is also important that vital parts of the community are intact after such an event. This implies that control consoles and other electromechanical equipment must have a granted function for ground vibrations corresponding to the "worst possible" earthquake. To be able to put components together in various designs it is then essential to have an independent seismic rating of each component. Hence, the problem is to find a simple measure, and a corresponding method of evaluation, for the dynamic properties of the components. The IEEE 344 standard and the ANSI standard C37.98 contain the ideas leading to a solution, and a proposed framework of a relevant testing procedure.

The basic idea is to shake the test object with a multifrequency excitation signal covering the frequency range which can be obtained when the motion is amplified through buildings and floor mounted consoles in a wide range of applications. Since the sensitive components in constructions are often mass-spring systems, (for example relays), the measure, the fingerprint, characterizing the multifrequency excitation is chosen in a related way. The excitation is described in terms of the maximum accelerations it would induce in each of a set of Single Degree of Freedom (SDOF) mass-spring-damper systems, with resonance frequencies in the range 1-40 Hz. The damping can be different in different tests, but a typical value is 5%. This so called Test Response Spectrum (TRS) is the output of a test.

By comparing the TRS from a test, where the tested unit is on the verge of malfunction, with a Standard Response Spectrum (SRS) according to *Figure 1*, a seismic rating of the unit covering all possible situations is obtained. The comparison is facilitated in a logarithmic diagram. Let the dots in *Figure 2* represent the TRS near the malfunction level, and the solid lines represent an SRS which is fitted to the TRS as closely as possible from below (note that the SRS has the same shape on a logarithmic scale, and is just translated vertically). Then the unit can certainly withstand an idealized multifrequency signal giving the SRS. The level of seismic durability can then be given simply by the asymptotic level for high frequencies, the Zero Period Acceleration (ZPA), of the SRS. By evaluating the lowest ZPA-value found for the various possible shaker directions under different operating conditions, the tested unit is characterized by one single value.



Figure 1: The normalized Standard Response spectrum, SRS, suggested by the ANSI standard C37.98.



Figure 2: Diagram for determination of seismic durability

The SRS is based on experience and covers a large variety of situations. However, sometimes it is unpractical to use it. One reason can be the width in terms of frequency of the region of maximum amplification of the broad band SRS. This width is much greater than the typical narrowband region of the Required Response Spectra, RRS:a, for each specific location. It can be mathematically shown that time histories fulfilling artificial broadened spectra have higher ZPA-values than real narrowband spectra. Using broad band spectra also implies risks for malfunctions due to interactions

between different critical frequencies of the tested unit. Such interactions do not occur during a real narrowband earthquake. Using the SRS therefore produces a severe overtest. Another reason for not using the SRS is that earthquakes in Scandinavia are expected to have a high frequency content and the ZPA-level is reached at a too low frequency if the SRS is used.

To avoid overtesting narrow band standard response spectra can be used. *Figure 3* shows such a spectrum. The ANSI standard suggests that series of tests with different narrowband spectra covering the whole broad band frequency region should be done. If the RRS for the application where the test object should be used is well known a single narrowband spectra can be used. However, in such case no general seismic qualification is obtained.



Figure 3: The normalized Narrowband Standard Response spectrum no: 4, suggested by the ANSI standard C37.98.

For applications in Scandinavia where a spectrum with higher frequency contents must be used, the broadened spectrum shown in *Figure 4* is suitable.



Figure 4: A broadened spectrum that can be used for applications in Scandinavia.

At sites where earthquakes occur frequently, a lot of smaller earthquakes causing low cycle fatigue damage can precede the "worst possible earthquake." In such case seismic ageing must be performed before the test run at the fragility level. This is done by running a number of tests simulating Operating Basis Earthquakes, OBE, before running the test simulating the Safe Shutdown Earthquake, SSE. Typically five OBE tests at 60% of the SSE level are required.

So, the problem is an implicit one: To give the test items a motion that produces a prescribed TRS, i.e., one that conforms as closely as possible with the SRS or RRS shape. The test rig is described in section 2, excitation signal generation in section 3, measurements and analysis in section 4 and result presentation in section 5.

2. Test rig

The principle of the two-axis vibration table at the Swedish National Testing and Research Institute is illustrated in *Figure 5*. The table is supported on three vertical actuators and the horizontal thrust is provided by a single horizontal actuator arranged as shown in the figure. The dimension of the table is $1.2 \cdot 1.2$ m. Due to the three vertical actuators the table is capable of reacting large bending moments.



Figure 5: Schematic sketch of the biaxial test rig.

The table can be used for tests with simultaneous vertical, horizontal and rotational motion. The dynamic capacity of the table is shown in *Figures 6 and 7*.



Figure 6: The dynamic capacity of the table in the horizontal direction.



Figure 7: The dynamic capacity of the table in the vertical direction.

Each actuator is servo controlled with acceleration and displacement feedback by a digital control system, INSTRON 8580. Transfer functions of servohydraulic equipment are always non flat, i.e., high frequencies are damped more than low. Before using a wave form as a drive signal it must therefore be adjusted. This is done by a special software package, called PROFILE CORRECTION, supplied by INSTRON. Before the testing the adjustment is done. The transfer function of the rig is determined when the table is run without any test object mounted on it. This software can also compensate for unwanted geometric displacement caused by angular movement of the actuators.

3. Excitation signals

There are various ways to achieve an excitation fulfilling the requirements of a broadband frequency signal.

The signals used at the Swedish National Testing and Research Institute are generated as sums of harmonic functions with different frequencies in the range 1 - 40 Hz according to Equation (1).

$$a(t) = \sum_{i} A_{i} \sin(\omega_{i} t + \varphi_{i}) \cdot \Psi(t)$$
(1)

The angular frequencies, ω_i , are spaced at 1/6 octaves. This ensures that there exist excitation within the 3-dB points of any possible resonant frequency with a damping higher than 2%. The amplitudes, A_i , of the different frequency components are chosen according to the SRS or RRS. By an iterative procedure achieving a time-history with a

TRS just enveloping the SRS or RRS is possible. The phase angles, φ_i , are chosen randomly. To get a signal with finite duration the signal is multiplied with a time window function, $\psi(t)$. This function also gives the time history a smooth start up and decay. The time histories are stored in the computer. Amplitude scaling is possible between each test run in order cover the whole possible range of amplitudes.

4. Measurements and analyses

Servo accelerometers are used for measuring the acceleration of the vibrator table. The measurement chain, for one accelerometer, is shown in *Figure 8*.



Figure 8: The measurement chain for acceleration measurement. Item no: 1 is an amplifier, item no: 2 is an analogue anti alias filter, item no: 3 is a sample and hold unit and item no: 4 is an A/D converter. The sampled signals can by software programs be resampled at other sampling rates and filtered digitally, showed by item no: 5 in the sketch.

By the data acquisition system the analogue acceleration signals are low pass filtered for frequencies below 1 kHz and sampled at 5 kHz. As the frequency contents of the signals is less than 50 Hz, the data are by software programs resampled at 200 Hz before long time storage on the disk. The number of data is then reduced without losing any information.

The analysis aims at finding the peak acceleration that can be achieved without malfunction of the test items when rigidly mounted at a site that may be described by a broad-band SRS or a RRS. The method used can be summarised as follows:

First find the acceleration response of the SDOF systems of interest to the acceleration signal used. The SDOF systems may be described by an impulse response according to Equation (2).

$$a(t) = \omega e^{-\varsigma \cdot t} \cdot \left[2\varsigma \cos\left(\omega \sqrt{1-\varsigma^2} t\right) + \frac{1-2\varsigma^2}{\sqrt{1-\varsigma^2}} \sin\left(\omega \sqrt{1-\varsigma^2} t\right) \right]$$
(2)

where

 $\begin{aligned} \omega &= 2\pi f \\ f & \text{resonance frequency [Hz]} \\ \zeta & \text{relative damping factor} \end{aligned}$

Then find the peak values of these acceleration responses and plot them on a logarithmic acceleration-vs.-frequency plane to obtain the acceleration response spectrum or as it might be called here, the test response spectrum, TRS.

At last compare the TRS with the broad-band SRS or RRS. The zero period acceleration, ZPA, of this spectrum when TRS just envelopes it is used as a rating of the acceleration signal measured.

The SDOF systems of interest normally have resonance frequencies in the range 1-45 Hz spaced 1/6 octave apart and a relative damping factor of 5%. This gives a total of 34 SDOF systems for which the acceleration response must be calculated. This can be done in at least three fundamentally different ways: (1) convolution in the time domain between the acceleration data obtained from the measurements and the impulse response of the SDOF systems; (2) multiplication in the frequency domain of the Fourier transforms of the above and inverse transformation of the results; (3) sequential calculation of the responses under the assumption of an excitation consisting of frequencies below the Nyqvist frequency. The last method has been chosen here. In order to get a high resolution in the determination the signals are interpolated to get a at least 20 sampling points at each fundamental period of the SDOF system responses. It can be shown that this method will give an error less than 2 percent. The calculated values will always be too small.

4. Presentation of results

Upon requests from the customer the results can be presented in different ways. The complete result presentation contains figures of recorded acceleration time histories and plots of the analyzed TRS.



Figure 9: An example of a graph showing a recorded time history. The plotted file and channel are shown in the upper left corner of the graph.



Figure 10: An example of a graph showing the results from the Test Response Spectrum analysis. The solid line is the required spectra and the stars show the TRS. In the top of the table to the right the analyzed file and channel are specified. At the bottom of the table the damping value used at the analysis is given together with the ZPA-value.