In-vehicle Measurement of the Apparent Mass of Small Children

J. Giacomin

Dept. of Mechanical Engineering
The University of Sheffield
Mappin Street
Sheffield, S1 3JD
United Kingdom

Abstract

This paper describes an apparatus designed for the purpose of measuring the apparent mass of small children while they ride in a child safety seat in an automobile. The paper begins by introducing the subject of child safety seat vibration and by providing examples of measured data which illustrate the complexity of the problem and the importance of performing apparent mass measurements of children. The apparatus, which uses 2 load cells and an accelerometer, was designed and inserted into a suitable child seat frame. The device was calibrated in the laboratory and road tests were performed in which the apparent mass was measured while travelling over a pave' road surface at 40 km/h. Both a 5.67 kg calibration mass and 6.6 kg child were measured. The high noise content of the results is noted, and methods for performing statistical calculation of the uncertainty bounds are suggested. Differences between the apparent mass measured for the child and that typically found for seated adults is noted.

1 Introduction

Much research had been dedicated to investigating the health [7,12,15,18,19,21,23] and comfort effects of mechanical vibration for adult human beings. Numerous studies have also investigated the vibrational comfort of vehicular primary seating systems [3,4,6,13] and test methods have been proposed for their evaluation [9]. A relatively new area of interest is that of child safety seats [10,11]. These systems have already benefited from research into crash safety issues [1,5,16,20], but postural, vibrational and other comfort issues are just now being addressed. Comfort is an important positive characteristic of any transportation system, hence the interest in providing high levels of vibrational comfort for children. Child comfort would seem important since research to date suggests that small children have well developed sensory capabilities, similar to those of adults [14,22].

2 Child Safety Seats

The heading "child safety seats" includes a number of different products which serve to provide a safe environment for small children when travelling in vehicles. While the main role of the child seat is to provide protection in the case of an accident, comfort is also important as the child can be constrained to remain in the seat for long periods of time.

Presented at the United Kingdom Group Meeting on Human Response to Vibration held at the ISVR, University of Southampton, Southampton, SO17 1BJ, England, 17-19 September 1997.

Since small children are in a period of rapid physical development, anthropometric changes make it necessary to provide a range of products to accommodate children of different ages and sizes. Several countries have adopted a system for defining the age and weight limits for child safety seats. The system of stages used in the United Kingdom is given in Table 1 below.

Stage	Weight	Approximate Age
1	- 10 kg	0 – 9 months
1 & 2	- 18 kg	0 - 4 years
2	9 - 18 kg	6 month - 4 years
2 & 3	9 – 25 kg	6 months – 6 years
3	15 – 36 kg	4 years - 11 years

Table 1) System of stages used for child safety seats in the United Kingdom.

This paper describes vibrational test data relative to Stage 1&2 seats and the children they are intended for. These seats typically have a plastic or Styrofoam basket frame which is covered by cloth and wadding. The cloth is usually either cotton or a polyester blend, while the wadding material is typically polypropylene. For most seats, the wadding and cover are the only soft materials between the seat frame and the child. In a few cases there is also a supplemental foam cushion between the frame and the wadding material. Figure 1 presents a stage 1&2 seat whose vibration properties are described in successive sections of this paper and which served to perform the apparent mass measurements.

Figure 1) Stage 1&2 child safety seat.

3 The Vibrational Environment in Child Safety Seats

Several road tests have been performed at the University of Sheffield in which acceleration signals were measured on the floor on an automobile, at the child seat frame and at the interface between the child and seat. Reference [10] describes road testing results from two child seats which showed that the vibration levels in child seats can be higher than those experienced by the adult driver of the vehicle occupying the vehicle seat. The study of reference [10] also showed that some child seats can produce strong amplification of the acceleration signals with respect to the floor of the vehicle at frequencies above 40 Hz. The general conclusion was that the system composed of vehicle primary seating system, child seat and child did not provide as high a degree of vibration isolation as that afforded the driver who occupied the vehicle seat in the case of the two seats tested.

Reference [11] describes a modal analysis performed on two Stage 1&2 child seats using a small laboratory-based test rig. This study was performed in order to identify the causes of the high frequency (above 40 Hz) vibration amplification found in reference [10]. The study showed that both of the seats had frame resonances in the frequency range of interest for human whole-body vibration (.05-100 Hz) and that the first mode of vibration could be as low as 17 Hz. The seat shown in Figure 1 was among those tested, and was found to be the stiffer of the two seat frames with a first natural frequency of about 35 Hz. The seat had two further resonances in the range of interest for human whole-body vibration. Table 2 lists the seat frame natural frequencies, the modal dampings and the mode shapes in the frequency range up to 100 Hz. The general conclusion of the study of reference [11] was that the first frame resonance could be low enough to be within the frequency range of greatest human sensitivity to whole body vibration, and thus would be likely to cause a worsening of human comfort due to exposure to the vibrating surfaces. It was therefore suggested that it would be important to include the flexible body dynamics of the seat frame in any vibrational modelling of the system when the first resonance frequency is low enough to be of concern for human comfort.

Mode Number	Frequency (Hz)	Modal damping (%)	Shape
1	35.18	5.2	Frame first torsion mode
2	74.05	1.96	Frame lateral bending
3	92.70	2.77	Frame side flapping

Table 2) Vibrational modes up to 100 Hz for the seat of Figure 1.

The seat of Figure 1 has also been road tested over the pave' surface (Mary Street, Sheffield) described in reference [10]. As in reference [10], the test speed used was 40 km/h as is typically the case for automobile and seat ride comfort evaluation [4,9]. At this speed, the pave' surface provides a broadband random input to vehicle, which for all the automobiles tested to date has provided significant vibrational energy up to frequencies in excess of 60 Hz. The pave' surface is shown in Figure 3.

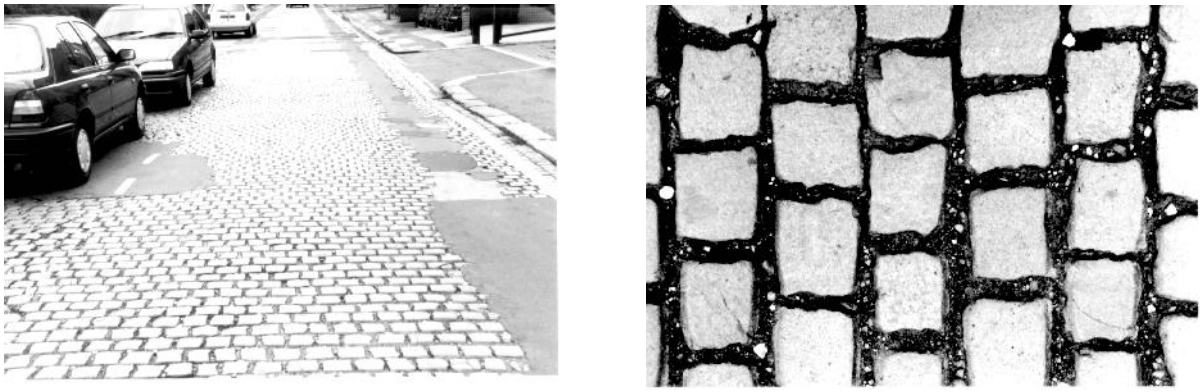

Figure 3) Two views of the pave' road surface of Mary Street.

The vehicle used for testing the seat of Figure 1 was a Citroen BX 1.4 L which had 103,104 km on the odometer at the start of testing. The 165/70 R14 radial tyres, dampers and other suspension components were efficient. Two female adults were present in the vehicle, one driving and the other operating the recording equipment. The driver was 20 years of age, weighed 75 kg and was 1.7 m tall while the passenger was 23 years of age, weighed 68 kg and was 1.6 m in height. In addition to the two adults, a small child participated in the testing by occupying the child seat which was placed in the front seat of the vehicle facing towards the rear. The child was 6 months of age, weighed 8 kg and was 76 cm in height.

Five runs were performed over the pave' surface (which gives about 25 seconds of steady-state vibration data for each run). The 40 km/h test speed was controlled by the driver as best possible using the vehicle's instrumentation. The vertical acceleration was measured at the three points shown in Figure 4. The three point measured were

- the floor of the vehicle next to the rear mounting bolt of the outer guide of the driver's seat
- the underside of the child seat frame where it meets the automobile seat cushion
- the child-bar mounted between the child seat and the child

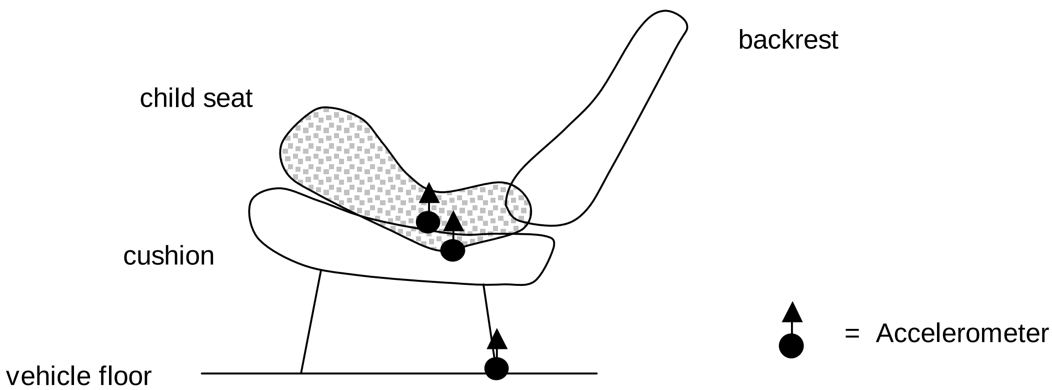

Figure 4) Accelerometer layout used for road testing.

The accelerometer measuring the floor vibrations was held to the vehicle by means of standard accelerometer wax which guarantees adequate coupling in the frequency range up to 100 Hz. The second accelerometer was fixed to the underside of the child seat by means of a mounting stud which was screwed into the plastic frame of the child seat. The third accelerometer was mounted inside a child-bar [10] designed for measuring vibrations at the interface between child seat and child. The child-bar, shown in Figure 5, was 50 mm in diameter and 15 mm in height and was manufactured from aluminium alloy. The weight of each child bar shell is 38 grams, which becomes 44 grams when the PCB model 336C04 accelerometer is installed. The child-bar was placed directly under the buttock region during all tests.

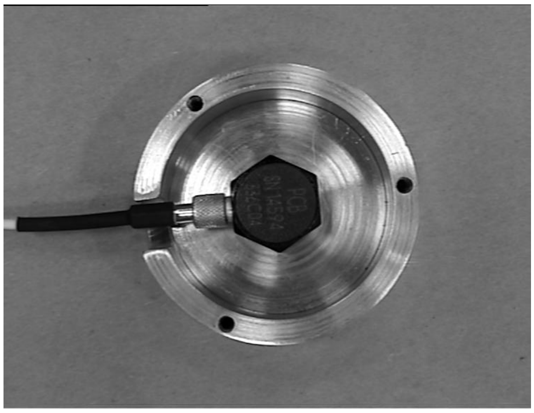

Figure 5) Two views of the child-bar used for testing child seats.

All three accelerometers were PCB model 336C04 accelerometers. The signals were amplified using a PCB model 483A amplifier rack then were recorded using a Kyowa RTP 610 analogue videocassette data recorder. Both the amplifier rack and the tape recorder were run from an independent 24V battery source so as to minimise any noise from the automobile's electronic systems. Data analysis was performed in the laboratory using the time data processing monitor [TMON] of the LMS CADA-X revision 3.4 software system [17]. The LMS software was run on an HP model 715/64 workstation and a Difa Measuring Systems SCADAS II front-end was used. The data was sampled at 300 Hz and a low pass filter was applied which had a 150 Hz cut-off frequency.

Figure 5 presents an example of the road test results for the seat of Figure 1. Figure 5 presents the acceleration power spectral density of the input signal at the floor of the vehicle, the acceleration transmissibility functions from floor to child seat frame and from floor to child-bar, and the relative coherence functions. The acceleration transmissibility functions confirm the modal analysis results for the seat because they show a strong resonance of the child seat frame at 30 Hz , which is slightly lower than the modal analysis results, probably due either to the mass loading of the child or due to the change in boundary conditions.

Figure 5 also shows that the acceleration measured at the child-bar was higher than that of the child seat frame directly underneath for frequencies in the range from 5 Hz to about 25 Hz, with a particularly high peak at roughly 7 Hz. This suggests that the system composed of child seat and child might have had a resonance frequency in the neighborhood of 7 Hz. This result is different from the acceleration transmissibilities for adults occupying vehicle seats. Acceleration transmissibility results for adults on vehicle seats normally show two system resonances, the first in the range from 2 to 5 Hz and the second in the range from 7 to 12 Hz. Child seat acceleration transmissibilities (measured for 3 children to date) have suggested that the natural frequencies of small children may be different from those of adults or, alternatively, that the seat wadding material may be providing a different stiffness than that of vehicle primary seating foams.

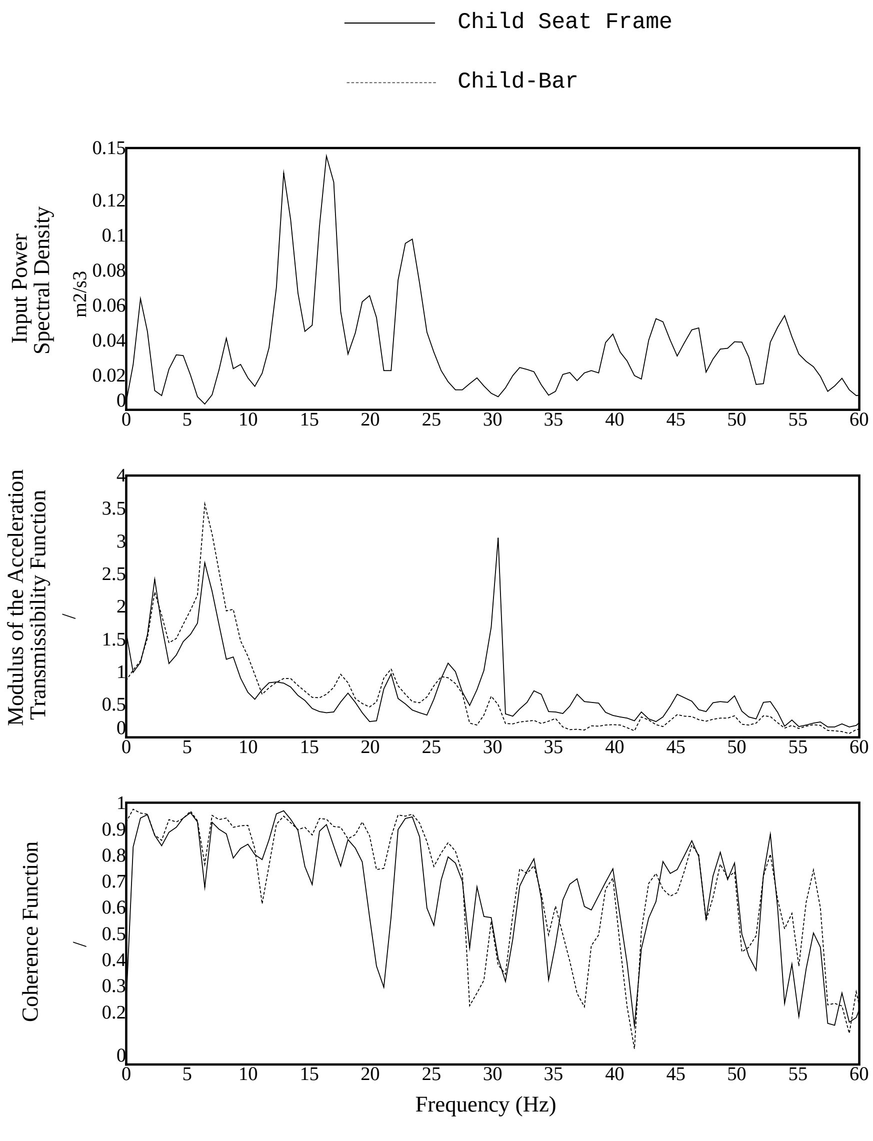

Figure 5) Input acceleration power spectral density, acceleration transmissibility function and coherence function for one run over the pave' surface with the seat of Figure 1.

The results of Figure 5 show many features other than the frame resonances of the seat, and the properties of the child would be expected to play an important role in determining the system dynamics at the lower frequencies. The possibility of differences between the whole-body vibration properties of small children and those known for adults is difficult to evaluate only by means of acceleration transmissibility measurements. Test results such as those of Figure 5 are difficult to interpret because they represent the combined workings of the system composed of the automobile seat, the child seat and the child. It was therefore decided to perform direct measurements of child apparent mass in the vehicle in sitting postures similar to those provided by child safety seats. From the road testing results, and from comparison to the whole-body vibration properties of adults [12], it was anticipated that child apparent mass should be measured in the range up to 20 Hz. The sensor designed to measure child apparent mass while traveling in the vehicle is the subject of the next section.

4 Child Apparent Mass Test Apparatus

Psychological and ethical considerations suggested that testing children in a normal child seat in a normal vehicle would be more appropriate than laboratory testing. To achieve this, an apparent mass sensor (Figure 6) consisting of two load cells, an accelerometer, and two aluminum plates was designed and built which could be mounted in a child seat. The sensor was designed to be as small as possible (given the available instrumentation) so as to have as small an effect as possible on the sitting posture of the child. The total height of the sensor unit (3.3 cm) did not greatly effect the overall sitting posture for the seat of Figure 1 because it had a deep crease between the bottom section and the backrest.

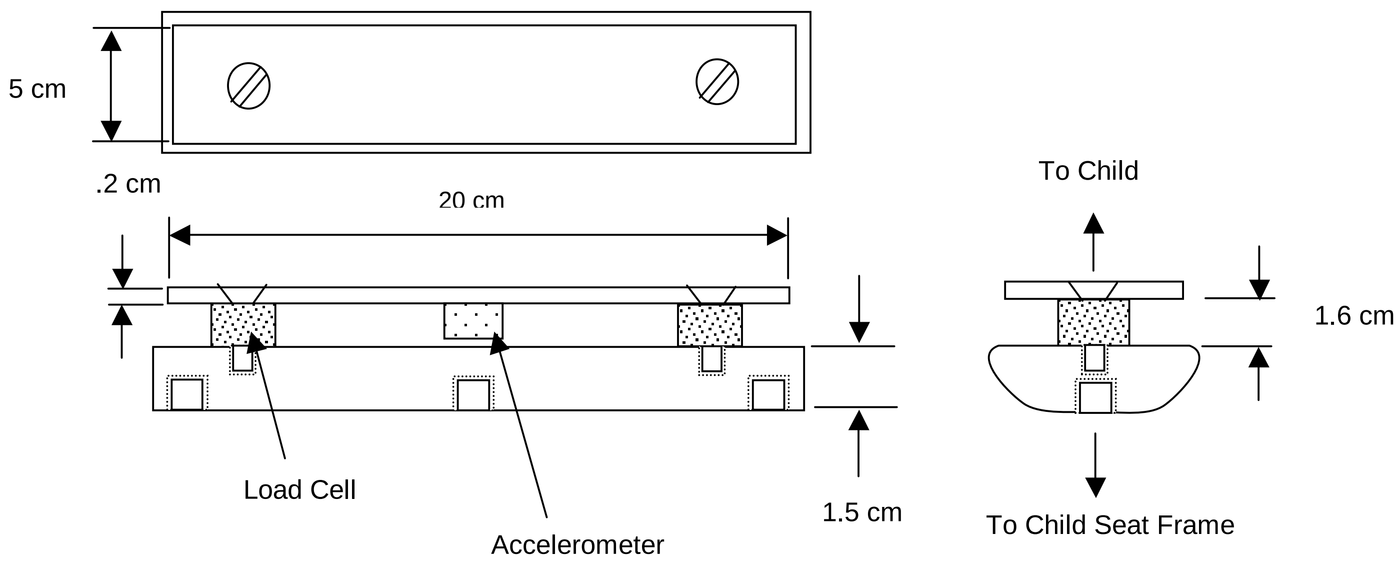

Figure 6) Apparent mass sensor for use in child seats.

From the modal analysis of reference [11] it was found that the seat frame of Figure 1 had a first resonance frequency of 35 Hz when in the travelling position. Road testing results such as those of Figure 5 also suggested that the frame resonance of the seat did not reach frequencies of less than 30 Hz, even when subjected to the mass loading of the child and to the boundary conditions of the vehicle. These observations suggested that the child seat frame could hold the apparent mass sensor without introducing structural resonances into the data in the frequency range up to 20 Hz. The sensor unit was therefore mounted in the child seat by fastening it to the frame by means of three bolts and an outer retainer plate on the underside of the child seat.

Laboratory tests soon showed, however, that this mounting arrangement would not work for the seat of Figure 1 because the plastic frame was too weak. The sensor unit concentrated the mass loading of both the child (simulated in the laboratory by means of a 5.67 kg mass) and the sensor into a very small area around the mounting bolts. This concentrated loading lowered the first resonance frequency of the child seat system to values in the neighborhood of 15 Hz. A general stiffening of the child seat frame was therefore necessary to guarantee a first resonance frequency above 20 Hz. The stiffening was achieved by fastening an external aluminum frame. The complete unit consisting of external frame, child seat frame and sensor unit is shown in Figure 7.

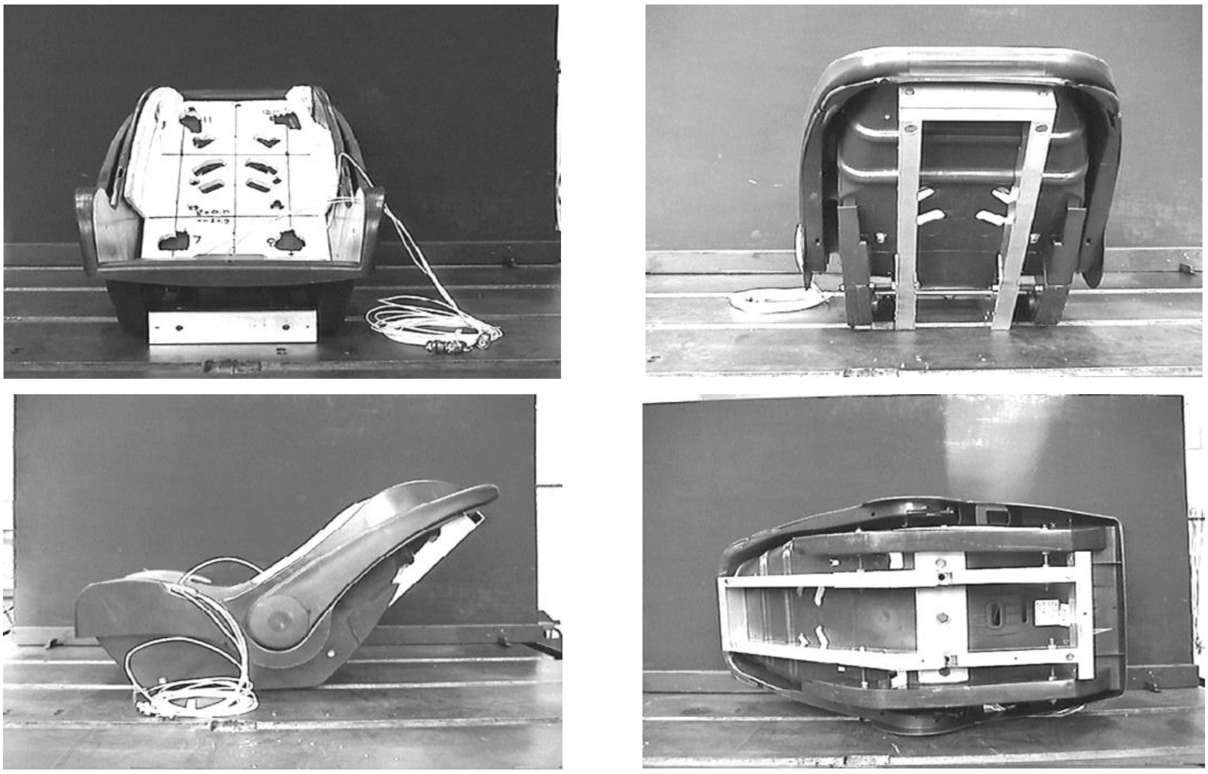

Figure 7) Four views of the child seat and apparent mass sensor.

5 Child Apparent Mass Test Results

The unit composed of the apparent mass sensor and the child seat was tested in the laboratory to check calibration and overall performance. The testing was performed by vibrating the child seat frame at different RMS vibration levels and by calculating the apparent mass of several test masses. The test masses used for the calibration were (including both mass and fixing clamps) 0.264 kg, 0.98 kg and 5.67 kg. The RMS acceleration levels produced at the plate accelerometer were chosen to be similar to those previously measured at the child-bar during road testing. The test signals ranged from a minimum of 0.89 m/s^2 to a maximum of 3.88 m/s^2. The laboratory tests showed that the apparent mass calculations were accurate (errors less than 4 %) for the 0.98 kg and the 5.67 kg masses, but that errors of as much as 60 % could occur at specific frequencies in the range from 1 to 20 Hz with the lowest test mass of 0.264 kg. Since the oscillating mass of small children was expected to be of the order of 1 kg, it was considered appropriate to proceed to road testing to measure the apparent mass of one child.

The road tests were performed on the pave' surface of Mary Street. The test automobile was a Rover 214 SLi with 175/SR14 tyres. The vehicle had 121,502 km on the odometer, suspensions and tyres were efficient. During all tests there were two adults in the automobile, one driving and the other running the recorder. The driver was female, was 35 years of age, weighed 59.2 kg and was 1.68 m in height. The passenger running the recorder was male, 33 years of age, weighed 90 kg and was 1.80 m in height. The tests consisted of 4 runs over the pave' surface with the 5.67 kg calibration mass, and a further 6 runs with a child occupying the seat. The child was 12 weeks old, weighed 6.6 kg and was 62.5 cm in height. The data was recorded and processed as described in section 3 of this paper.

Figure 8 presents the acceleration power spectral density at the measurement plate, the calculated apparent mass, and the coherence function for the 4 test runs with the 5.67 kg mass. The acceleration power spectral density at the interface plate was more concentrated (mostly in the band of frequencies below 18 Hz) than is normally the case for measurements made at the child seat interface with children. As can be seen from Figure 9, the complex vibrational environment inside the automobile (all 6 degrees of freedom) produces noisy apparent mass data. The results from any single run were found to contain large errors at certain frequencies. For example, large errors can be found in the apparent mass curves of Figure 8 at 3.08 Hz (50%), 3.37 Hz (20%), 6.3 Hz (41%), 16.11 Hz (152%), 16.5 Hz (136%) and 18.02 Hz (38%). Frequency domain averaging is required to reduce the measurement error due to the noisy vibrational environment in the automobile. The high coherence values suggest that there were no problems with the sensors or with signal conditioning.

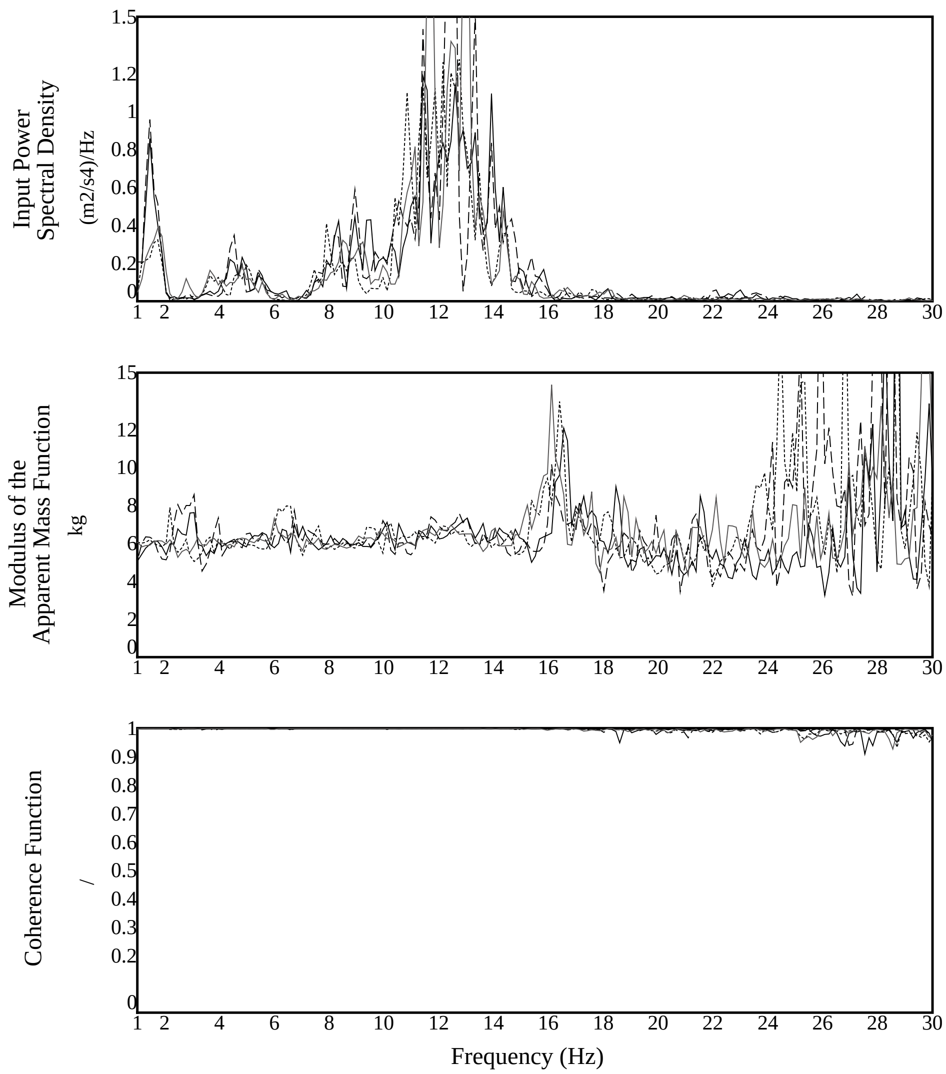

Figure 8) Apparent mass results from the 4 runs over the pave' surface with the 5.67 kg mass.

Figure 9 presents the results from the 6 runs over the pave' surface with the 12 week old child. The power spectral density shows a more even spread over the frequency band up to 30 Hz than was the case with the calibration mass. The apparent mass functions from each run suggest two resonance frequencies, the first in the neighbourhood of 2.3 Hz and the second in the neighbourhood of 6.4 Hz. These frequencies are lower than those normally measured for seated adults. The apparent mass functions are again noisy as with the 5.67 kg mass. Especially large variations in the apparent mass are found in the vicinity of the two resonance peaks. If these were human body resonances, the noise could be explained by the fact that the apparent mass sensor measures force and acceleration at the point of input to the child subsystem, and that both the input force and input acceleration go towards zero for any vibrating system when a resonance condition is attained. Very low signal values at the measurement plate due to a resonance condition lowers the signal-to-noise ratio and makes the ratio calculation of the apparent mass prone to large errors. The behaviour of the coherence functions, which drop somewhat at the two peaks, may support this hypothesis.

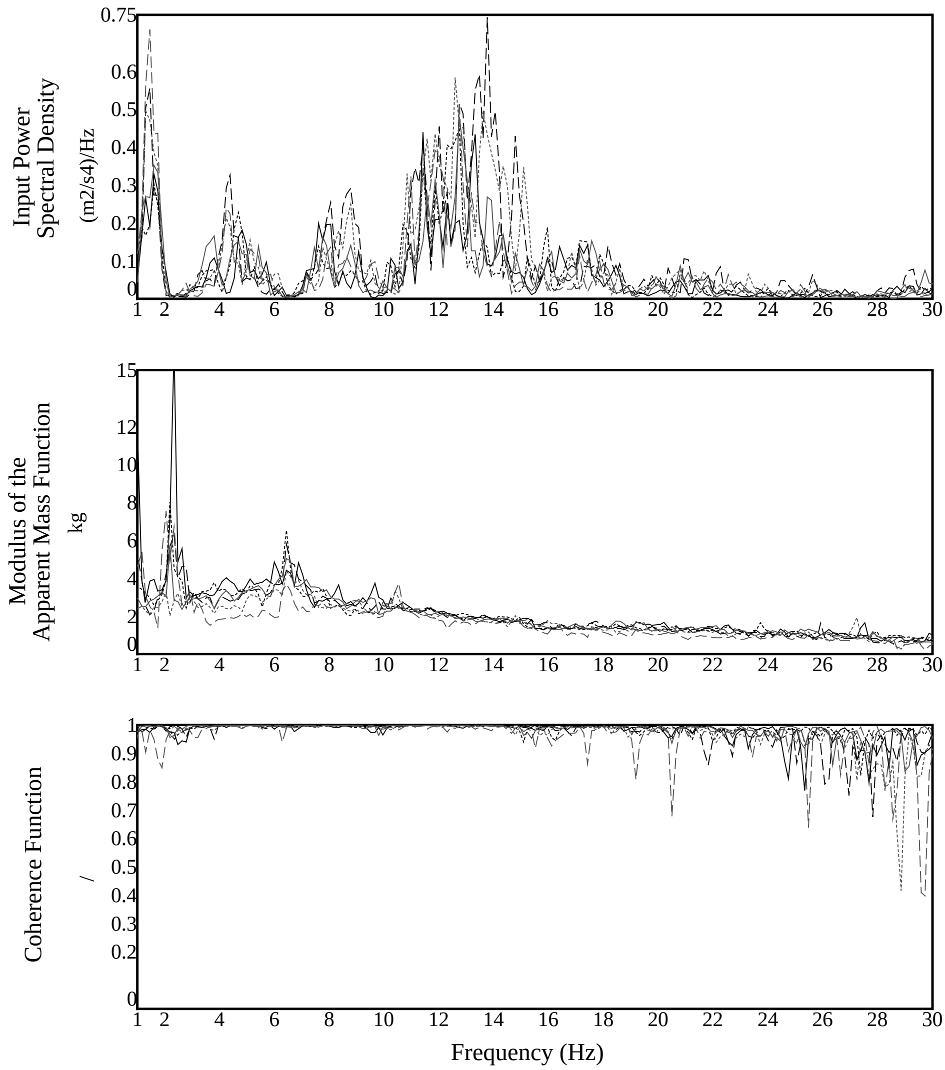

Figure 9) Apparent mass results from the 6 runs over the pave' surface with the child.

Discussion

The results presented in this paper provide insights regarding the vibrational environment in child safety seats. The complexity of the problem suggested the usefulness of measuring child apparent mass as an aid to interpreting experimental acceleration data measured in child seats. A device was designed and built for this purpose, and in-vehicle tests were performed using both a mass and a small child.

The results illustrate the difficulty of performing in-vehicle measurements of vibrating systems. The lack of control over the input vibration spectrum and the problems caused by the simultaneous presence of all 6 movement degrees of freedom of the vehicle make it challenging to accurately measure the desired system properties. The effect of the vehicle vibrational environment can be seen by the high level of noise present on the test signals. Nonetheless, useful results were obtained and new insights gained, and a number of techniques can be applied to improve the apparent mass estimates. For example, averaging the results from the various test runs can be expected to help improve the accuracy of the spectral estimates. Upcoming research will test several small children and will estimate the uncertainty bounds for the averaged results in at least three ways:

- using the normalised random error suggested by Bendat and Piersol which assumes both a Gaussian input signal and a Gaussian error distribution [2]
- by direct calculation of the statistics (mean and standard deviation) at each frequency line
- by calculation of the statistics (mean and standard deviation) using the bootstrap technique[8]

An important issue brought up by this study is that the whole-body resonance frequencies of small children may be different from those of adults. The results suggest that the child had a first resonance in the neighbourhood of 2.3 Hz, whereas a typical seated adult would be expected to have this resonance frequency in the region from 4 to 5 Hz. The second resonance of the seated child appeared to be at about 6.4 Hz, whereas an adult might be expected to have this resonance at frequencies in the range from 7 to 10 Hz [12]. While the work performed to date using only one child is not sufficient to draw conclusions, it is interesting to consider the implications of child natural frequencies being different than those of adults. If this were the case, it would be necessary to evaluate the appropriateness of the comfort weightings defined by standards [12] such as BS 6841 and ISO 2631. Since the human whole-body resonance would be expected to be important towards defining human sensitivity to whole-body vibration, it would appear possible that the comfort weighting curves for small children might necessarily be different from those of adults because of the different natural frequencies involved.

Acknowledgements

The author would like to express his thanks to Mrs. Heather Worden and Ms. Josephine Phua for providing the vehicles, and for their help with the testing. Thanks are also do to Dr. Fabrizio Scarpa for his assistance with the road tests and for his suggestions regarding the contents of this paper. Thanks are also due to Mrs. Suzanne Came for her help, and above all to Louis Alexander Came and to Callum, the children whose participation made this research possible.

References

[1] Bell, R., Burleigh, D. and Czernakowski, W. 1994, ISOFIX: The potential of a universal vehicle/child restraint interface for misuse reduction and performance enhancement, SAE paper 942220

[2] Bendat, J.S. and Piersol, A.G. 1980, Engineering applications of correlation and spectral analysis, John Wiley & Sons, New York

[3] Berger, E. and Gilmore, B.J. 1993, Seat dynamic parameters for ride quality, SAE paper 930115

[4] Brite Euram Project 5549 Advanced Technologies for Automotive Seat Evaluation and Design 1995, 30 Month progress report for the European Commission, Contract BRE2-CT92-0246 (SED)

[5] Carlsson, G., Norin, H. and Ysander, L. 1991, Rearward-facing child seats: the safest car restraint for children ?, Accid. Anal. Prev., Vol. 23, No. 2-3, pp 175-182

[6] Corbridge, C., Griffin, M.J. and Harborough, P.R. 1989, Seat dynamics and passenger comfort, Proc. Instn. Mech. Engrs., Vol. 203, pp 57-64

[7] Dupius, H. and Zerlett, G. 1986, The effects of whole-body vibration, Springer-Verlag, Berlin

[8] Efron, B. and Tibshirani, R.J. 1993, An introduction to the bootstrap, Chapman Hall, 1993

[9] Giacomin, J. and Bracco, R. 1995, An experimental approach for the vibration optimisation of automotive seats, ATA 3rd Int. Conf. on Vehicle Comfort and Ergonomics, Bologna, Italy, March 29-31, pp 199-208

[10] Giacomin, J. 1996, Vibration characteristics of child safety seats, Conference Metodologie per l'Ergonomia, Torino, Italy, 21 November

[11] Giacomin, J. 1997, Modal properties of child safety seats, ATA 4th Int. Conference on Comfort in the Automobile Industry, Bologna, Italy, Oct. 2-3

[12] Griffin, M.J. 1990, Handbook of human vibration, Academic Press, London

[13] Joyce, J. and Dunn, W.H. 1992, Evaluation of seat design parameters for improved occupant ride, IMechE paper 925172

[14] Kaufmann, F. 1995, Development of motion perception in early infancy, European Journal of Pediatrics, Vol. 154, No. 9, S4, s48-s53

[15] Kelsey, J.L. 1975, An epidemiological study of the relationship between occupations and acute herniated lumbar intervertebral discs, Int. Journal of Epidemiology, Vol. 4, No.3, pp 197-205

[16] Kuhane, C.J. 1986, An evaluation of child passenger safety: the effectiveness and benefits of safety seats, DOT-HS-806-890, National Highway Traffic Safety Administration, Washington D.C.

[17] LMS International 1996, LMS CADA-X Modal Analysis Manual, Revision 3.4, LMS International, Leuvan

[18] McLain, R.F. and Weinstein, J.N. 1994, Effects of whole body vibration on dorsal root ganglion neurons, Spine, Vol. 19, No. 13, pp 1455-1461

[19] Necking, L.E., Dahlin, L.B., Friden, J., Lundborg, G., Lundstrom, R. and Thornell, L.E. 1992, Vibration induced muscle injury, The Journal of Hand Surgery, Vol. 17B, No. 3, June, pp 270-274

[20] Pedder, J., Legault, F., Salcudean, G., Hillebrandt, D., Gardner, W. and Labrecque, M. 1994, Development of the CANFIX infant and child restraint/vehicle interface system, SAE paper 942221

[21] Pope, M.H. and Hansson, T. 1992, Vibration of the spine and low back pain, Clinical Orthopaedics and Related Research, No. 279, June, pp 49-59

[22] Roessler, J.S. and Dannemiller, J.L. 1997, Changes in human infants' sensitivity to slow displacements over the first 6 months, Vision Res., Vol. 37, No. 4, pp 417-423

[23] Wilder, D.G., Frymoyer, J.W. and Pope, M.H. 1985, The effect of vibration on the spine of the seated individual, Automedica, Vol. 6, pp 5-35