AN EXPERIMENTAL APPROACH FOR THE VIBRATION OPTIMISATION OF AUTOMOTIVE SEATS

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This paper discusses an experimental approach for the vibrational optimisation of automotive seats. Vehicle mission profiles, a test bench and S.E.A.T. indices are combined to produce an objective evaluation of the vibration isolation properties of the seat with human occupants aboard. The test procedure described in this paper is currently being used to test prototype seat designs so as to select those seat designs which provide the best possible vibration characteristics for a given vehicle environment.

Introduction

There are several automobile subsystems that contribute to the overall vibrational comfort of passenger automobiles. These subsystems include the tyres, main suspensions, engine suspensions, car body and seat. Of these subsystems, the seat is especially important since it is one of the few components of the automobile that comes into direct contact with the human occupant. The vibration isolation properties of the seat are not only important, but also difficult to study since the dynamics are strongly affected by the human occupant. The measured dynamics are in reality those of the coupled man/seat system, and a good seat design must provide effective isolation when coupled to a wide range of human occupants.

Significant effort [1,2,3] has been invested recently at the Fiat Research Centre (CRF) towards establishing a testing procedure for quantifying the vibration characteristics of automobile seats. This paper presents a brief overview of the various problems that were addressed during the course of the research. The final sections conclude with the flowchart of the test procedure and an example of some test data.

Seat vibration missions

One of the most difficult aspects of the vibration testing of automobile systems is the definition of the vibration mission. In the case of car seats, the establishment of accurate vibration missions is particularly important since both the human occupant and the seat are non linear in nature. This intrinsic non linearity causes the system response to vibration inputs to be a function of both the physical characteristics of the man/seat system and the vibration input itself [6,12].

The first step towards selecting vibration missions for seat testing was to study the design objectives issued for new automobiles. Marketing departments perform statistical analysis of the habits of the driving public so as to determine design objectives for the automobiles of each market segment. One of these design objectives is the percentage of the useful life of the vehicle that will be spent driving in various environments, the main three environments being city driving, country driving and highway driving. From this starting point, it was necessary to identify test tracks that could be associated with each of the three driving conditions. An exercise was undertaken so as to determine one track and one automobile driving speed (over the track) for each condition.

The mission exercise consisted of a series of tests in which a group of drivers drove various automobiles for several days, then filled out subjective questionnaires regarding the vibrational behaviour of the vehicle. These same automobiles were also tested on the Fiat test tracks, and a statistical correlation was performed between the answers (on a five point scale) to the various parts of the questionnaire and the acceleration data measured at several points along the vehicle [1,9]. The test tracks and the automobile speeds that best correlated with the subjective judgements of the drivers were then formalised as those for comfort testing and are listed in Table 1 below.

FIAT Test Track	Driving condition for which this track is representative	Automobile Speed
Pave'	City driving	40 Km/h
Comfort	Country driving	60 Km/h
Highway	Highway driving	100 Km/h
Rectangular Obstacle	Bumps in road or potholes	50 Km/h
Railroad crossing	Railroad crossing	20 Km/h

Table 1) Test tracks and automobile speeds obtained from the mission analysis exercise.

Only three of the five tracks were selected for seat testing. The first is the Pavè track which consists of cobblestones, and thus corresponds to driving conditions often found in historic city centres. The second is the Comfort track which is an asphalt segment with irregular deformations which approximates a poorly kept country road. The final track is the Highway track, which is a length of smooth asphalt such as that found on a typical European highway. The rectangular obstacle and the railroad crossing were deleted from the testing program for several reasons. The first is that it is difficult to estimate how often the average driver will encounter these types of events during city, country or highway driving. A second consideration is that while the three tracks that were selected produce steady state vibrations, the rectangular obstacle and railroad crossing produce transient events with rather high crest factors. These signals tend to strongly excite system non linearities, thus producing difficult to interpret system response functions [6,12].

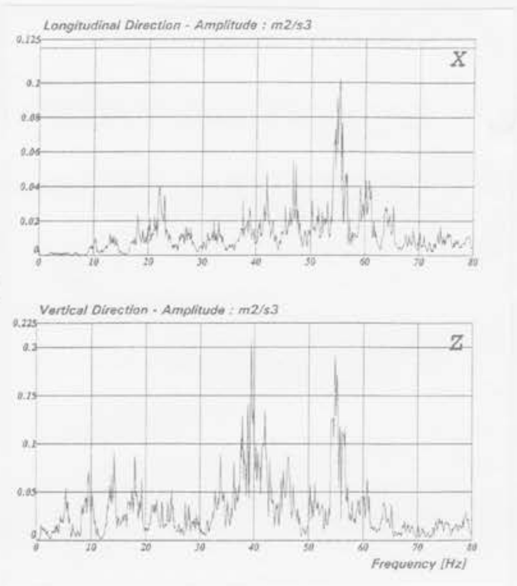
For a given track, the test speed which provided the highest correlation with the judgements of the test jury was selected. Comparison of these values with the results of statistical analysis performed on data [15] relative to the Italian driving public showed that the selected speeds are very close to the average value over the given road surface.

Two reference axis were selected for defining the seat vibration mission. These axis are the vertical and the horizontal (fore-aft) in the plane of the automobile, and are labelled as Z and X in this paper. These two axis were selected because they are usually the directions with the highest vibration levels in normal production automobiles, because the human occupant is very sensitive to vibrations in these directions, and also for simplicity since no rotations need be reproduced in the laboratory.

An important aspect that needed defining was the placement of the seat guide accelerometer for measuring the vibration mission. A study [3] was performed with three automobiles in which the vertical and longitudinal accelerations were measured at each of the four mounting bolts of the seat guides. Third octave and narrow band spectral analysis were performed, and it was seen that large differences often existed between the acceleration signals measured at the different points. These differences were found to be mainly associated with frequencies above 30 Hz, however, where human vibration perception is much reduced. Filtering the acceleration data with the BS 6841 whole-body vibration perception filters [4] showed that the overall vibration levels were similar (after filtering) regardless of which mounting bolt was chosen as the measurement point. This result indicated that only one measurement point was required on the seat guides for obtaining the seat vibration mission. This point was chosen as the rearmost mounting bolt of the outer seat guide of the driver's seat.

Figure 1 presents the seat vibration missions of a Fiat automobile. As can be seen from the data, the Pavè track produces seat guide acceleration signals in which most of the energy is concentrated at the high end of the frequency spectrum, above about 40 Hz. The Comfort track, instead, produces seat guide acceleration signals in which most of the energy is concentrated below 40 Hz. The last track, the highway track, produces seat guide accelerations at both low and high frequencies localised specifically at the resonance frequencies of the automobile chassis and tyres. The three tracks selected for seat testing therefore provide a good set of test signals since one produces low frequency excitation, another produces high frequency excitation and the third tests the response of the man/seat system to only the resonant frequencies of the tyres and chassis.

a)



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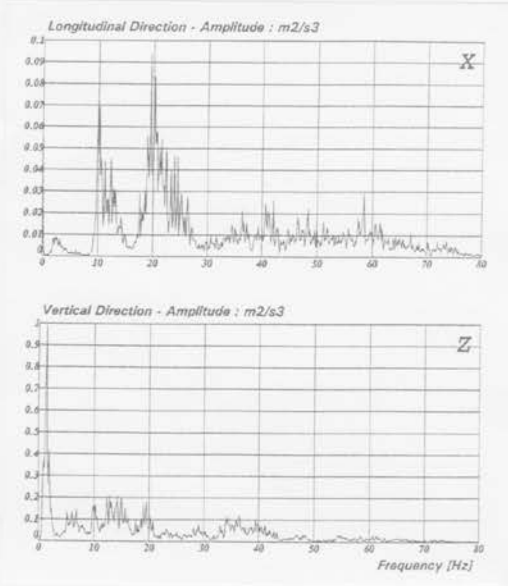

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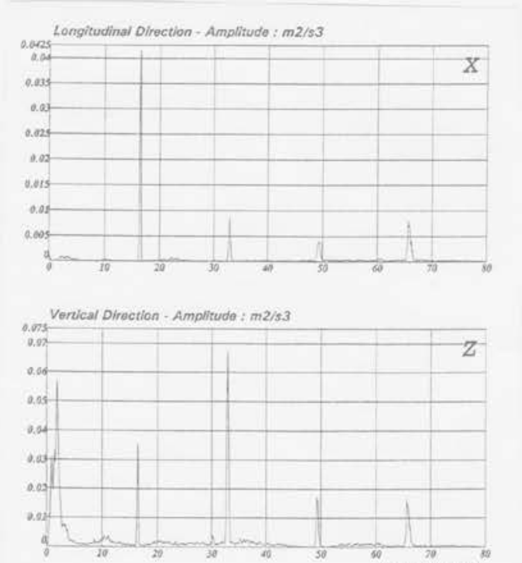

Figure 1) Vibration missions for seat testing.

a) Pavè
b) Comfort
c) Highway

Human test subjects

An important part of any seat testing procedure is the consideration of human variability [11,13,16,17]. An optimal seat must provide the best possible behaviour over as wide a range of human occupants as possible. In order to facilitate the choosing of human subjects, 15 anthropometric variables were measured for each of 85 staff members in CRF so as to constitute an internal anthropometric data base. The overall statistics of the current CRF anthropometric data base are presented in Table 2 below. All length and weight values are given to only one place past the decimal point since this is roughly the maximum accuracy of the measurements. Subject age has been rounded to the nearest year.

Male Subjects				
Measure	Min	Max	Average	Std. Deviation
Age [years]	22.0	50.0	34.4	7.9
Weight [Kg]	59.5	102.4	76.7	10.5
Overall Height [cm]	162.0	192.8	175.0	7.5
Acromial Height [cm]	130.5	159.7	142.3	7.0
Trochanteric Height [cm]	77.5	98.6	87.5	5.1
Lateral Malleolus(ankle) Height [cm]	5.4	8.9	7.1	0.7
Horizontal Arm Reach [cm]	70.7	83.9	76.5	3.4
Knee Height [cm]	49.4	61.8	54.2	2.9
Hip Breadth [cm]	33.4	40.3	36.7	1.9
Buttock to Popliteal Length [cm]	50.1	63.6	55.2	2.9
Erect Sitting Height [cm]	52.2	95.8	87.3	7.0

Female Subjects				
Measure	Min	Max	Average	Std. Deviation
Age [years]	22.0	52.0	32.5	10.1
Weight [kg]	50.7	70.0	57.4	5.8
Overall Height [cm]	142.5	178.5	161.6	7.7
Acromial Height [cm]	116.0	143.1	131.1	6.4
Trochanteric Height [cm]	72.9	89.7	81.5	4.3
Lateral Malleolus(ankle) Height [cm]	5.2	7.4	6.3	0.6
Horizontal Arm Reach [cm]	62.5	75.2	68.9	2.9
Knee Height [cm]	43.1	54.9	49.1	2.8
Hip Breadth [cm]	33.8	40.6	36.6	1.8
Buttock to Popliteal Length [cm]	49.4	57.2	53.1	2.8
Erect Sitting Height [cm]	75.3	91.7	84.1	4.5

Table 2) Anthropometric statistics of the CRF data base.

Of the anthropometric variables measured, the weight, hip breadth and sitting height were considered to be very important towards determining the vibration characteristics of the man/seat system. The weight and hip breadth were considered important because these two parameters give an idea of the average pressure that is exerted on the seat cushion. Seat cushions are often made of polyurethane foam whose mechanical characteristics are very sensitive to the loading acting on them. The sitting height of the human occupant was also considered important because it provides a very simple information related to the inertia characteristics of the upper body of the human subject. A correlation analysis between the test results and the anthropometric data of the subjects still needs to be performed, but initial data suggests that the three parameters are quite important in determining the vibration characteristics of the man/seat system.

Seat vibration test system

Seat vibrational mission reproduction requires the simultaneous and sequential actuation, along orthogonal directions, of the mission signals (in displacement, velocity, acceleration or force). A testing bench was constructed specifically for the purpose of studying the vibrational behaviour of the man/seat system. The bench develops horizontal and vertical bi-axial vibration through the use of a 0.6 X 0.6 meter table attached to Shinken electrodynamic vibration generator assemblies. The bench was designed so as to have an adequate dynamic stiffness, low waveform distortion (less than 10% as measured on the table surface) and low cross-talk values between the orthogonal movements (less than 10% as measured on the table surface) in the frequency range of human sensitivity to whole-body vibration (from 0 to 100 Hz).

The vibration generator assembly of the test bench is composed of three separate driving elements. Two of these elements (of the push-pull type) generate the X axis vibration, while the third generates the Z axis vibration. The elements are guided by a unique hydrostatic bearing which provides smooth axial movements with low mechanical friction and low cross-talk values. The bench currently provides two axis vibration generation but has been designed so as to be expandable up to 3 axes in the future. The analysis of mission signals from several production automobiles led to the specification of the maximum displacement, velocity and acceleration levels which were:

stroke of ± 25 mm along the two orthogonal axis
velocity of 1.2 m/s along the two orthogonal axis
acceleration of up to 30 m/s2 along the two orthogonal axis (with a 200 kg payload)

The bench control system consists of a multi-axial, cross-coupled digital control which guarantees accurate reproduction of the reference signals (in both amplitude and phase) at user selected measurement points on the object being tested (the reference point for seat testing is the seat guide). The control algorithm is based on multi-input-multi-output (MIMO) techniques which optimise the transfer function matrix (TFM) between the drive signals and the responses of the measurement points on the test structure. The vibration bench and control system are shown in Figure 2.

The data acquisition and signal processing system is based on the LMS CADA-X platform which runs on an HP/9000 392 workstation. The system includes a Difa-Scadas measurement front-end for signal generation, acquisition, amplification and conditioning. Seat testing routines were written using the LMS User Programming facilities.

Figure 3 presents the accelerometer layout used for the seat testing activities described in this paper. Two Bruel & Kjaer type 4368 accelerometers were mounted on the bench table near the seat guides. These two accelerometers were used to measure the vertical and longitudinal acceleration input to the man/seat system, and as such were considered to be the seat guide channels. This was acceptable because the bench table is rigid at all frequencies contained in the vibration mission (from 0 to 100 Hz). Two Bruel & Kjaer type 4322 seat pads were attached to the seat cushion and backrest so as to measure the acceleration at the man/seat interface.

The test bench is equipped with safety devices for testing with people aboard. The various safety systems were designed in accordance with the indications provided by British Standard 7085 [5]. A seat testing cell was built at CRF, and is presented in Figure 4. The cell design places the man/seat system at ground level, guarantees constant environmental conditions (noise, temperature, etc.) and adequate comfort for the human test subjects.

Seat position

A series of vibration tests were performed to study the effect of the sitting posture of the human occupant on the measured results. These tests were performed using both standard vibration test signals (band limited white noise and sine waves) and the three vibration missions. The results [2,3] of the testing program showed that the sitting posture of the human subject played a large part in determining the vibration response of the man/seat system. The data suggests that the differences caused by the sitting position can be as large as those between different seat designs. The backrest angle was found to be very influential on the vibration characteristics relative to the vertical direction. Both leg position and backrest angle were found to be of similar importance in determining the response in the longitudinal direction.

The influence of the sitting posture on the vibration testing results was expected. For example, the mass of the two legs (up to 30% of the total body weight) is supported differently depending on the sitting posture of the human subject. An angle between Femur and Tibia of roughly 90 degrees places most of the mass of the two legs directly on the footrest. A much larger angle begins, instead, to approximate a situation where the human subject lifts his or her legs completely from the floor, maintaining them in the air by means of muscular reactions which must be supported on the seat. Similar arguments can be put forward in the case of the backrest angle. There is also an additional problem at the backrest since changes of the backrest angle also change the direction of the measurement axis of the accelerometers trapped between the human subject and backrest.

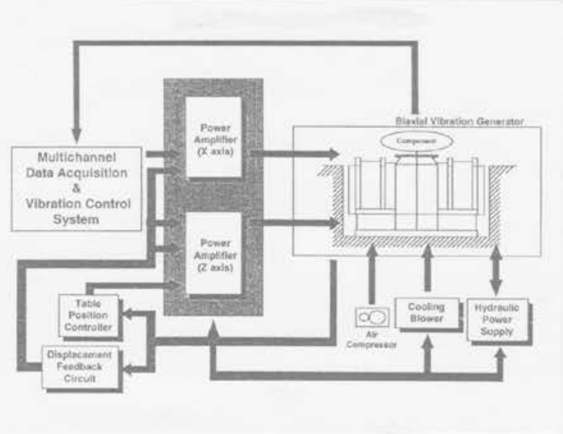

Figure 2) Seat vibration test system.

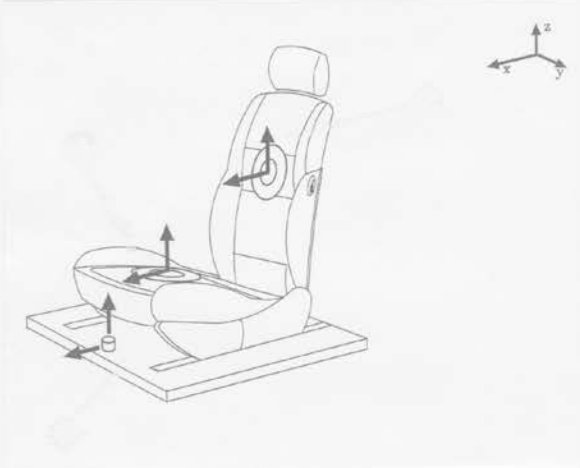

Figure 3) Accelerometer layout.

Figure 4) CRF Seat testing cell.

The information obtained to date suggests that a standard sitting posture is required in order to permit comparisons between different seat designs. The current testing activity is concentrating on a sitting position defined by a fixed backrest angle of 23 degrees with respect to the vertical axis and an angle between Tibia and Femur of 115 degrees. These angles have been taken from previous experience and from the literature [10,18].

S.E.A.T. INDICES FOR THE MAN/SEAT SYSTEM

The S.E.A.T. index

The synthetic measure selected for the purposes of large scale seat rating is the S.E.A.T. index [11]. This index is useful because it reduces the vibration isolation properties of the seat to a single set of percentages. The S.E.A.T. index is defined as

$$S.E.A.T.\ \ [\%] \ = \ 100 \sqrt{\frac{\int G_{ss}(\omega)\, W^2(\omega)\, d\omega}{\int G_{ff}(\omega)\, W^2(\omega)\, d\omega}}$$

where

$$G_{ss}(\omega) = \text{acceleration power spectral density measured at the seat (seat pad).}$$

$$G_{ff}(\omega) = \text{acceleration power spectral density measured at the floor (seat guide).}$$

$$W(\omega) = \text{human perceived disturbance weighting for the relative vibration axis.}$$

This index is the ratio of the disturbance perceived by the passenger when sitting on the test seat and the disturbance that the passenger would have felt if the seat were rigid in the frequency range of interest. The S.E.A.T. index contains the three principal components required of any vibration isolation index, namely the input spectrum (vibration mission), the human vibration perception filters [7,8,11] and the input/output characteristics of the man/seat system. The input spectrum (mission) is a necessary part of the seat rating procedure because the seat, and above all the human occupant, are non linear in nature and therefore respond very differently when subjected to different vibration inputs. The BS 6841 human perception filters [4] are important because the objective of the seat system is to reduce the vibration disturbance perceived by the human seat occupant. The final ingredient is the ratio of disturbances which provides a simple model of the input/output characteristics of the man/seat system.

An example

Figure 5 presents a flow chart of the testing procedure developed from the work completed to date. This procedure has been standardised and is in use for testing current and new seat designs. An example of the use of this test method is given by the data of Table 3 which presents the results from a current production seat. The vibration missions for this seat are those of Figure 1. From the data of Table 3 it can be seen that the S.E.A.T. values are highly dependent on the vibration mission. The S.E.A.T. values rise when passing from Pavè to Comfort to Highway in the case of the measurements made at the seat cushion while they decrease, instead, for the measurements made at the backrest in the Z direction. The data of Table 3 (and from the all tests performed to date) suggest that a seat design which is optimal for a particular vibration mission may not be optimal for a different mission.

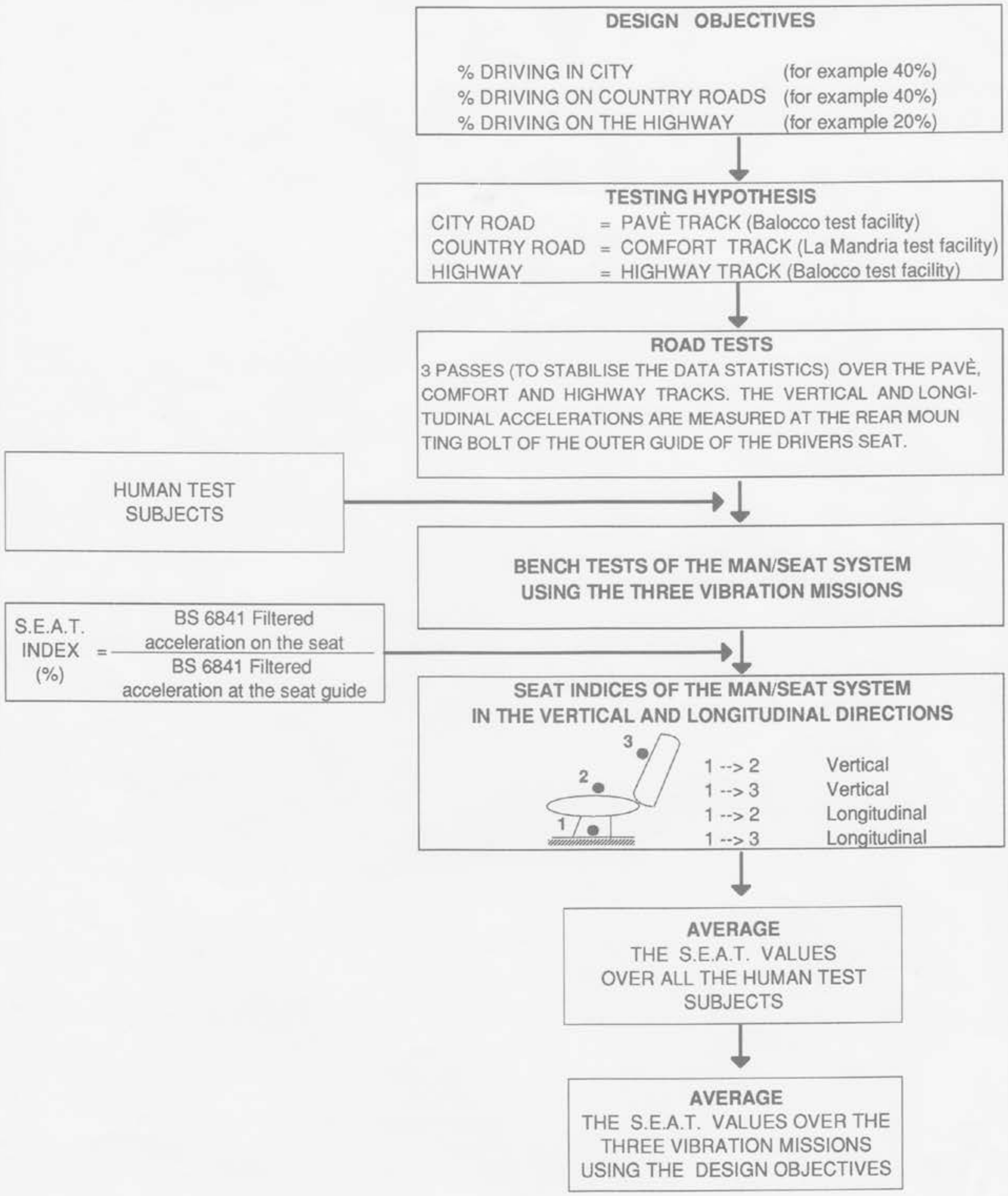

Figure 5) Seat vibration testing procedure.

Measurement point	Pavè track	Comfort track	Highway track	Average
X - seat cushion	138	184	234	176
Z - seat cushion	62	72	93	72
X - backrest	271	307	363	304
Z - backrest	104	80	73	88

Table 3) S.E.A.T. indices for a FIAT seat averaged over four test subjects.

In order to choose a seat design for a particular automobile it is therefore necessary to weight the three base missions by the design objectives of the automobile so as to obtain the average rating. The column of Table 3 that is labelled as average uses the design objectives of

City driving	40 %
Country driving	40 %
Highway driving	20 %

From the data of the average mission column it can be seen that the seat produced reductions in the vibration disturbance (values less than 100 percent) in the vertical direction, but amplifications for the longitudinal direction. This tendency is typical of many seats tested to date.

CONCLUSIONS AND RECOMMENDATIONS

A testing procedure has been formalised for the purpose of quantifying the vibration isolation properties of seats with human occupants. The procedure makes use of automobile mission profiles, a test bench and S.E.A.T. indices. This testing procedure has been applied to several seats, one of which has been presented in the data of this paper.

The testing procedure described in this paper is straightforward, but provides useful information for selecting between seat designs for what regards vibrational comfort. The procedure has provided promising results and will be further improved in the upcoming months.

Among the topics that will be addressed in the coming months is that of how many human test subjects should be used so as to guarantee representative statistics. A closely related topic is the correlation analysis that will be performed between the test results and the anthropometric data of the subjects so as to identify the most important characteristics to look for when choosing subjects for the tests. A final subject is the testing of parametric seats, which will serve to evaluate the influence of various seat design parameters on the obtained vibration properties.

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REFERENCES

[1] Brite Euram Project 5549, 6 month progress report, (1993)

[2] Brite Euram Project 5549, 12 month progress report, (1993)

[3] Brite Euram Project 5549, Midterm progress report, (1994)

[4] British Standards Institution, Measurement and evaluation of human exposure to whole-body vibration and repeated shock, BS 6841 (1987)

[5] British Standards Institution, Safety aspects of experiments in which people are exposed to mechanical vibration and shock, BS 7085 (1989)

[6] Brown, D., Carbon, G. and Ramsey, K., Survey of excitation techniques applicable to the testing of automotive structures, SAE paper 770029 (1977)

[7] Coren, S. and Ward, L., Sensation and perception, Harcourt Brace Jovanovich, London (1989)

[8] Dupuis, H. and Zerlett, G., The effects of whole-body vibration, Springer-Verlag, Berlin (1986)

[9] Giuliano, F. and Ugo, A., Experimental assessment of ride comfort: a statistical approach, ATA 2nd International Conference on Vehicle Comfort, Bologna (1992)

[10] Grandjean, E., Sitting posture of car drivers from the point of view of ergonomics, Human Factors in Transport Research (Edited by D.J. Osborne and J.A. Levis) Academic Press, London (1980)

[11] Griffin, M.J., Handbook of human vibration, Academic Press, London (1990)

[12] Halvorsen, W. and Brown, D., Impulse techniques for structural response testing, Sound and Vibration, pp 8-21, November (1977)

[13] Kroemer, K.H.E., Kroemer, H.B. and Kroemer, K.E., Ergonomics: how to design for ease and safety, Prentice Hall, Englewood Cliffs, New Jersey (1994)

[14] LMS CADA-X Fourier Monitor Manual, Revision 3.2, LMS International, Leuvan (1992)

[15] Marchesani et al, Integrated method to define the mission profile of a passenger car, ATA International Conference, Florence (1992)

[16] Pheasant, S., Bodyspace: Anthropometry, Ergonomics and Design, Taylor & Francis, London (1988)

[17] Sanders, M.S. and McCormick, E.J., Human factors in engineering and design, McGraw-Hill Inc., New York (1992)

[18] Troup, J.D.G., Drivers back pain and its prevention, Applied Ergonomics, Vol. 9, Pg 207-214 (1978)