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# EXPERIMENTAL EVALUATION OF EARTHQUAKE INDUCED RELAY CHATTERING[1]

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## ABSTRACT

An experimental evaluation of relay performance under vibratory environments is discussed in this paper. Single frequency excitation was used for most tests. Limited tests were performed with random multifrequency inputs. The capacity of each relay was established based on a two-millisecond chatter criterion. The experimental techniques are described and the effects of parameters in controlling the relay capacity levels are illustrated with test data. A wide variation of the capacity levels was observed due to the influence of parameters related to the design of the relay and nature of the input motion.

## INTRODUCTION

Evaluations of safety systems have indicated that the reliability of performance of electrical and mechanical equipment under an earthquake environment depends to a large extent on the performance of relays [Budnitz, 1987]. In many instances, the relays exhibit a temporary change of state, popularly known as relay chatter, at a vibration level significantly lower than the level that most other components present in the circuit can safely withstand. The qualification of relays, therefore, becomes an important aspect of the seismic qualification of nuclear plant systems. A systematic study of the existing seismic test data performed at BNL as part of the Component Fragility Research Program has shown that efforts were undertaken by the major manufacturers as early as the 1970's to characterize relay performance in a vibratory environment [Bandyopadhyay, 1990]. These early tests were performed primarily with excitations at discrete frequencies using various means. The electrical monitoring procedures in these tests were also not consistent. Multifrequency excitation was used in the mid-seventies; but the shapes of the test response spectrum (TRS) curves were not usually consistent. A standard shape of the response spectrum with a consistent set of electrical monitoring procedures was recommended by the IEEE Committee [IEEE, 1978]. Since then the manufacturers have used the IEEE approach to determine the capacity of the relays.

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In the above test programs, there was indication that the performance of the relay in a vibratory environment depends on various parameters related to its design and the test input motion. In particular, the electrical mode, contact state, adjustment, chatter duration acceptance criteria, and the frequency and direction of the input excitation influence the seismic capacity of a relay. In order to better characterize the effect of these parameters on relay performance, BNL has conducted a test program mostly by use of single frequency sine dwell excitation such that the capacity of a relay is determined at each frequency of vibration. Limited multifrequency tests have also been performed for establishing a correlation between the single frequency and the multifrequency capacity results. This paper describes the testing objectives and methodologies, and presents a summary of important test results.

## OBJECTIVES

It has been observed from a review of the existing test data that the capacity levels of a particular relay established by various test programs are not necessarily consistent. The following causes, separately or in any combination, can be postulated to be responsible for such inconsistencies:

a) True frequency sensitive capacity TRS data were not obtained in the multifrequency tests.
b) There were differences in testing techniques, time history and acceptance criteria.
c) The test specimens were really not identical although the basic model numbers were the same.
d) The vibration level that causes a specific amount of relay chatter varies over a wide range.

The essential objectives of the BNL test program were to address the above inconsistencies and to demonstrate how to construct frequency dependent capacity TRS. The objectives are enumerated and further detailed as follows:

a) To determine frequency sensitivity of relays by single frequency testing.
b) To determine the effect of adjustments (e.g., spring tension) on the relay capacity.
c) To verify similarity of relays with identical general model numbers for which the manufacturers have recommended the same seismic capacity.
d) To construct frequency dependent capacity TRS by use of multifrequency vibration input.
e) To determine a conversion factor that can be used to obtain a multifrequency capacity TRS from single frequency capacity test data.

## TEST SPECIMENS

A total of forty-six (46) relays of nineteen different models manufactured by General Electric, Westinghouse and Square D Company were tested. The test specimens were selected to represent various types (e.g., auxiliary, protective and general purpose), operating mechanisms (e.g., hinged armature, rotary induction disk, plunger and solenoid), mounting configurations (e.g., flush, semi-flush and surface) and electrical voltage (e.g., AC and DC). For thirteen (13) models, three specimens of each model were tested in order to verify consistency of results. All relays were procured recently (i.e., current vintage) and forty-two (42) of them were commercial grade items (i.e., non-class IE).

## MOUNTING FIXTURES

The relays were installed on rigid test fixtures following the mounting patterns and cutouts that are required for each specimen. The fixtures were welded to the shake table in a manner such that the front-to-back (FB) direction of the relays was colinear with one of the two principal horizontal axes of the test machine.

## TESTING METHOD

A major part of the test program was devoted to single axis, single frequency tests with sinusoidal wave inputs applied in the FB, side-to-side (SS) and vertical (V) directions, each axis being excited separately. Testing was performed in the frequency range 1-50Hz at an interval of 2.5Hz. The test amplitude was gradually increased or decreased until the failure threshold was observed. A contact chatter of two milliseconds duration was considered as the failure criterion. The relays were tested for all three electrical conditions (i.e., operating, nonoperating and transition) and two contact states (i.e., normally open and normally closed). These tests were performed with the setting and adjustment as made by the respective manufacturers. Subsequently, selected relays were also tested with alternate settings (e.g., spring tension and contact gap) to determine the influence of adjustment on the relay capacities. The adjustment tests were performed for the weakest electrical condition and contact state as determined from the earlier single frequency tests.

Random multifrequency tests were performed on twelve relay models. The TRS shapes were matched, as far as possible within the shake table limitation, with the respective single frequency capacity results so that true frequency dependent capacity TRS curves were obtained. These tests were also performed for the weakest electrical modes.

## TEST RESULTS

The capacity levels were obtained in terms of the sine dwell input acceleration values for the single frequency tests and in terms of the TRS at a 5% damping value for the random multifrequency tests. Unless otherwise mentioned, the capacity level is defined in this paper as the maximum acceleration level the specimen withstood without exhibiting a chatter duration of two milliseconds or greater. At a level slightly above the capacity level the specimen has indicated a chatter exceeding this limit. The results revealing the influence of each parameter are discussed in the following paragraphs. The test data presented in this paper are to illustrate the influence of the parameter and are not necessarily typical for all relays.

Frequency of Vibration Input

The single frequency test data demonstrate that relays are sensitive to the frequency of the vibration input, i.e., the capacity levels at certain frequencies are much lower than those at other frequencies. Depending on the design and the electrical state, some relays are sensitive at low frequencies (e.g., 5-15Hz), some at medium frequencies (15-30Hz) and some at higher frequencies. For example, in the FB direction a CO-6 specimen which is a rotary disk relay, is very weak at 5Hz with a capacity of only 0.2g compared to the capacity level exceeding the shake limit at other frequencies (e.g., 2.5g at 7.5-20Hz) in the same direction, as shown in Figure 1[1]. On the other hand, an SC specimen, a plunger relay, is sensitive at 40Hz in the SS direction. Unlike these two examples, some relays are weak over a range of frequencies rather than at a particular frequency value. One such example is an HFA (hinged armature) relay which demonstrated a high capacity level in the V direction at low frequencies (e.g., greater than 1.8g at 5-17Hz), and a very low capacity level at high frequencies (e.g., 0.4g or less at most frequencies between 23 and 50Hz), as also shown in Figure 1.

Direction of Vibration Input

The relay capacity level changes with the direction of the vibration input. For example, the capacity levels of an SG relay in the FB, SS and V directions are shown in Figure 2. At low frequencies, the capacity level is governed by input in the FB direction, whereas at high frequencies, the vertical direction controls the capacity level. The SS input governs at 27Hz. For some relays, one direction controls the entire frequency range. One such example is an SC relay which is much weaker in the vertical direction (at 7-20Hz: < 1.0g in FB vs > 2.5g in SS and V directions). Usually, either the FB or the V direction controls the relay capacity levels in the low frequency range. For most relays, excitation in the V direction is more damaging than the FB direction at high frequencies. For example, consider Figures 3, 4 and 5. Figure 3 shows that at low frequencies the capacity of an HFA relay in the FB direction (e.g., 1.2g) is much less than that in the V direction (e.g., 2.5g); whereas at all frequencies above 22Hz the capacity in the vertical direction is lower. In Figure 4 at low frequencies (e.g., < 25Hz) the capacity of another HFA relay is controlled by either the FB or the V direction input and at higher frequencies the capacity in the V direction is much lower than that in the FB direction. Figure 5 exhibits the capacity of an SVF relay which is very weak against vertical excitation at all frequencies. The SS direction rarely controls the relay capacity and, even if it does, it governs only at a short frequency range. For example, the SS direction governs the capacity of an IAV relay only in the frequency range 22-24Hz.

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[1] In all Figures, the single frequency test data are plotted at an interval of 2.5Hz and are presented as curves connecting the data points.

Operating Mechanism and Dynamic Characteristics

Although the dynamic characteristics such as resonance frequency of a relay were not monitored during the vibration tests, the movement of the operating mechanism was captured through chatter detection. Hinged armature operating mechanisms were observed to vibrate causing chatter over a wide frequency range. For example, Figure 3 shows how the movement of a hinged armature mechanism in the FB direction causes chatter. The capacity in the FB direction did not change much over the entire frequency range (0.7-1.3g). More importantly, there are other elements in the relay design that can affect the capacity level. The influence of these elements can be exhibited at several distinct frequencies analogous to multimode behavior in vibration mechanics. As illustrated in Figure 4, the HFA relay (which has an armature mechanism in the FB direction) was distinctly sensitive at 10, 15, 22 and 27 and 35-45Hz in the vertical direction exhibiting resonant-type characteristics.

Electrical Condition

Most relays are stronger in the operating mode. As illustrated in Figure 6 the HMA specimen withstood vibration inputs at all frequencies up to the machine limit (e.g. 2.5g at 7-20Hz) in the operating mode; whereas, the capacity level in the nonoperating mode is less than 0.5g sine dwell input. However, some relays are stronger in the nonoperating mode. The SVF relay is one such example as shown in Figure 7. In the nonoperating mode the relay was successfully tested almost at all frequencies to the machine limit, but in the operating mode its capacity at most frequencies is limited to less than 0.3g sine dwell input. Again, there are some relay models for which the capacity level at some frequencies are controlled by the nonoperating mode and at other frequencies by the operating mode. For example, an HFA relay performed better in the nonoperating mode at low frequencies (up to 25Hz), and in the operating mode at high frequencies, as shown in Figure 8.

In summary, the electrical mode strongly influences the relay performance and the precise electrical mode controlling the capacity level depends on the relay model and, in some instances, on the frequency of the vibration input.

Same Model, Different Specimens

For many relays, multiple specimens of the same model were tested. Depending on the frequency and direction of vibration, electrical mode and contact state, a moderate to wide variation of the capacity levels is observed for specimens of the same model. For example, three HMA124 relays in the nonoperating mode exhibited a large variation of their capacities at most frequencies in all three directions of which the results in the FB direction are as shown in Figure 9 (e.g., at 25Hz: 0.2g, 1.4g and 0.8g). Similar characteristics were also exhibited by three CO-6 relays in the operating mode for the vertical direction which is the weakest direction for these relays at most other frequencies as shown in Figure 10.

In summary, the test data indicate that a variation of the capacity among specimens of the same relay model can easily be 50%-100% for many relays and can be much higher for a few others.

Spring Tension Adjustment

The relays were initially tested in the as-received condition (i.e., factory setting). However some relays were adjusted during the test program and tested at alternate settings. The test data for an HFA51 specimen at three different tension settings are shown in Figure 11 for the nonoperating mode in the FB direction. The results indicate substantial variation of the capacity levels due to spring tension settings. However, a general trend of the data could not be established. For example, at low frequencies the specimen followed the expected trend that the capacity increases with the spring tension; however, at high frequencies the data greatly defy the expected trend (e.g., at 20Hz the capacities for the high, medium and low tension values are respectively 0.4, 1.7 and 0.7g). In summary, the effect of a change of spring tension setting on the capacity level can be from moderate to substantial. It appears that each relay specimen (and not just the model name) has an optimum tension setting at each frequency at which it performs best and outside this setting range, whether higher or lower, the capacity level drops. However, further investigation is required in order to exactly relate the change in the relay capacities with the spring tension settings and the vibration frequencies.

Multifrequency Capacity TRS

Generation of a capacity TRS matching the shape of the capacity sine dwell input accelerations is demonstrated in Figure 12 for an SG relay. The multifrequency input in the FB direction was gradually raised from Level 1 to Level 4 with the target to match the single frequency input shape at each level. Up to Level 3, the relay did not exhibit chatter greater than 2ms duration and at Level 4 the relay chattered for 10ms. Therefore, the Level 3 TRS is considered to be the capacity TRS for this relay. Ideally, the target was to generate the TRS such that at every frequency the response acceleration can be obtained by multiplying the respective sine dwell input by a constant factor. However, due to limitations in controlling the TRS shape at the laboratory, the Level 3 TRS has been considered to meet the target for practical purposes. Figure 13 shows the conversion (or amplification) factor relating the single frequency input with the multifrequency response at every frequency. The so-called amplification varies between 2.1 and 4.5 in the frequency range 5-30Hz. The average value is 2.3 in the frequency range 5-15Hz and 3.0 in the frequency range 5-30Hz.

Dynamic Similarity

Four HFA relay models (three specimens of each model) of the Century Series were tested for exploration of dynamic similarity of relays of the same type. First, all twelve relays were tested with biaxial excitation in the nonoperating mode and chattering of the normally closed contacts were monitored. Since the single frequency tests showed that the HFA154 relays are also almost equally sensitive in the operating condition due to dropping of the latch, these six relays were next tested with multifrequency inputs in the operating condition. The four HFA models did not exhibit similar vibration characteristics at all. In the nonoperating electrical mode, the 151AF relays showed the lowest capacity and the 154EH relays demonstrated to be the strongest while the 151BH and 154BF were in the middle. On the other hand, in the operating mode only the 154EH and

154BF relays malfunctioned and not the other two models. These results are consistent with the corresponding single frequency test data as shown in Figures 14 and 15.

## CONCLUSIONS

The vast amount of single frequency test data for many relays generated as part of the test program reveals a comprehensive picture of relay performance under a vibratory environment. Dwelling on one frequency at a time provides a unique opportunity to characterize the relay under various electrical conditions and other parameters. A substantial amount of variation and, consequently, unpredictability was observed at the single frequency level. It is suspected that the single pass-fail criterion (i.e., 2ms) might have contributed to some extent towards such variation. The current test program at BNL will focus on the two-millisecond chatter acceptance criterion and is expected to produce information that will, in turn, help make a better and an appropriate use of the existing data.


## ACKNOWLEDGEMENTS

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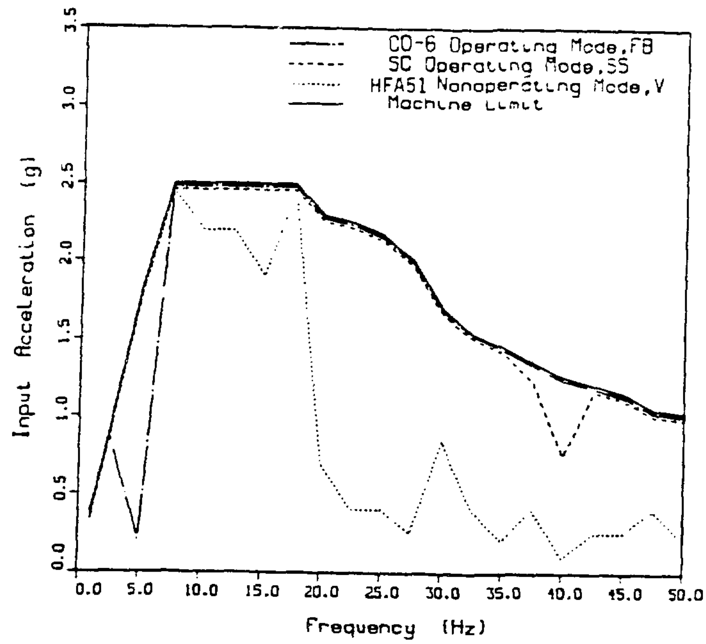


Figure 1 Influence of Vibration Frequency
Sine Dwell Capacity Level

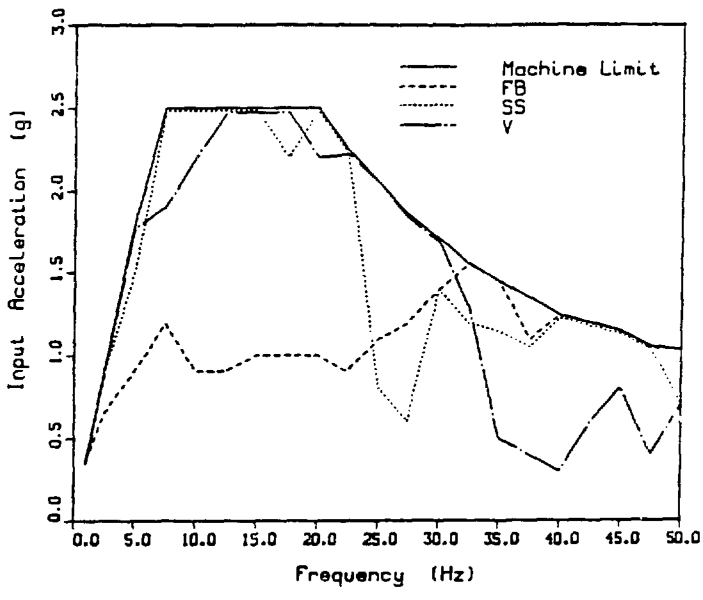


Figure 2 Sine Dwell Capacity Level
SG, Specimen 3
Nonoperating Mode, NC Contact

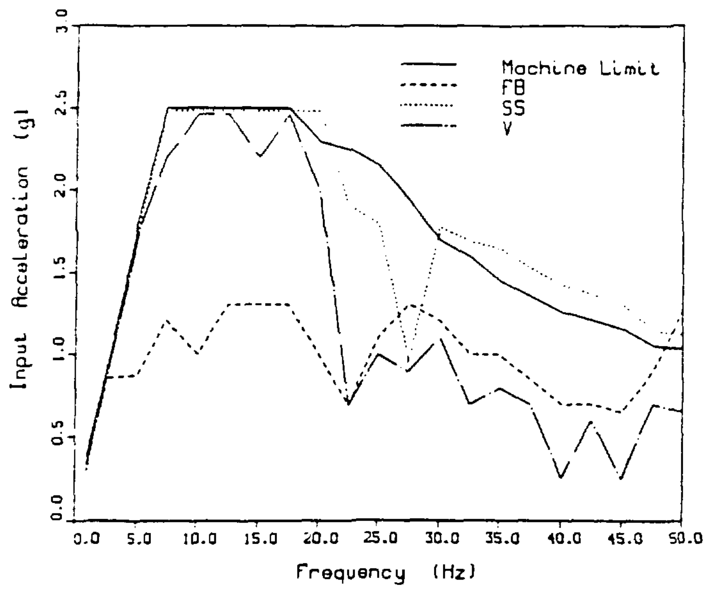


Figure 3 Sine Dwell Capacity Level
HFA151A, Nonoperating Mode, NC Contact

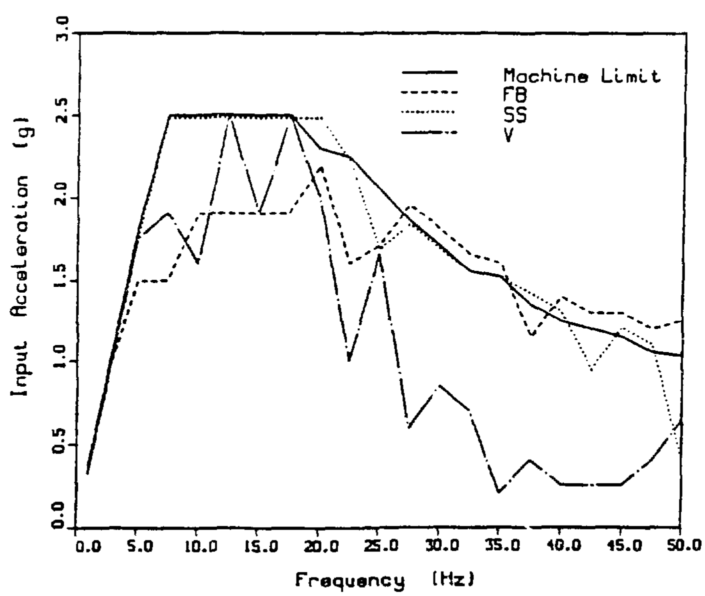


Figure 4 Sine Dwell Capacity Level
HFA51, Specimen 2
Nonoperating Mode, NC Contact

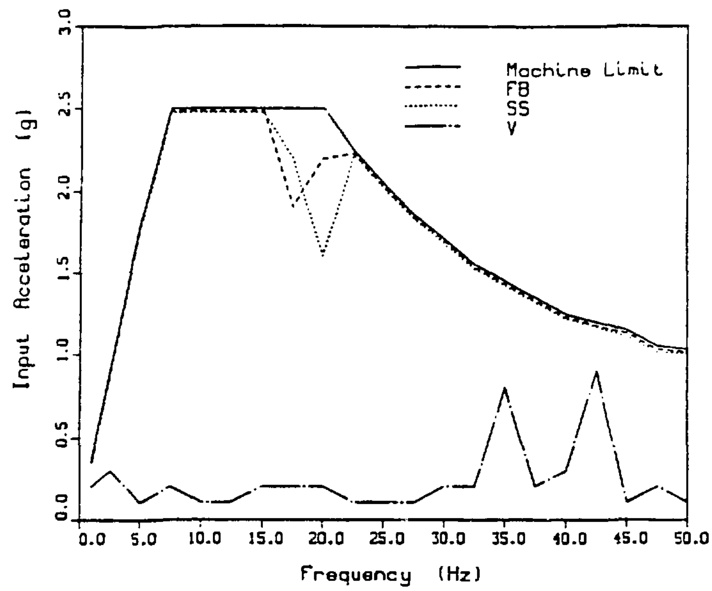


Figure 5 Sine Dwell Capacity Level
SVF, Specimen 3
Operating Mode, NC Contact

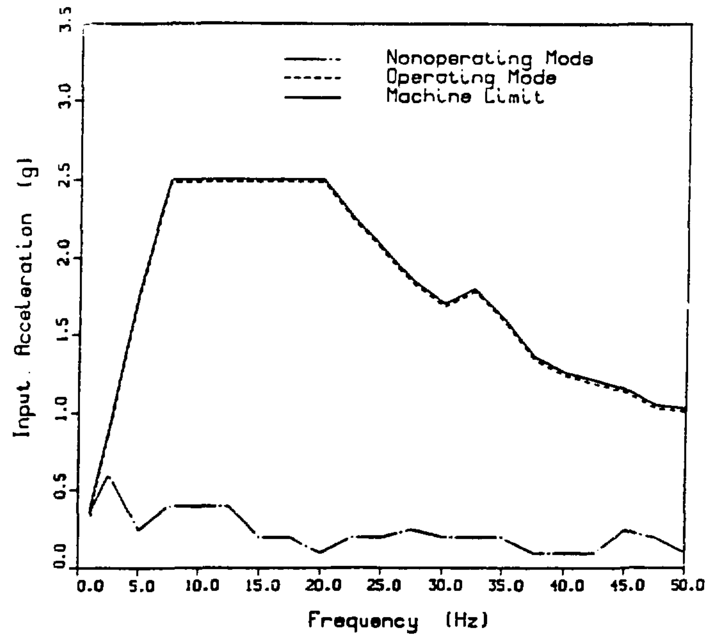


Figure 6 Influence of Electrical Conditions
Sine Dwell Capacity Level
HMA124, Specimen 1, V Direction

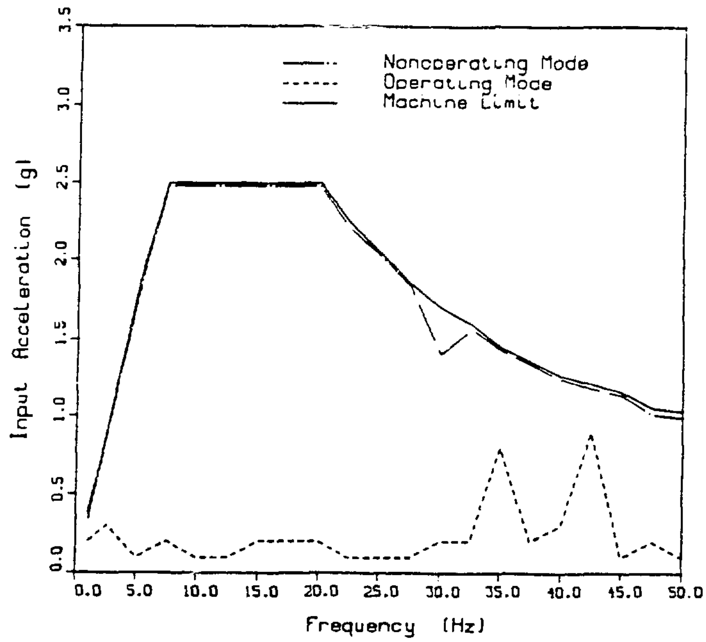


Figure 7 Influence of Electrical Conditions
Sine Dwell Capacity Level
SVF, Specimen 3, V Direction

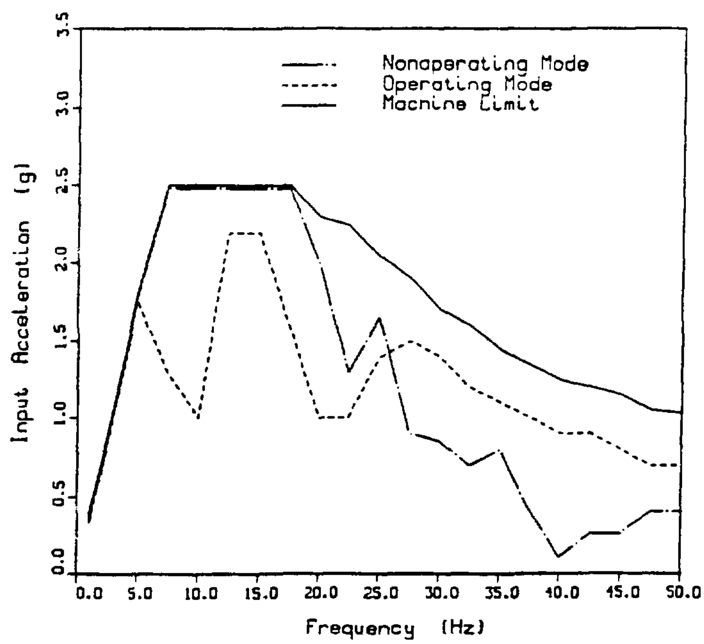


Figure 8 Influence of Electrical Conditions
Sine Dwell Capacity Level
HFA154B, V Direction

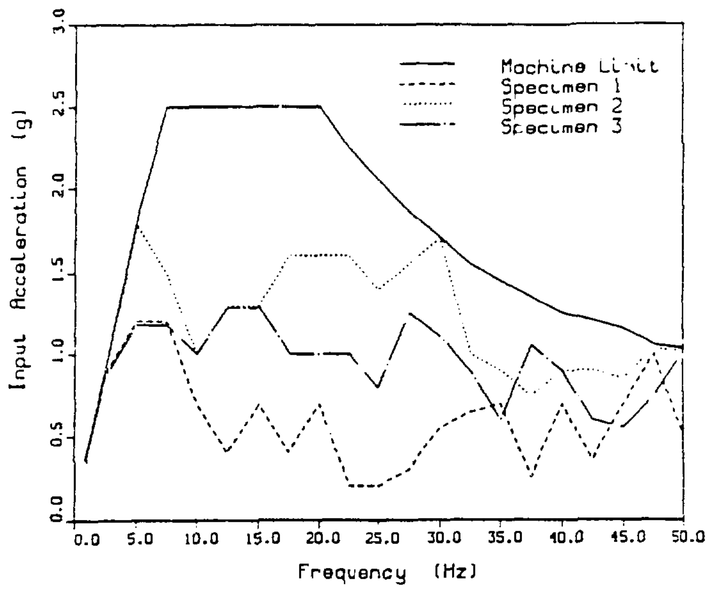


Figure 9 Comparison of Specimen Capacities - HMA124
Sine Dwell Amplitude, FB Direction
Nonoperating Mode, NC Contact

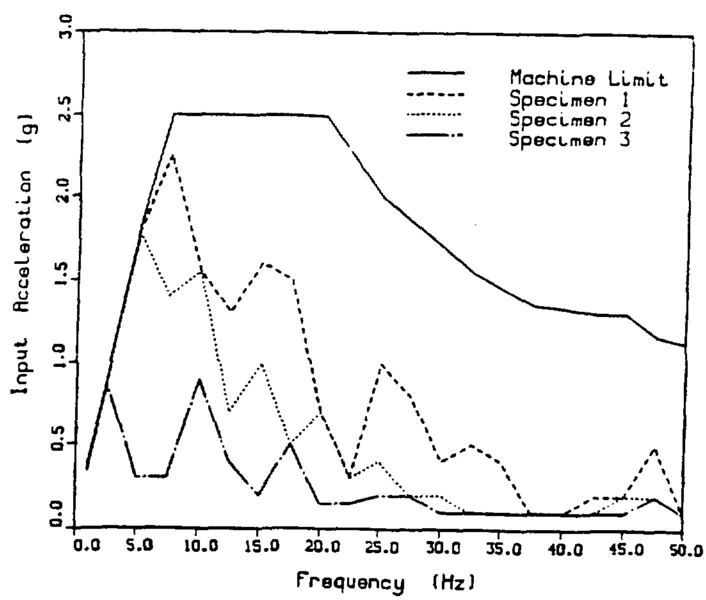


Figure 10 Comparison of Specimen Capacities - CO-6
Sine Dwell Amplitude, V Direction
Operating Mode, CO Contact

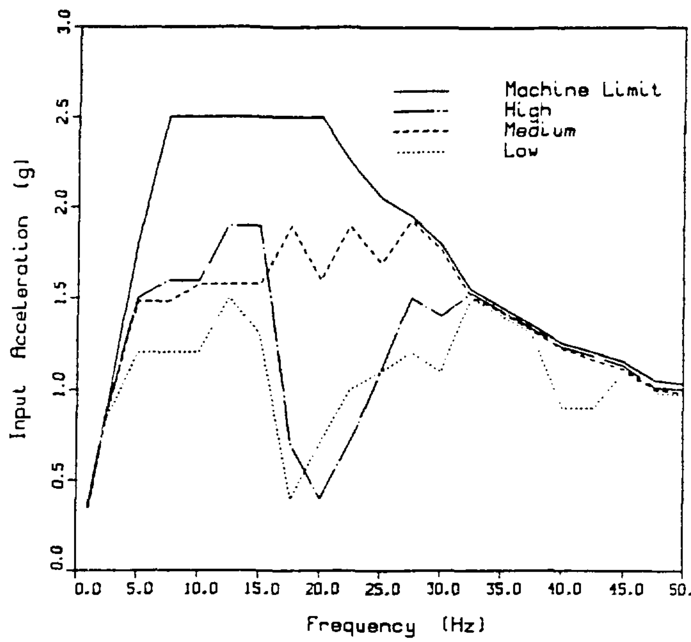


Figure 11 Influence of Spring Tension Adjustment
Sine Dwell Capacity Level, HFA51, Specimen 1
FB Direction, Nonoperating Mode, NC Contact

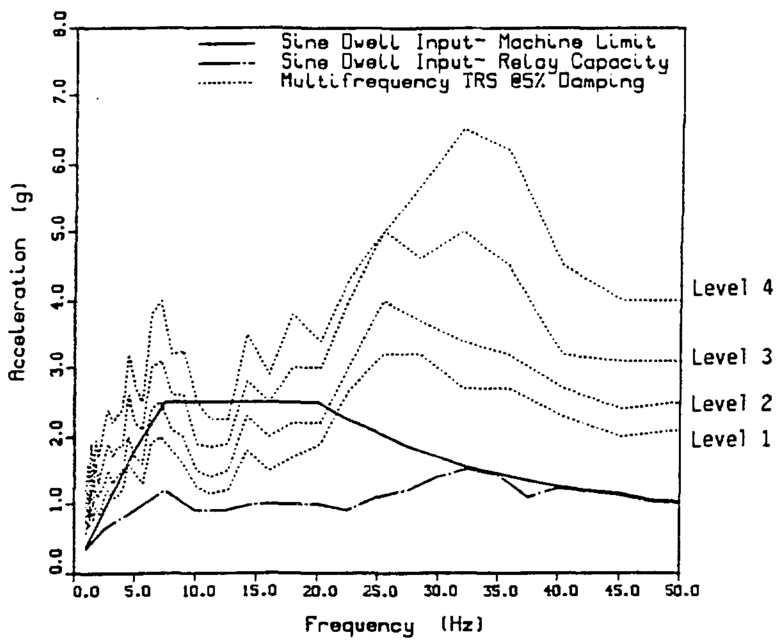


Figure 12 Generation of Capacity TRS
for Sine Dwell Input, SG, Specimen 3
Nonoperating Mode, NC Contact

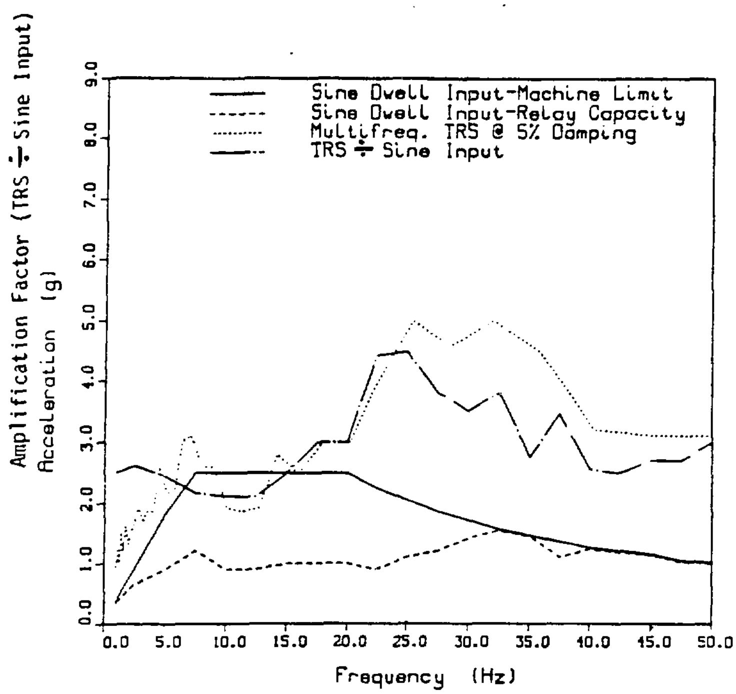


Figure 13 Correlation of Sine Dwell Input and Multifrequency TRS, SG, Specimen 3 FB Direction, Nonoperating Mode, NC Contact

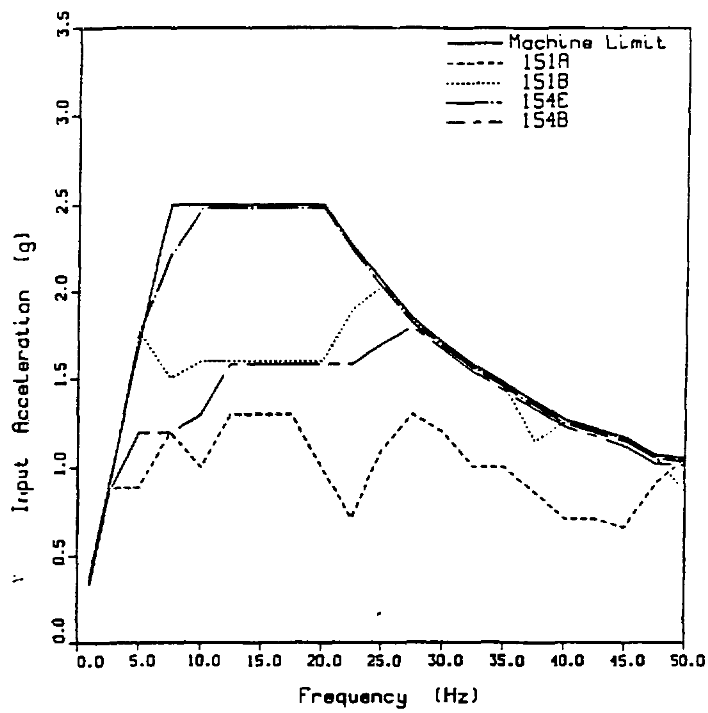


Figure 14 Dynamic Similarity of HFA Relays Sine Dwell Capacity Level FB Direction, Nonoperating Mode, NC Contact

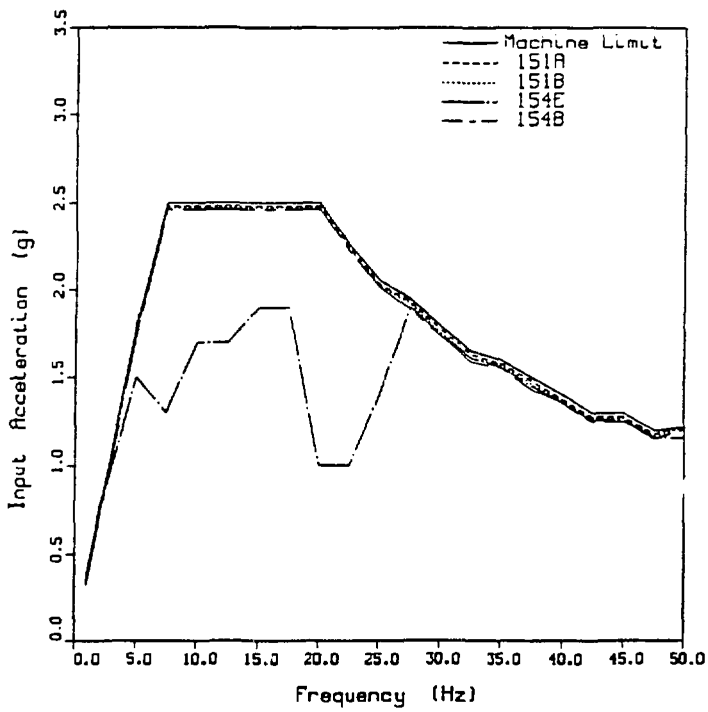


Figure 15 Dynamic Similarity of HFA Relays
Sine Dwell Capacity Level
FB Direction, Operating Mode