A THREE DIRECTIONAL VIBRATION SYSTEM

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The design and performance of a Three Directional Vibration System to allow the simulation of ground and air transportation vibration environments is presented. The basic system was built at White Sands Missile Range, New Mexico and utilizes a multiaxis drive unit designed and constructed by Team Corporation.

INTRODUCTION

It has been the desire of White Sands Missile Range (WSMR) to have a three directional vibration system for two major reasons. First, the time required to make setups and perform specification type single axis vibration tests would be greatly reduced, especially when the test involved temperature conditioning. Secondly, being able to apply vibration environments in three directions simultaneously would allow more realism to exist when vibration levels measured during equipment operation were to be reproduced in the laboratory. The measurement made on missile components during flight and on radios during helicopter flight indicates very little rotational motion of a vibratory nature exists. Because of this and to allow for single axis vibration testing, the design for the three directional vibration system was to have only orthogonal motion along the three principal axes.

To meet the WSMR needs, three systems have been evaluated experimentally. The first two were discarded for reasons given later. The third system which is described in this paper and in operation has the following additional design criteria.

a. No resonance below 500 Hz

b. Usable to 2 kHz

c. Capable of 0.025 m double amplitude in each of three directions

d. An attachment surface of at least 0.90 x 0.90 m

e. Capable of accelerating a 90 kg package to 10 g's

f. Isolated from its foundation

g. Multiple uses

INITIAL SYSTEM

In the early 60's, the first 3-D System at WSMR was assembled having as the driven unit a 0.13 m aluminum cube. This system is depicted in Figure 1 and used three MB C5-H Exciters to supply the driving force. As is apparent from the sketch, there was no place to mount a test item without causing severe moments about at least two of the driving axes. These moments would cause the drive plates to separate from the cube since they were only attached by a thin film of oil supplied by gravity.

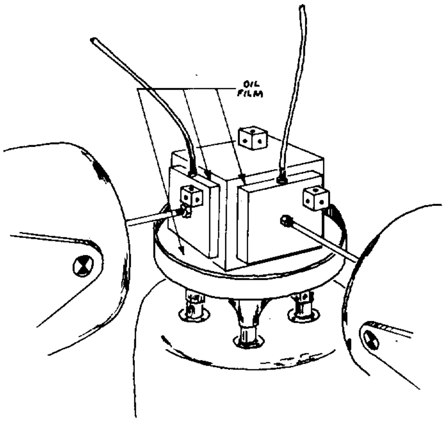

Fig. 1 - Sketch of first 3-direction vibration setup

This system operated extremely well at low frequencies and relatively low accelerations, but as the frequencies were increased, the oil film decoupled causing an attenuation of the acceleration of the cube. This decoupling continued until eventually the cube would separate from the horizontal drive plates. Although the setup did demonstrate the feasibility of a 3-D vibration system, it had no use as a testing tool and was dismantled.

The second 3-D vibration system to be evaluated at WSMR was designed, built and operated by the Wyle Laboratory at Huntsville, Alabama. This system was used to test radios to a three directional vibration environment measured on the radios during helicopter flight. Figure 2 shows the Wyle system as it was set up at WSMR.

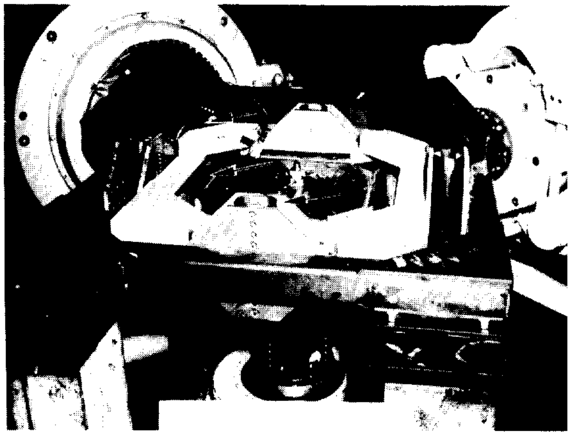

Fig. 2 - The Wyle built 3-Direction vibration table

The vertical input rod was attached to the lower side of the approximately 0.4 m square table while the two transverse input rods were attached to two of the corners of the table. Connected to the exciter were large tubes welded to the armature attachment plate. Four circular steel flexures 90° apart are mounted between the tube and the drive rod. The longitudinal axis of the flexures was the same as the drive rod, thereby, permitting the excitation to be reasonably transmitted while allowing the drive rod and table freedom to move in directions normal to the exciter's direction of motion.

The mechanism used to restrain the rocking motions of the table is two sets of four circular flexures. The first set was attached to each side of the table and to an intermediate frame. The second set of flextures are mounted perpendicular to the first set between this intermediate frame and the main frame that supports the system. The flexures are identified by arrows on the figure. The intermediate frame is free to move, in fact,driven by the flexures in the horizontal direction.

Mechanically, this system was much more complex than the first 3-D Setup and proved to have several advantages. A test item could be mounted on it and it would not fall apart during operations. However, a severe resonance occurred at 150 Hz due to the mass of the input drive rods and at several frequencies, the variation in the acceleration level in the vertical direction was 40 db. Over 100% distortion existed at many frequencies. The distortions were presumably caused by the flexures, intermediate frame, and the input rods. Some distortion was also caused by the shaker support system, main frame, and the wide flange beams that supported the main frame. It was found that a test item having an appropriate mass could be placed on the table such that its mass counteracted the mass of the drive rods. With this mass, some of the bad resonances in the vertical direction were minimized, but resonance problems in the horizontal directions were increased. For these reasons, this system was also disassembled and the exciters put to better use.

CURRENT THREE DIRECTION (3-D) VIBRATION SYSTEM

The previous testing and setups provided enough information on distortion to know that the support system for the exciters and table had to have high stiffness and reasonable damping. As these characteristics would be expensive to obtain, this system had to have something more than salvage value if the three directional concept did not prove to be useful. For this reason, three modes of operation were conceived. These consisted of three axis, vertical, and slip table operations as depicted in Figures 3, 4, and 5. To facilitate uniaxis testing, one exciter could be used for horizontal testing and another used for vertical excitation. The 3-D system was constructed by WSMR and Team Corporation using slightly modified Ling 335-B Exciters. A cut away sketch is shown in Figure 6.

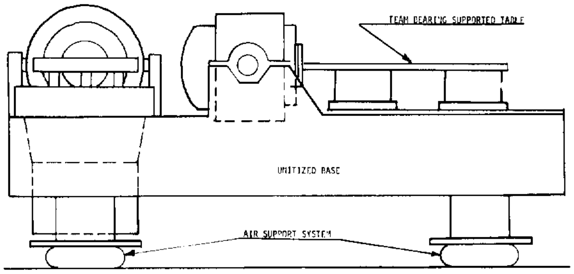

Fig. 3 - Horizontal Uniaxial Testing Mode

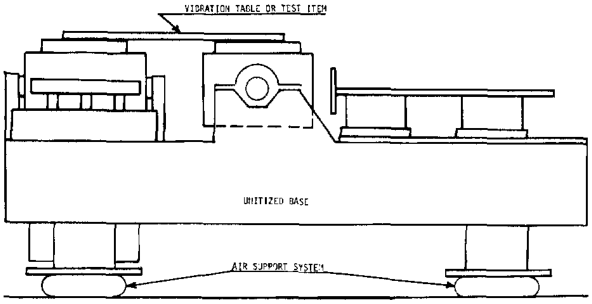

Fig. 4 - Sketch of the vertical uniaxial testing mode

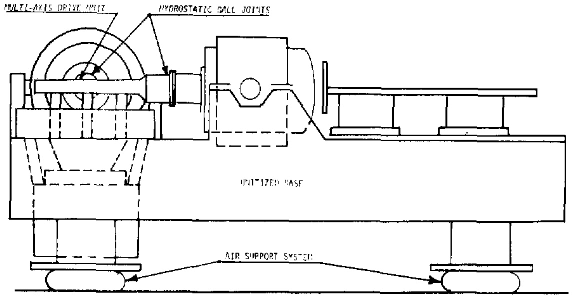

Fig. 5 - Sketch of 3-Directional mode for the current system

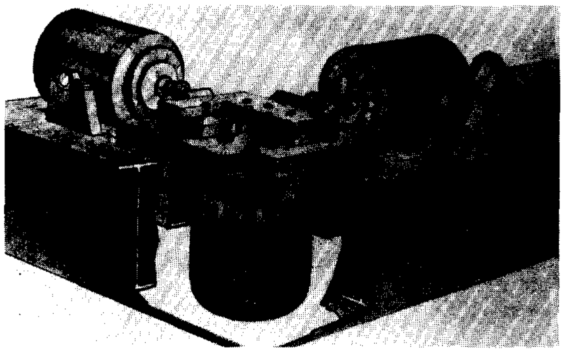

Fig. 6 - Cutaway sketch of the new 3-directional vibration system

CONSTRUCTION

The base is approximately 0.915 m thick, built using wide flange beams boxed in by welding .0254 m thick steel plates to each side. The base is L-shaped, having side lengths of 5.10 and 3.30 m. The width of each side is 2.06 m. The wide flange beams are placed around the peripheral of the base and across the sides in front and back of each horizontal exciter. In addition to boxing in the wide flange beams, the plate is used to enclose the area utilized for the Team table support. To dampen the structure, sand has been added to all enclosed volumes and when the sand fill is complete, water will be added to fill all voids. Past tests have shown that the water will double the damping coefficient and increase weight by 20%.

The support for the horizontal exciters are 0.1525 m thick steel plates mounted vertically by welding to the base with the upper end machined to accept a trunnion mounting assembly. This assembly is made so that vertical or horizontal changes (up to .0165 m) in the position of the exciters can be made by the use of shims. After the exciters are positioned, the assemblies are bolted down forcing two wedge shaped portions of the assembly into the side of the 0.1525 m trunnions. The trunnions are pressed into the body of the exciters and then welded. This is the only modification to the standard Ling 335-B Exciter. The vertical exciter is hung from the main structural support plate of the multiaxis drive unit. Bolted to this plate are twenty-four steel rods, .010 m in diameter, .030 m long. These in turn are bolted to an adaption ring bolted to the top body of the exciter. The structural support plate is .020 m thick by 1.37 m square. To provide a flat smooth surface for the support plate to mount on, machine steel strips were placed on stand offs and adjusted until they were in a horizontal plane. The void between these strips and the base was then filled with a high strength epoxy. Using this technique, a minimum amount of machining was required and a solid flat surface was obtained for mounting the multiaxis drive unit.

Vertical excitation is transmitted to nine journal bearing posts .01525 m in diameter through a transition block or head spreader .635 m square by 0.22 m deep attached to the armature. These posts go through journal bearings mounted in the main structural plate. Two bolts going through each post into the transition block hold a lower bearing plate to the posts. The journal bearings restrict the motion of this 0.127 m thick bearing plate to the vertical direction. The top surface of this lower plate has bearing surfaces machined into it, allowing the upper bearing plate or test table to slide in the horizontal directions. The upper bearing plate is held in place by bolts that go through the lower plate, the bearing posts, and into the transition block. Cutouts are made in the lower bearing plate and the posts to allow the upper plate to move .0254 m in any horizontal direction. To reduce high stresses at the ends of these bolts, inserts are mounted in the upper plate and at the lower end of the posts to reduce bending of the thin bolts at these locations.

All bearings in the system operate from a 3.48 MPa hydraulic oil supply and vacuum is used to return the oil to the pump reservoir. Vacuum is also applied between the test table and the lower bearing plate at all non-bearing locations to assist the bolts in counteracting any overturning moments induced by test items. This vacuum can be varied manually from 5 m Hg to 63.5 m Hg and air and dust are prevented from entering the system by teflon seals placed between and along the perimeter of the 0.915 m be 0.915 m bearing plates.

Drive is applied to the table in the horizontal directions through Team 1/2-17 BQ spherical couplings. The mechanical preload on these couplings was increased until they would just be free at 13.7 MPa hydraulic oil pressure and they are operated at a pressure of 19.3 MPa. One pair is used in one direction and two pair are used in the other. All torsional moments created about the vertical axis are transmitted through the two couplings to the exciters flexures and bearing systems. The assembled system ready for an initial evaluation is shown in Figure 7. The moving element weight is 3451 kg in the vertical direction and 1729 kg in the horizontal direction.

Fig. 7 - 3-directional vibration system setup for initial evaluation

When the 3-D system was first operated, no isolation was present between the base and the floor. This operation caused the base to walk across the floor and the cinder block building to vibrate. Although this operation did greatly assist in distributing the sand within the base, it was immediately stopped and an isolation system using five Model 196 Barry stable level air support units was installed. Tests conducted at WSMR demonstrated that each unit will support 10909 kg at 620 KPa (their maximum rated operating pressure). The complete system will weigh 2.07×10^5 kg and weighs 1.88×10^5 kg without the Team slip table. The resonant frequency of the three directional system mounted on this isolation is 2.4 Hz. This means that virtually no vibration forces are transmitted to the floor as a result of the unit operation.

SYSTEM PERFORMANCE

The evaluation of the system performance characteristics was accomplished using sine sweeps in one direction at a time and random noise in three directions simultaneously. During evaluation, accelerometers were mounted in the three directions of excitation at the four locations shown in Figure 8.

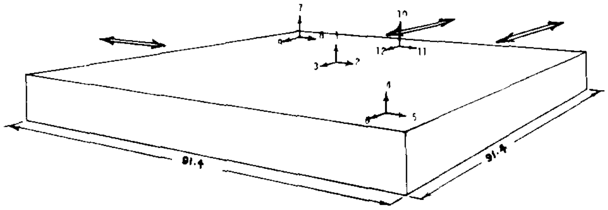

Fig. 8 - 3-Direction sine vibration accelerometer locations

Control was maintained at the center of the table (Accelerometer 1, 2, or 3) for all tests. The cross axis sensitivity of these Endevco Model 2213E Accelerometers ranged from 1.8% to 2.9%. For sine wave operation, all amplifier and field supplies were on, but the inputs to the nonoperating exciters were shorted. Five minute logarithmic sweeps were conducted from 10 Hz to 2 kHz at an input level of one g peak. As the sine wave input level was maintained at one g with less than 0.1 g variation, no plot of the input is presented. Figures 9, 10, and 11 show vertical table responses to a vertical input. Figures 12, 13, and 14 show the responses to inputs from the exciter having one pair of ball joints and Figures 15, 16, and 17 show the response to an input in the final horizontal direction. During sine excitation in the horizontal directions, the cross axis motion in the vertical direction was low, normally less than 50%, however, the other horizontal directions exhibited high cross axis motion. Excitation along the axis of Number 3 accelerator resulted in the cross axis motion shown in Figures 18, 19, and 20, while motion in the direction of accelerometer Number 2 resulted in the cross axis motion shown in Figures 21, 22, and 23. When excitation was in the vertical direction, nearly all accelerometers exhibited high cross axis motion. These responses are shown in Figures 24 through 29.

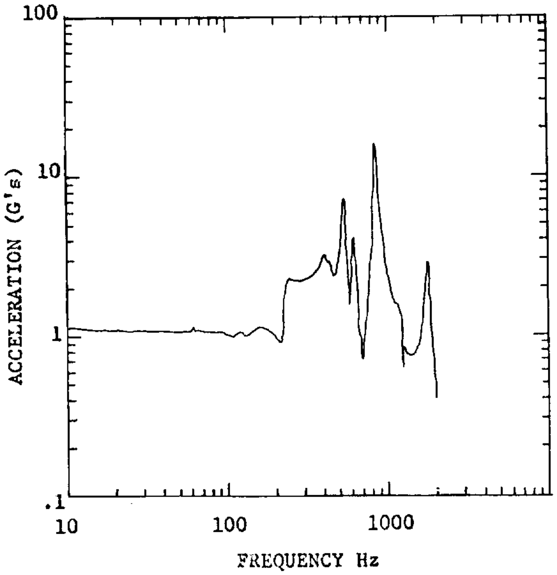

Fig. 9 - Acceleration Measured from No. 4 Accelerometer when No. 1 Accelerometer was maintained at 1 "G" peak

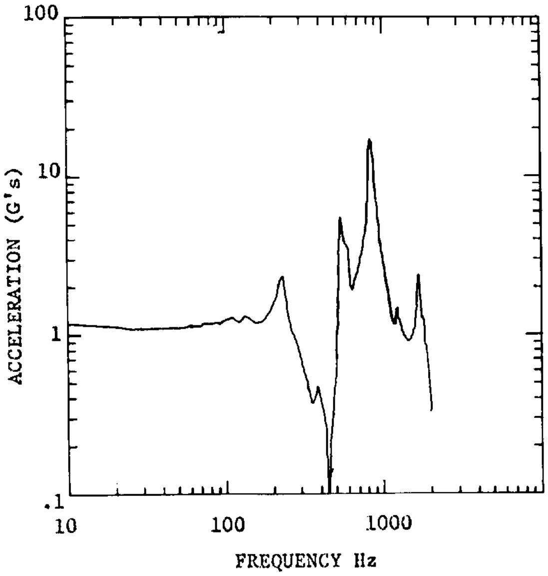

Fig. 10 - Acceleration measured from No. 7 Accelerometer when No. 1 Accelerometer was maintained at 1 "G" peak

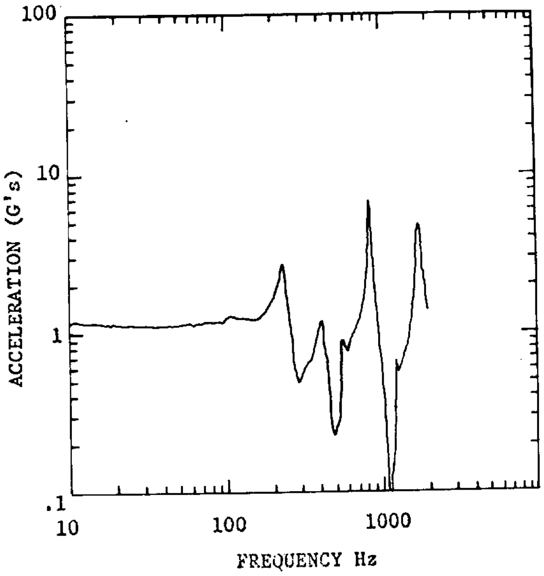

Fig. 11 - Acceleration measured from No. 10 Accelerometer when No. 1 Accelerometer was maintained at 1 "G" peak

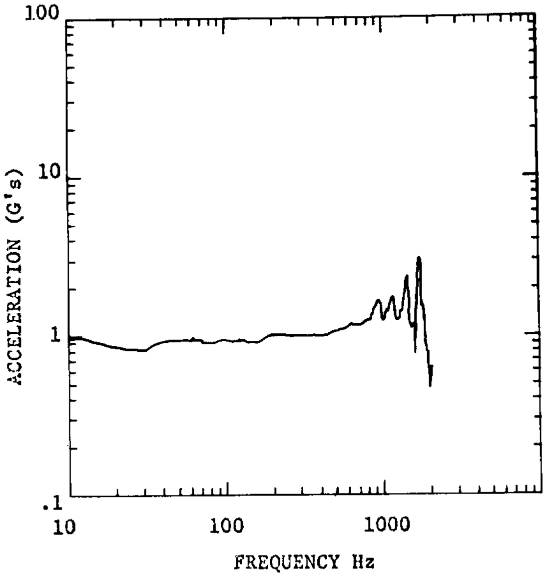

Fig. 12 - Acceleration measured from No. 5 Accelerometer when No. 2 Accelerometer was maintained at 1 "G" peak

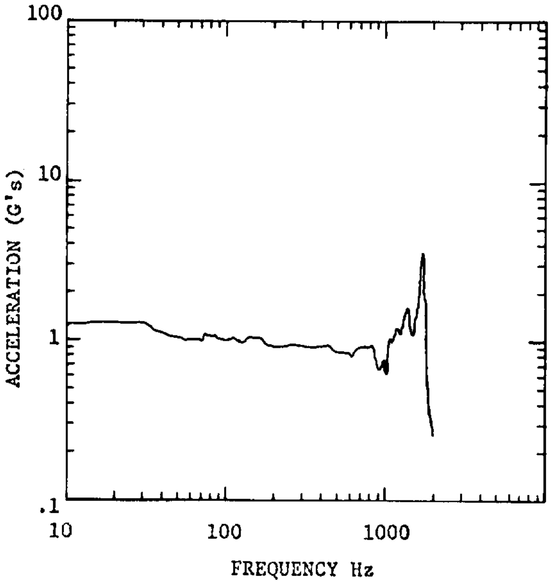

Fig. 13 - Acceleration measured from No. 8 Accelerometer when No. 2 Accelerometer was maintained at 1 "G" peak

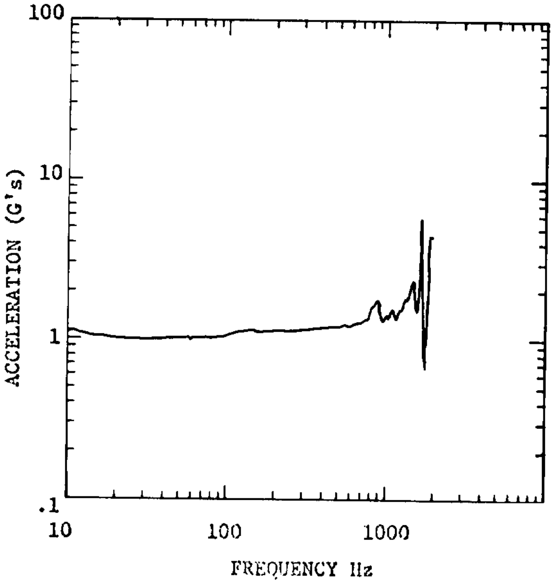

Fig. 15 - Acceleration measured from No. 6 Accelerometer when No. 3 Accelerometer was maintained at 1 "G" peak

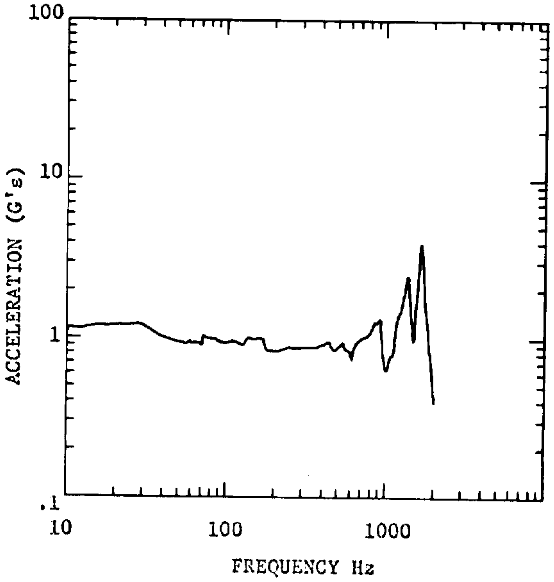

Fig. 14 - Acceleration measured from No. 11 Accelerometer when No. 2 Accelerometer was maintained at 1 "G" peak

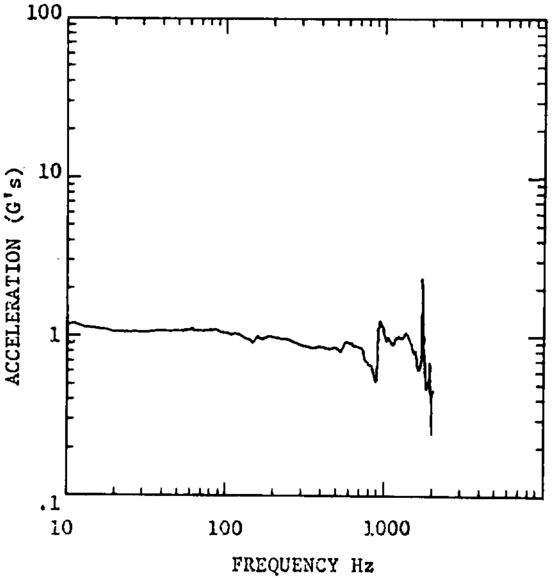

Fig. 16 - Acceleration measured from No. 9 Accelerometer when No. 3 Accelerometer was maintained at 1 "G" peak

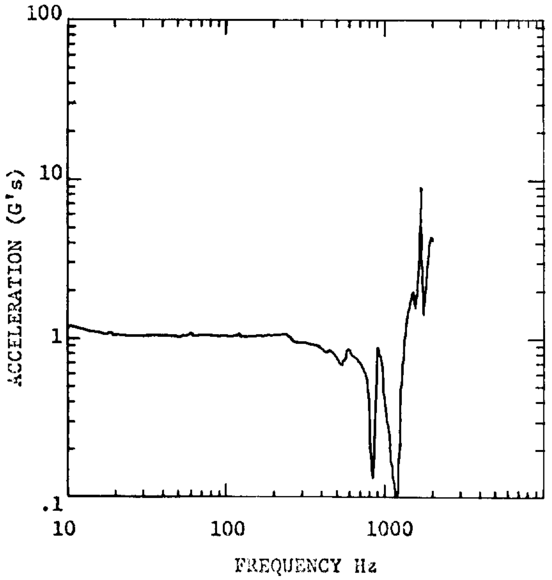

Fig. 17 - Acceleration measured from No. 12 Accelerometer when No. 3 Accelerometer was maintained at 1 "G" peak

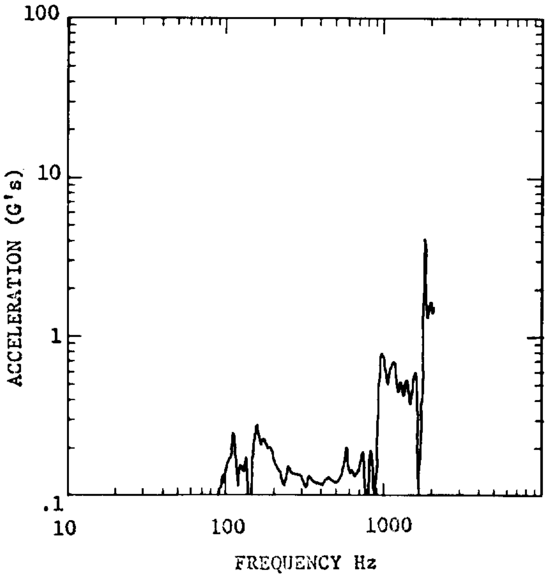

Fig. 19 - Cross Axis Acceleration measured by No. 8 Accelerometer when No. 3 Accelerometer was Excited to 1 "G" peak

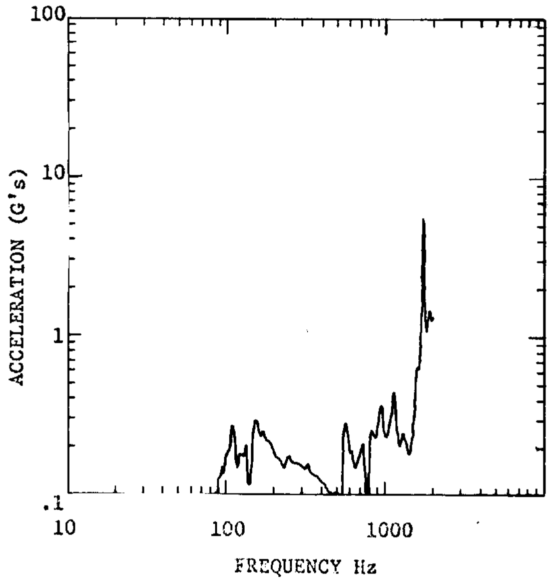

Fig. 18 - Cross Axis Acceleration measured by No. 11 Accelerometer when No. 3 Accelerometer was Excited to 1 "G" peak

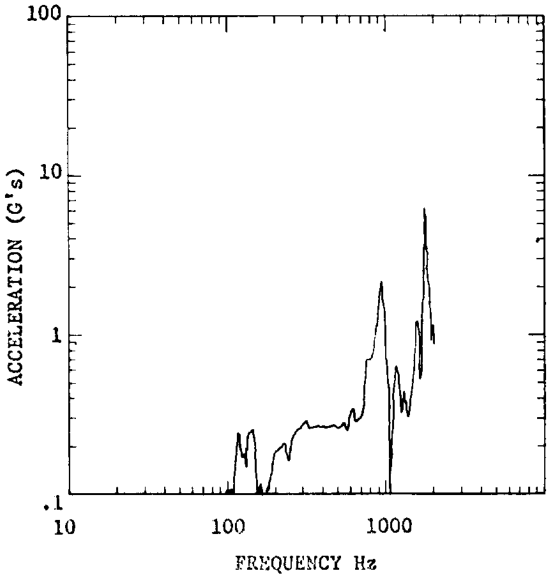

Fig. 20 - Cross Axis Acceleration measured by No. 5 Accelerometer when No. 3 Accelerometer was excited to 1 "G" peak

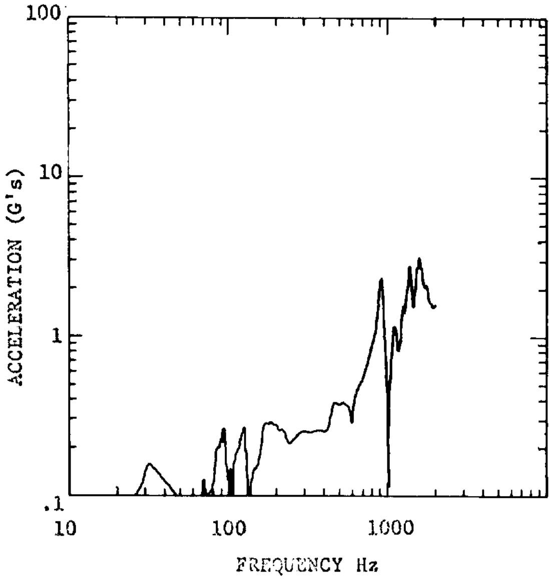

Fig. 21 - Cross Axis Acceleration measured by No. 6 Accelerometer when No. 2 Accelerometer was excited to 1 "G" peak

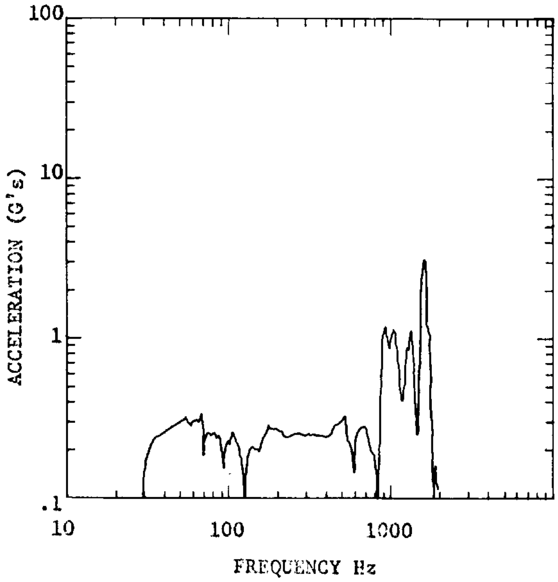

Fig. 22 - Cross Axis Acceleration measured by No. 9 Accelerometer when No. 2 Accelerometer was excited to 1 "G" peak

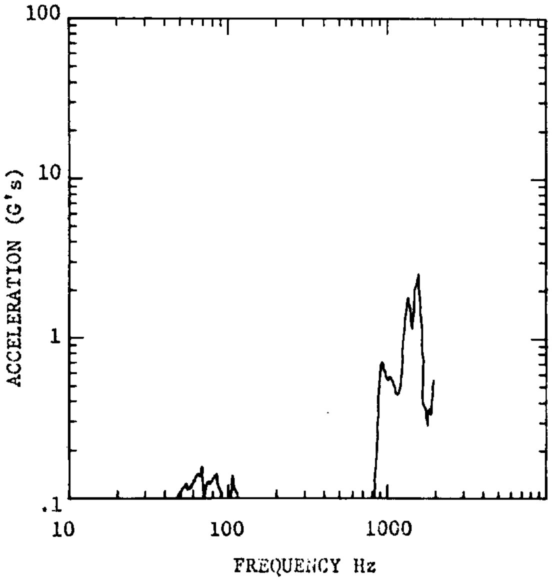

Fig. 23 - Cross Axis Acceleration measured by No. 12 Accelerometer when No. 2 Accelerometer was excited to 1 "G" peak

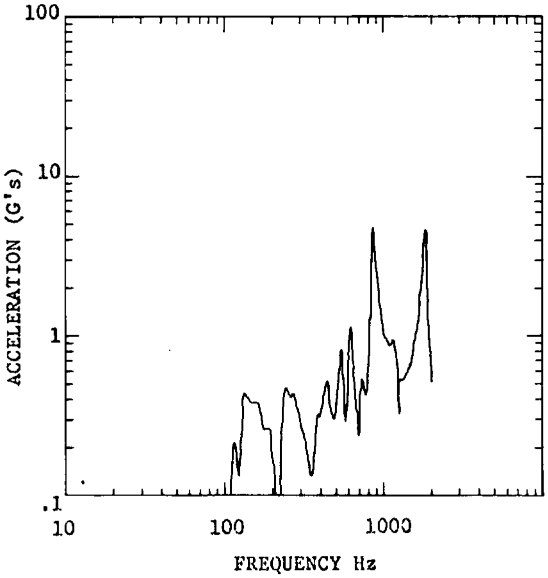

Fig. 24 - Cross Axis Acceleration measured by No. 5 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

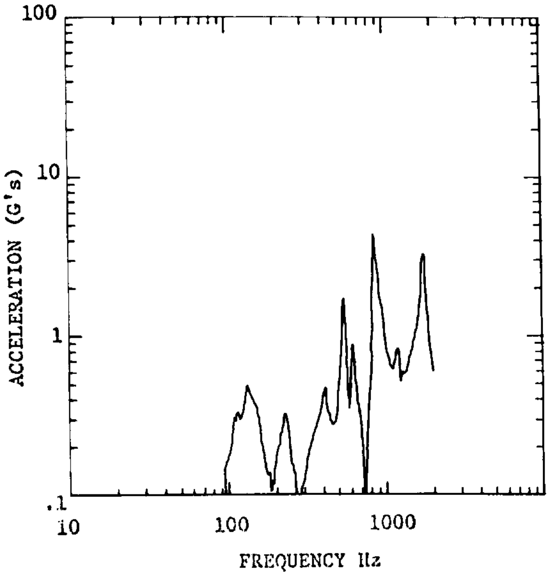

Fig. 25 - Cross Axis Acceleration measured by No. 6 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

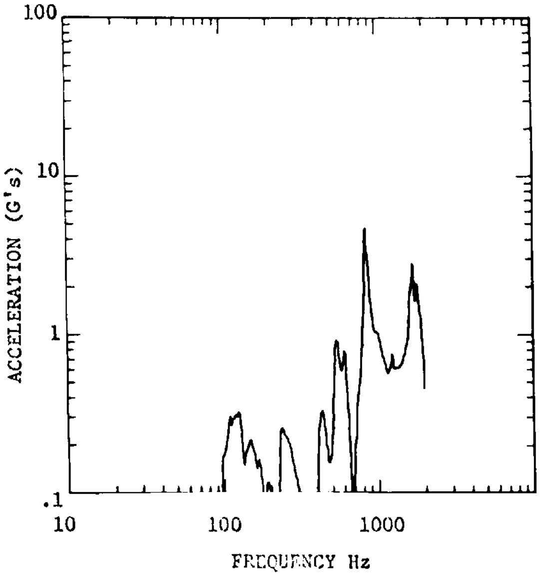

Fig. 27 - Cross Axis Acceleration measured by No. 9 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

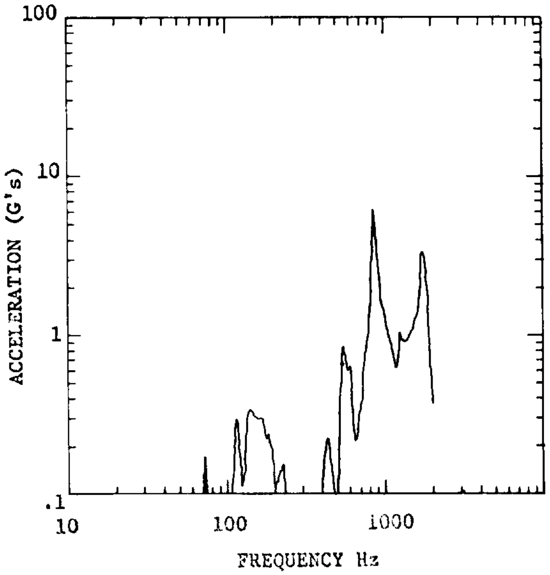

Fig. 26 - Cross Axis Acceleration measured by No. 8 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

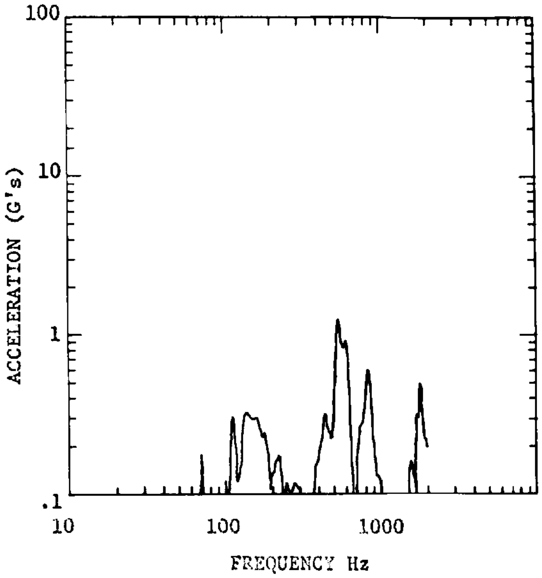

Fig. 28 - Cross Axis Acceleration measured by No. 11 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

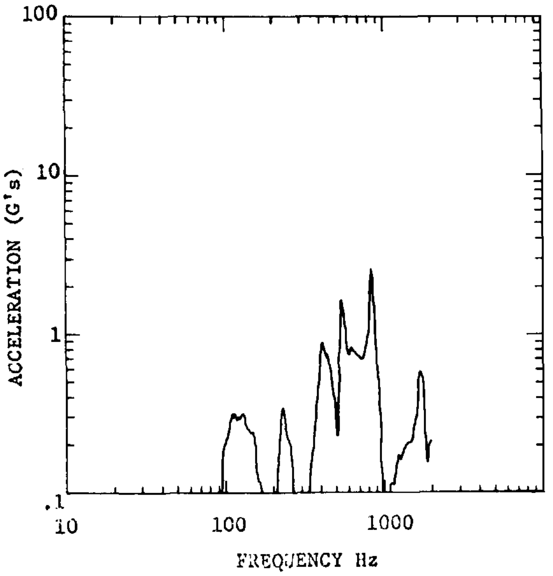

Fig. 29 - Cross Axis Acceleration measured by No. 12 Accelerometer when No. 1 Accelerometer was excited to 1 "G" peak

Measurements have indicated that the variation in the vertical direction and much of the cross axis motion is caused by a lack of stiffness in armature supports of the Ling 335-B Exciters. This lack of stiffness is emphasized when the excitation is applied by the shaker driving through one pair of ball joints. The armature of the other horizontal shaker is rocking such that its outside edge is moving a total of .0048 m. A much stiffer flexure system is available from the manufacturer, however, with the present flexure, the system is usable but may have a reliability problem. This is particularly true if the system is to be operated at low frequencies.

Random vibration was used with the system in two configurations. The first was with no load and three non-correlated inputs were applied in three directions simultaneously. It was attempted to equalize to a flat spectrum using the Accelerometers 1, 2, and 3 for feedbacks. The equipment used for equalization was two MB equalizers, Models 389 and 589, with peak notch and graphic equalizers. The results of this equalization using 12.8 Hz effective bandwidth for analysis are shown in Figures 30, 31, and 32. For the second configuration, one of the horizontal exciters was removed so that the test item (two structural dummy Chaparral missiles) could be attached to the table, see Figure 33.

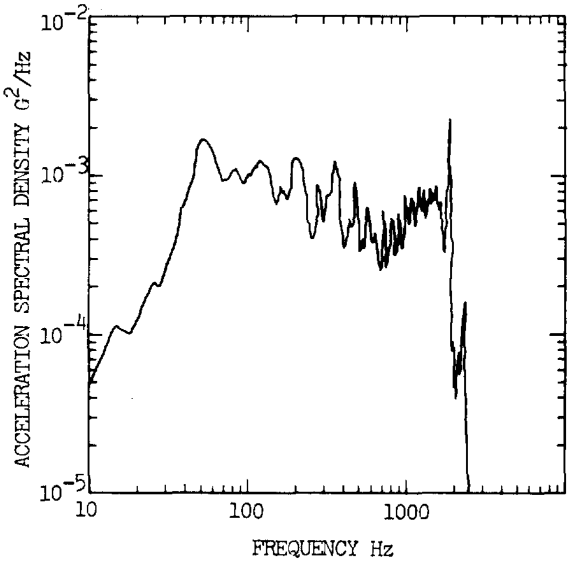

Fig. 30 - Equalization obtained in the Vertical direction during three directional vibration

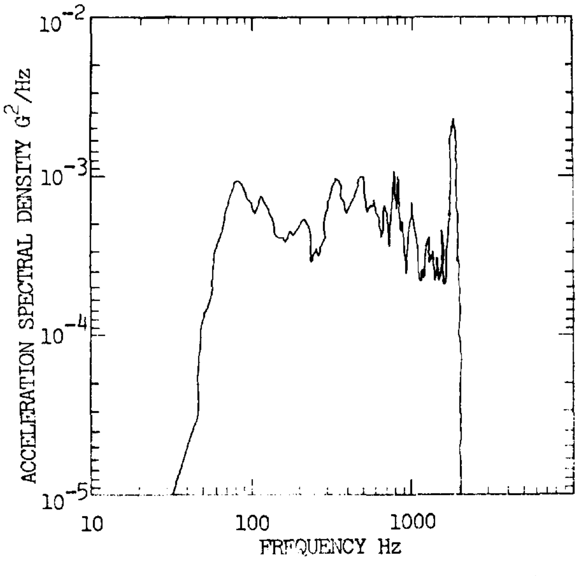

Fig. 31 - Equalization obtained in the No. 2 Horizontal direction during three directional operation

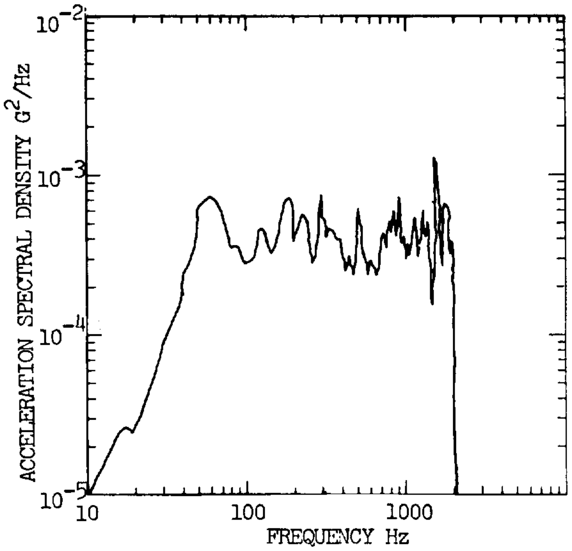

Fig. 32 - Equalization obtained in the No. 3 Horizontal direction during three directional operation

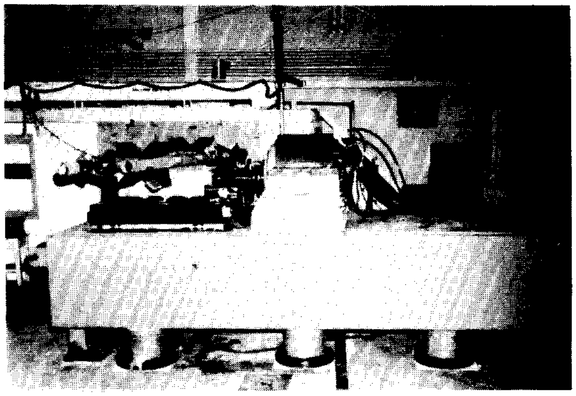

Fig. 33 - Overall view of the setup used to excite two Chaparral missiles in the Vertical and Horizontal directions

The weight of this setup was 225 kg. The input spectrum curves are those actually used for ground transportation testing. The missiles are orientated 13° off of the horizontal axis as they are normally during single axis testing, this is to account for the longitudinal input. The required spectrum and that obtained using an 8 Hz analysis bandwidth are presented in Figures 34 and 35 for the vertical and transverse input directions respectively.

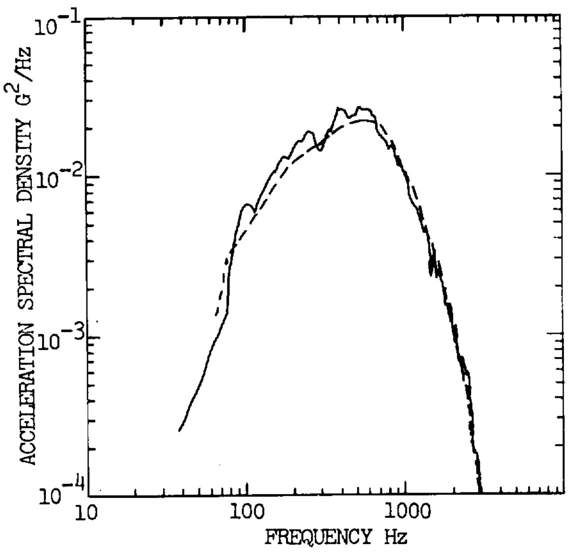

Fig. 34 - Required and desired spectrum from horizontal excitation of the Chaparral missiles

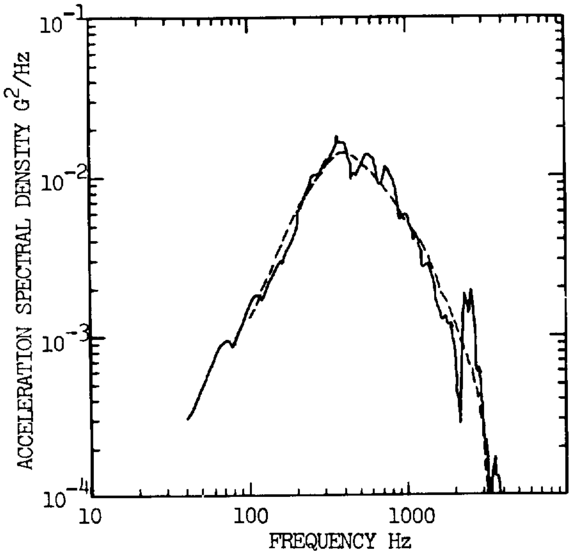

Fig. 35 - Required and desired spectrum from vertical excitation of the Chaparral missiles

It is felt that had beeter equalization equipment been available, the bare table could have been equalized to within 2 db at all but a few points. These points are at 1900 Hz in the vertical direction at 1700 through 1800 Hz in the direction of the one ball joint and at 1550 in the other direction when a flat input spectrum is desirable. As the intent of the system is to test missile and helicopter components to flight environments, both high and low frequency performance will be required. Each type of excitation will have to be checked before the systems capability will be known. If flight levels can be reproduced on all test items as well as the setup used on the Chaparral missiles, the system will well be worth its investment both as a three directional test system and for testing items sequentially using only one setup. This is particularly true if temperature conditioning is required.

PROPOSED CHANGES

To increase the reliability and performance of this system, several changes are anticipated. The first is to install stiffer flexures in the horizontal exciters. This will reduce cross axis motion, flatten the frequency response in the vertical direction and immensely improve the reliability of the system. The second is to transfer the torsional moments about the vertical axis to both horizontal exciters. This will be accomplished by installing a second pair of hydrostatic ball joints between the table and the exciter which only has one set now. A third change is to add an automatic centering system to the vertical exciter. The standard leveling system on the 335B Exciter is extremely difficult to set such that the table will not drift off center after a half hour or longer period. As expected, this drift causes the system to be shut down by the over travel switch. The last is to install a modified armature in the vertical exciter to increase the force output for short tests (reproducing missile flight vibration environments). It is believed that as much as 1.3610^4 kg force can be generated from the exciter by adding an additional cooling system and changing the armature.

CONCLUTIONS

The Three Directional Vibration System represents a vast improvement over what was previously available. This system can be used for the testing of small items to vibration environments measured during missile and aircraft flight or ground transporation. These measured vibration environments or other test specifications can be applied to the test item either simultaneously or sequentially as desired. Modifications are required to improve the three directional vibration system's performance and reliability.