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DEVELOPMENT OF A DEDICATED TRANSPORT ISOLETTE VIBRATION TEST APPARATUS

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Abstract**—** The Neonatal Patient Transport System (NPTS) collaborative research team seeks to measure and mitigate vibrations experienced by neonatal patients during ground and air transport. A custom test apparatus was designed for use with an electrodynamic shaker to investigate the effectiveness of transport mattresses and harnesses used inside the isolette. The apparatus couples the shaker with a representative transport isolette, which is the portion of the NPTS in which the infant travels. The design allows the isolette to be shaken along any principle axis while maintaining the vertical orientation of the isolette. linear guides without rolling elements were used to constrain motion to the preferred excitation axis. Preliminary results using a prototype apparatus revealed that the vertical axis requires a guided carriage system to generate purely linear excitation, rather directly affixing the isolette to the shaker head. Once fully operational, the apparatus will enable a parametric study of the vibration performance of transport mattresses and harnesses.

Keywords – neonatal transport; mechanical design; vibrations testing

I. INTRODUCTION

Neonatal patients in need of interfacility transport experience unwanted vibration transmitted through the stretcher to the Neonatal Patient Transport System (NPTS) [1]. Several groups have examined vibrations during neonatal transport, as recently reviewed by Goswami et al [2]. In most studies, data are collected by instrumenting transport equipment during real-world or simulated patient transfers by ground or air vehicles. Recognizing the need to control confounding variables, such as traffic conditions, weather, road condition, etc. between successive trials. Some groups (including ours) are developing controlled test environments, in which transport is simulated via a shaker table to investigate design parameters in a repeatable way [3][4].The selection of transport mattress and restraint harness within the isolette are two of several areas that present opportunities to mitigate the vibrations experienced by the patient. In order to evaluate the effectiveness of commercially-available transport mattresses, a series of tests focused on the isolette level of the transport environment were defined. The tests are intended to evaluate the vibration performance of the mattresses and harnesses on a per-axis basis in a parametric study of patient weight, mattress type, and harness type. A test apparatus was designed to adapt the isolette, provided by the Children's Hospital of Eastern Ontario (CHEO), to Carleton University's electrodynamic shaker, a Bruel & Kjaer Type 4802 exciter with a Type 4818 "Big Table" head. The test apparatus was manufactured in Carleton University's Department of Mechanical and Aerospace Engineering Machining Laboratory. This paper will explore key points of the design, address the effectiveness of the free-standing vertical apparatus, describe the path forward, and introduce the parametric study for which the apparatus was made.

II. DESIGN REQUIREMENTS

Design requirements were defined early in the design process. Table I summarizes the applicable design requirements.

TABLE I. TEST APPARATUS DESIGN REQUIREMENTS

Requirement	*Specifies*	*Value*
The combined weight of the payload and carriage shall not exceed 100 lbs	Max payload weight	100 lbs
The fixture shall use linear guides to constrain the motion of the specimen	Rail type	Linear guide
The payload shall secure to the shaker using a 121 mm x 121 mm diamond bolt pattern	Shaker interface type	121 mm x 121 mm diamond
The payload shall connect to the shaker using four (4) 5/16-18 bolts	Shaker head bolt type	5/16-18
The full assembly, shaker included, shall be able to excite the payload between 1 Hz and 50 Hz at varying amplitudes	Vibration frequency range	1-50 Hz
No assembly members shall resonate below 100 Hz	Assembly resonances	>100 Hz
The assembly shall be anchored to the floor at a minimum of four (4) points	Anchoring	-
The shaker shall be firmly constrained within the assembly	-	-
All pieces of the assembly shall fit through a maximum 840 mm wide door	Max assembly piece width	840 mm
The assembly shall be capable of translating the test articles in each of the three axes with minimal out-of-plane excitation	Single-axis excitation	-

III. Apparatus Design

The isolette test apparatus was designed to accept the test isolette and couple it to the electrodynamic shaker for single axis excitation. Design took place during Summer of 2021 with its preliminary commissioning following in Fall 2021. This section will explain key design choices with regards to the general design, the frame and dock, the carriage and guides, the fixturing, the vertical apparatus, the instrumentation, and the vibration response. Figure 1 shows the apparatus after assembly.

A. General

The general form of the apparatus must be a rigid structure in which the shaker may sit and be secured. The frame and subassemblies must be stiff to mitigate undesirable vibrations and deflections. The geometry of the apparatus must allow the shaker to be easily reconfigured between the horizontal and vertical configurations. The apparatus must have a horizontal translating table which must accommodate the isolette in either orientation. A similar vertical carriage or a free-standing apparatus would be used to excite the isolette in the vertical direction. The test specimen would be secured to the table using custom fixturing. The tables would be simple in design to support reconfiguration for other test efforts within the lab. The major design elements listed above can be seen in Figure 1.

During the design phase, a three-step plan for the design and commission of the apparatus was developed. The plan broke down the commission of the apparatus into three distinct steps:

- Step 1 involves the design and commission of the horizontal table and supporting structures.
- Step 2 involves the design and commission of a free-standing vertical apparatus - an interim solution to determine if a table and linear guides are required to restrain vertical excitation.
- Step 3 involves the design and commission of a vertical structure to restrain the motion of the specimen, pending the outcome of Step 2

All stock metals used in the construction of the apparatus were 44W grade steel. This selection was based on its low cost, good availability, and good machinability. Structural tubing was used in most places to reduce the weight of the full assembly.

Figure 1. Complete test apparatus

The cumulative weight of the test specimen could not exceed 100 lbs – payloads above 100 lbs run the risk of overloading the excitation capacity of the shaker, leading to inaccurate test results or hindering the shaker from operating altogether. The isolette, pictured in Figure 1, weighs 35 lbs.

The test apparatus will be used to reproduce field data, the bulk content of which is below 50 Hz. As such, most pseudo-random tests conducted will run within a 0-50 Hz bandwidth. To avoid affecting test results, the apparatus was designed not to resonate below 100 Hz (one octave above). Finite Element Analysis (FEA) was used as a tool to predict the frequency response of the apparatus throughout the design process.

B. Frame and Dock

The frame was designed to be simple, stiff, and compact. One end of the frame was left open for removal of the shaker, such that it may also be used in other projects. Simple standoffs were designed to hold the linear guides. The frame anchors to the ground in six locations to prevent translation along the floor during testing and to prevent the frame from resonating along its side members. Figure 2 shows the frame.

As outlined in the design requirements, the apparatus must constrain the shaker in place. A “dock”, seen in Figure 3, was designed to accept and secure the shaker. The dock uses six toggle clamps with leveling feet to secure the shaker. The on-off nature of the clamps allows the fit to be customized and the test setup to be repeatable. The front face of the shaker is secured against a rubber bumper, with two clamps securing each remaining face. The rubber bumper is attached to a slotted

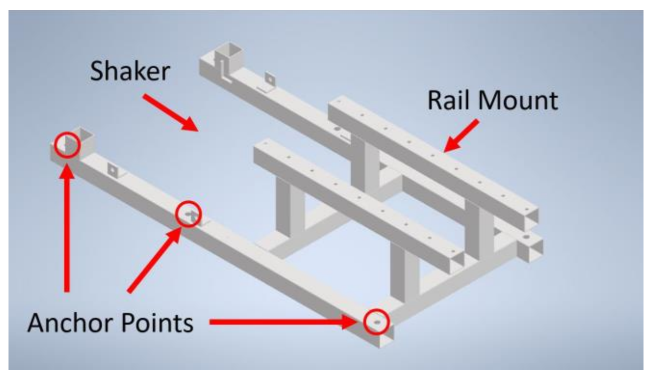

Figure 2. Labeled test apparatus frame.

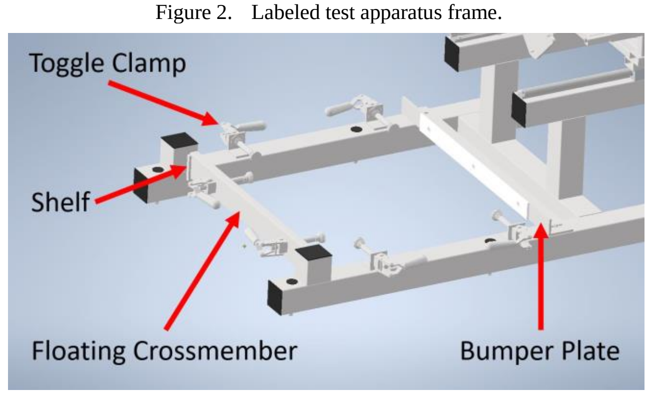

Figure 3. Labeled apparatus “dock”.

bumper plate which acts as a reference surface to align the shaker with the linear guides. The back of the "dock" is closed off by a floating crossmember. The floating crossmember rests on short sections of steel angle welded to the frame and is secured by the reaction force experienced by the clamps when engaged against the shaker base. The toggle clamps are secured to the frame via brackets and secured directly to the floating crossmember.

C. Carriage, Guides

A carriage was designed as a reliable method of coupling the test specimen and linear guides. The carriage is a simple tube frame with a square pattern of weld nuts to secure the test specimen to. A two-rail, four-guide system was selected for robustness and stability. IGUS Drylin W-Series linear guides were selected [5]. Drylin linear guides use no rolling elements which, when damaged, are liable to introduce unwanted vibrations. As a result, they are also low maintenance. The carriage-guide system can be seen in Figure 4

D. Fixturing

The test fixture had to be light to comply with the maximum payload weight of the shaker and stiff so as to not resonate below 100 Hz. The fixture closely replicates the in-situ mounting of the provided isolette by supporting the edges of its molded plastic base. The bottom of the isolette supports various electrical equipment – most notably the blower motor which hangs down by approximately 4.5 inches. The top members of the fixture are biased to one side longitudinally to allow the motor to clear the carriage and fixture. The fixture can be used for all 3 axes of excitation; thus two adapter plates were mounted for lateral and longitudinal excitation. The longitudinal adapter was made removable in order to reduce the amount of cantilevered weight; and consequently raising the resonant frequency of the top members. Due to the offset position of the isolette, ballasting points were added to permit shifting of the centre of mass of the payload to align with the axis of the shaker. The test fixture is shown in Figure 5.

E. Vertical Apparatus

Preliminary design of the vertical apparatus included a vertical structure to support a secondary table-guide system. The design included a tall supporting structure, a secondary table and set of guides, braces to mitigate vibrations in the support structure, and a spring to support the static weight of the table. The complete design can be seen in Figure 6.

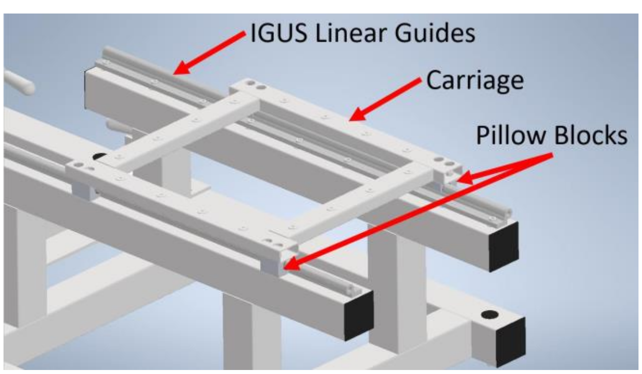

Figure 4. Labeled carriage-guide system.

Feedback from a design review recommended attempting a free-standing vertical assembly with no linear restraints – the test specimen would be secured directly and only to the shaker head. The feedback directly prompted the development of the three-step plan for commissioning the apparatus (detailed in Section III-A). If the free-standing vertical apparatus were unable to adequately isolate the excitation to the vertical axis, the original design for the vertical apparatus would be built.

The free-standing vertical apparatus uses a simple adapter to secure the test fixturing to the shaker head without linear guides. The adapter is a minimalist solution to vertical excitation, though it relies on the centre of mass of the test specimen being closely aligned with the excitation axis. The fixture secures to the adapter via two square U-bolts. The addition of slots to the adapter beam allows for lateral and longitudinal adjustment of the test fixture. The adapter may be seen in Figure 7 and the vertical apparatus can be seen in Figure 8.

F. Instrumentation

Attachment points for shaker control accelerometers were placed close to the shaker head on the test fixtures. The control accelerometers are Dytran 3055B1T [6] single-axis accelerometers and secure via #10-32 set screws as shown in Figure 9.

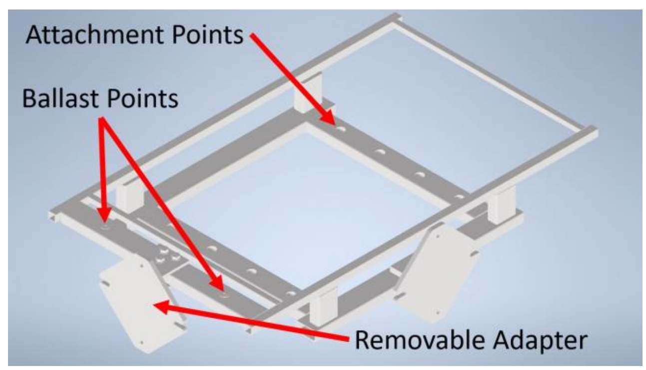

Figure 5. Labeled isolette test fixture.

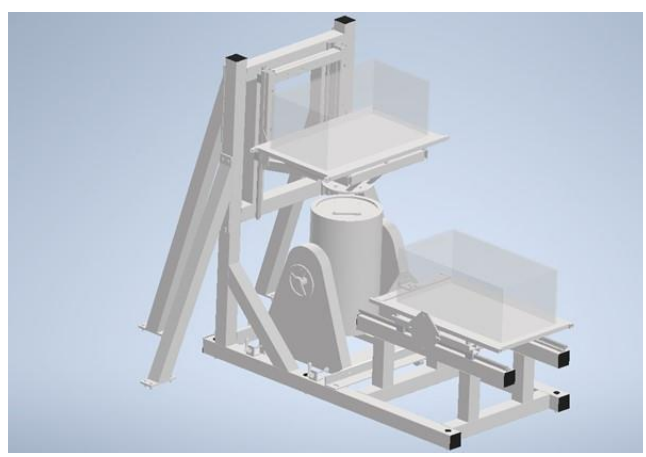

Figure 6. Original vertical apparatus design.

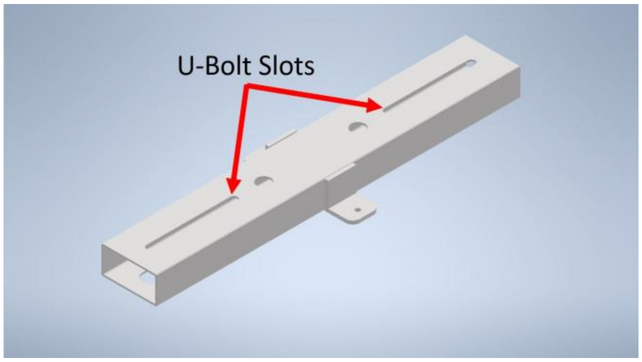

Figure 7. Vertical shaking adapter, labeled.

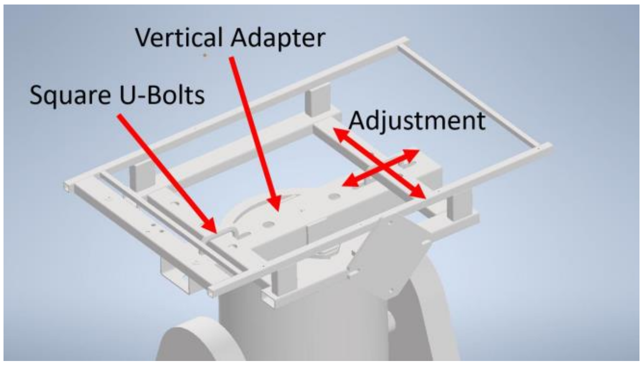

Figure 8. Vertical apparatus, labeled.

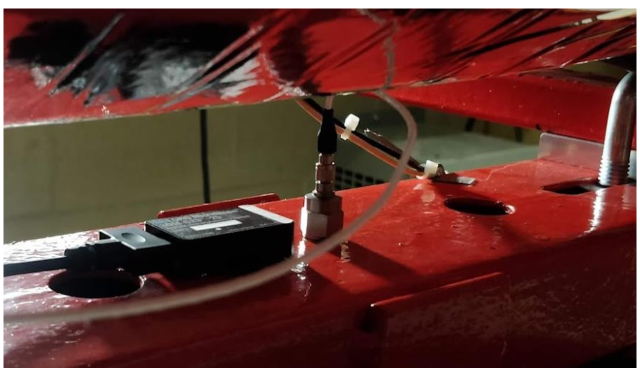

Figure 9. Control accelerometer mounted.

G. *Vibration Response (FEA)*

FEA was used as a design tool to ensure the resonances of the apparatus would not affect test results. Autodesk Inventor (Autodesk Inc., California, United States) was used to perform basic modal analyses on the individual sub-assemblies of the apparatus. The results of the modal analyses are summarized in Table II. Modal vibrations all are predicted to have modal frequencies above the target of 100 Hz with one slight exception. FEA results indicate that the test fixture in the vertical configuration resonates at 89 Hz. This resonance was not located on the isolette loading path and was therefore disregarded.

IV. Vertical Apparatus Evaluation

A. *Challenges*

Initial assembly and tests of the apparatus highlighted several challenges associated with the free-standing vertical apparatus. First, the collective weight of the test specimen (approximately 80 lbs) is close to the upper limit of the shaker's capabilities; a lighter solution may offer more accurate results. Second, adjustability of the fixture in the vertical apparatus is hindered by the isolette's blower motor interfering with the U-bolts. Finally, preliminary measurements indicate that the specimen is experiencing off-axis angular motion.

B. *Testing*

To evaluate the off-axis motion of the test specimen, the pitch and roll of the loaded and unloaded vertical apparatus was measured. To measure the roll and pitch, the adapter piece was instrumented as shown in Figure 10 with two single axis accelerometers (Dytran 3055B1T [6]) at a time. Two tests were performed to observe the pitching and rolling motions The bare adapter was tested first, and the full vertical assembly was tested second. The phase and magnitudes of the opposing accelerometers could be compared to determine if the test specimen is adequately balanced.

C. *Results*

Testing the unloaded vertical adapter revealed an undesirable vibration response at low frequencies. Figures 11 and 12 show the accelerations measured, in g's, for the pitch and roll measurements respectively. Figures 13 and 14 show the phase difference between the measurement accelerometers, in degrees, for the pitch and roll measurements respectively. The pitch measurements show that even the unloaded adapter experiences unpredictable vibrations at low frequencies, with the phase between the ends of the beam differing by as much as 44 degrees.

TABLE II. Summary of FEA Results

FEA Results Summary		
Component Name	*Mode No.*	*Frequency (Hz)*
Vertical Adapter	1	270
	2	528
	3	553
Test Fixture (Longitudinal)	1	117
	2	164
	3	200
Test Fixture (Transverse)	1	151
	2	166
	3	186
Test Fixture (Vertical)	1	89*
	2	126
	3	154
Frame	1	156
	2	184
	3	218

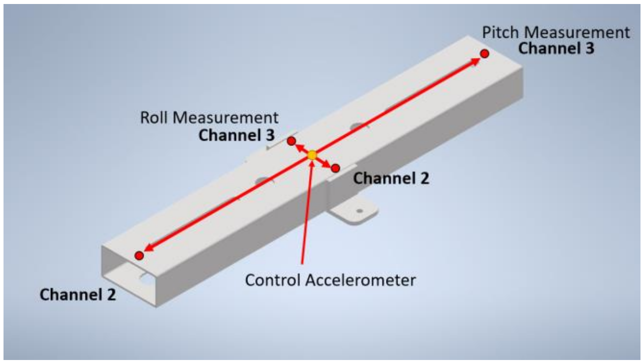

Figure 10. Control accelerometer placement for roll and pitch tests.

V. Discussion

The unpredictable vibration response of the unloaded vertical adapter in the pitching direction indicates an inability to isolate the vibrations to the axis of excitation. This unpredictable behaviour will become exaggerated with the additional off-balance weight of the test fixturing and isolette. To properly limit the excitation of the specimen to the vertical axis, the design must include the second carriage-guide system.

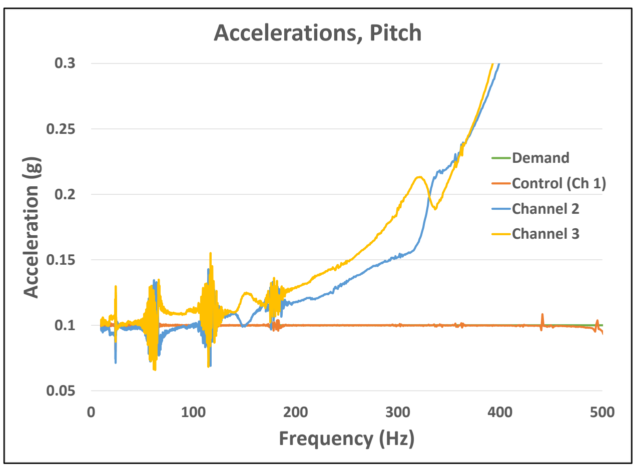

Figure 11. Plot of accelerations in pitching direction.

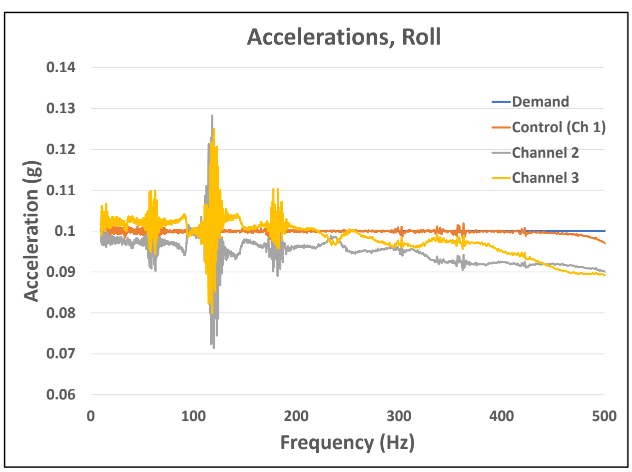

Figure 12. Plot of accelerations in roll direction.

Next steps include finalizing the design and commission of a vertical supporting structure for vertical excitation, characterizing the vibration response of the built apparatus, and proceeding with the parametric study of transport isolette elements.

VI. Future Testing

A. *Parametric study*

Once operational, the test apparatus will be used to conduct a parametric study of the effectiveness of different combinations of manakin weight, mattress type, and harness type at mitigating the vibrations experienced by the patient. The vibration profiles used to perform the tests will be a combination of sinusoidal sweeps, pseudo-random vibrations designed to replicate driving on various road types, and discrete events such as driving over speed humps and cushions, and elements of fixed- and rotary-wing air transport. The vibrations profiles will be based on data collected during on-road testing in collaboration with Ottawa Paramedic Services. The test will measure the performance each permutation, one axis at a time. The study will look at all unique combinations of the test articles listed below. Measurement will

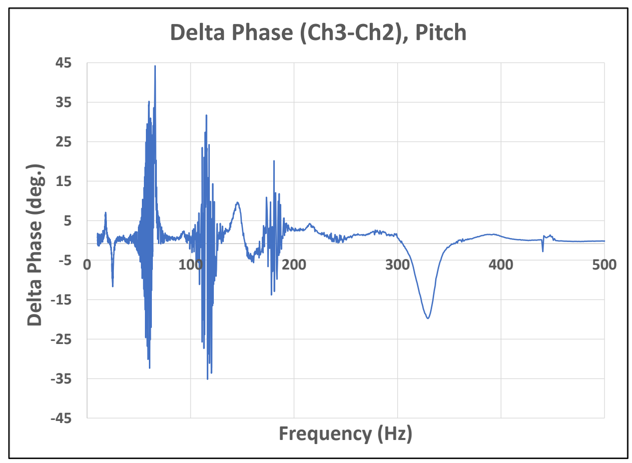

Figure 13. Plot of delta in phase of beam ends in pitching direction.

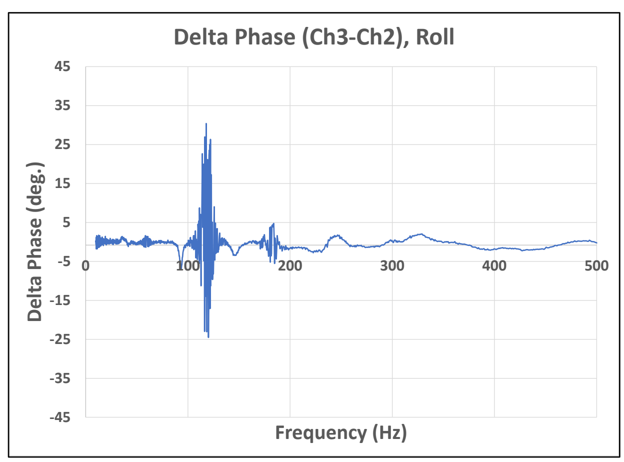

Figure 14. Plot of delta in phase of beam ends in roll direction.

focus on the vibrations experienced at the manakin's chest and head.

B. Test Articles

The full list of test articles can be found in Table III, including all mattresses, harnesses, and manakins.

C. Instrumentation

To minimize the effects of instrumentation on test results, small and light accelerometers were selected. PCB Piezotronics model 356A03 tri-axial accelerometers [7] were selected for their exceptionally small form factor (0.25 in x 0.25 in x 0.25 in) and low weight (1 g). The low weight would cause no change to the manakins' vibration response and the small form factor allows for discrete placement.

VII. Conclusions

In summary, a custom apparatus was designed to use an electrodynamic shaker in evaluating vibrations experienced in a transport isolette when using different mattress and harness combinations. The shaker is secured to the apparatus with a series of toggle clamps and the shaker head bolt directly to the test fixture. The apparatus uses linear guides to restrain the motion of the specimen in the longitudinal and transverse directions while a simple adapter is used to create a free-standing vertical test configuration. Testing revealed that the free-standing vertical apparatus was insufficient in restraining motion to the vertical axis and that a supporting structure and guides are required. Moving forward, a vertical structure will be added to the test apparatus to better support testing in the vertical direction. Once operational, the vibration response of the entire apparatus will be measured, and the parametric study of isolette-level elements can begin.

TABLE III. Parametric Study Test Articles

Test Articles	
Article Type	*Description*
Mattress	International Biomedical stock mattress
Mattress	SleepAngel mattress
Mattress	Geo-Matrix gel mattress, most used by CHEO
Mattress	Turtle Mattress
Harness	International Biomedical stock harness
Manakin	StandInBaby manakin, 4.2 kg, "Scooter"
Manakin	Gel premature infant manakin, 500g
Isolette	International Biomedical transport isolette

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