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THE INFLUENCE OF END-STOP BUFFER CHARACTERISTICS ON THE SEVERITY OF SUSPENSION SEAT END-STOP IMPACTS

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Suspension seat end-stop impacts may be a source of increased risk of injury for the drivers of some machines and work vehicles, such as off-road vehicles. Most suspension seats use rubber buffers to reduce the severity of end-stop impacts, but they still result in a high magnitude of acceleration being transmitted to drivers when an end-stop impact occurs. An experimental study has been conducted to investigate the effect of buffer stiffness and buffer damping on the severity of end-stop impacts. The results show that the end-stop impact performance of suspension seats with only bottom buffers can be improved by the use of both top and bottom buffers. The force–deflection characteristics of rubber buffers had a significant influence on the severity of end-stop impacts. The optimum buffer should have medium stiffness which is nearly linear and occurs over a long deflection, without being compressed to its high stiffness stage. It is shown, theoretically, that buffer damping is capable of significantly reducing the severity of end-stop impacts. However, since current rubber material provides only low damping, alternative materials to those in current use, or either passive or active damping devices, are required.

1. INTRODUCTION

It is believed that severe shocks and vibration encountered by some off-road vehicle drivers may induce various disorders in the human body, particularly low back injury [1]. Although these shocks and vibration can often be reduced by a suspension seat, end-stop impacts, occurring when the suspension reaches the end of its travel during exposure to low frequency high magnitude motion, may result in an increased risk of injury. Adjustments to the stiffness and damping of the suspension mechanism so as to minimise the occurrence of end-stop impacts may compromise the isolation provided by the suspension in conditions where end-stop impacts do not occur.

There is currently no mandatory requirement to measure the severity of the acceleration that occurs during an impact with an end-stop. It is common to use rubber end-stop buffers to limit the suspension displacement to within a fixed clearance, but some seat designs use buffers which result in high magnitude shocks during end-stop impacts. The optimisation of suspension seats should involve recognition that both the motions transmitted to the human body caused by terrain roughness and also the shocks arising from end-stop impacts are relevant to the health of drivers.

One of the earliest models for describing human response to vibration, the "dynamic response index", *DRI*, considered shock as the main component for assessing the severity

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of vibration on the spine [2]. The *DRI* was based on the assumption that spinal injury can be predicted from the peak response of a single-degree-of-freedom model in which the peak acceleration response represented the peak stress acting on the spine. This model was initially developed to account for back injury caused by aircraft seat ejection. The original *DRI* approach is not directly applicable to suspension seat end-stop impacts as it did not give a reasonable response to continuous vibration and made no allowance for repeated shocks. There have been various attempts to extend the method to modify the frequency response of the model and allow for the number of shocks, but a mature and suitable method for the present application has not yet emerged (see references [3–5]). The use of a running r.m.s. measure has been suggested, using the highest value obtained as an indication of the severity of a mixed exposure to vibration and shock (International Organization for Standardization [6]). However, as this also makes no allowance for the number of shocks, it does not seem a good choice for the present application.

A method which appears appropriate to the evaluation of the severity of end-stop impacts occurring during vibration is the vibration dose value. The vibration dose value is not only influenced by the most severe shock: it accumulates in value according to the magnitude and duration of the frequency-weighted acceleration time history. The vibration dose value is used to provide guidance on exposures to vibration or shocks that may cause injury (see, e.g., references [6, 7]).

The present authors have developed a generalized test method for end-stop impacts based on vibration dose values [8]. A suspension seat was excited at the resonance frequency of the suspension using a sinusoidal motion with gradually increasing magnitude. The severity of end-stop impacts was evaluated by the ratio of the vibration dose value measured on top of the suspension to that measured at the seat base. The test shows the input magnitude required to cause end-stop impacts and the severity of end-stop impacts with a specific input magnitude.

Several studies have involved the development of models of suspension seats that may be used to predict the probability of end-stops impacts or their severity. Wu and Griffin [9] used a non-linear two-degree-of-freedom model to investigate factors influencing the severity of suspension seat end-stop impacts. In the model, end-stop buffers were represented by dual-linear stiffness characteristics. Boileau *et al*. [10] investigated the influence of suspension seat travel limiting end-stop impacts on a driver's whole-body vibration exposure levels through the applications of a non-linear analytical model combining both the suspension seat and the driver. A semi-active control policy designed to reduce the occurrence and severity of end-stop impacts in a suspension seat by modifying the damping in an electrorheological fluid damper has been proposed and tested [11]. In such a system, the damping coefficient usually has a low value in order to isolate steady state vibration but is increased automatically when an end-stop impact is expected to occur.

The present experimental study was conducted to investigate the effect of top buffers, and the influence of buffer force–deflection characteristics and buffer damping on end-stop impacts in a suspension seat. The study was conducted with three pairs of rubber buffers, made from two different rubber materials, together with the original buffers of the suspension seat.

2. THE SUSPENSION SEAT AND RUBBER BUFFERS

The suspension seat used in this study had a cross-linkage mechanism. There were two bottom buffers, 35 mm thick, fixed vertically to the right and left sides of the base of the cross-linkage mechanism. There were no top buffers. The upward travel was limited by a rigid horizontal end-stop in the guide rail of the cross-linkage mechanism. When required, top buffers were fixed horizontally. The deflection and stiffness of the top buffers in the horizontal direction had equivalent vertical values, determined by the geometric and mechanical relations of the suspension mechanism, respectively. The seat suspension did not have a damper.

Three pairs of rubber buffers were made for the study. The force–deflection characteristics of these buffers were measured using a static loading rig. The rig was attached to a rigid steel frame so that it could be screwed up or down by turning a handle, so as to exert a load on the seat suspension. The applied force was measured with a piezoelectric force link, while the position was measured with a linear variable differential displacement transducer. The buffers were fixed to the seat suspension (with no seat cushion). The force–deflection curves were pseudostatically measured. Determined in this way, the curves reflect the influences of both the suspension spring and the suspension friction, in addition to the stiffness of the buffers. After subtracting these two factors from the measured data, the force–deflection characteristics of the buffers could be obtained.

3. METHOD AND EVALUATION CRITERION

The suspension seat was excited at the resonance frequency (1·6 Hz) of the seat suspension on a vertical vibrator having a stroke of 1 m. Sinusoidal motions were used with increasing magnitudes at intervals of $0{\cdot}2\,\mathrm{ms}^{-2}$ r.m.s. up to $2{\cdot}0\,\mathrm{ms}^{-2}$ r.m.s. Two accelerometers were used to measure the vibration excitation and response: one was attached on the vibrator table and another was attached to the top of the suspension. The suspension VDV ratio was used to describe the dynamic performance of the seat suspension:

$$\text{Suspension } VDV \text{ ratio} = VDV \text{ on suspension}/VDV \text{ at base}$$

Here VDV is the vibration dose value, calculated with frequency weighting W_b [British Standards Institution, 1987]

$$VDV = \left[\int_0^T a_w^4(t)\,\mathrm{d}t\right]^{1/4}.$$

The use of the VDV ratio is consistent with the use of $SEAT$ values (as defined in current seat testing standards), but replaces the r.m.s. values by vibration dose values so as to more appropriately take account of short duration high acceleration during any impact with the end-stop [1].

A sandbag of 560 N was loaded on the suspension seat for the tests. Human subjects were not employed in the tests due to the potential health hazard caused by repeated shocks.

4. RESULTS AND ANALYSIS

4.1. INFLUENCE OF TOP BUFFERS

Some suspension seats are fitted only with soft bottom buffers, for impacts at the bottom of the stroke, presumably on the assumption that impacts in this direction are either most likely or most severe. Severe end-stop impacts may also occur when the sprung mass of a suspension seat reaches the end of its upward travel. Howarth and Griffin [12] found no difference between the discomfort caused by "up" and "down" shocks when the

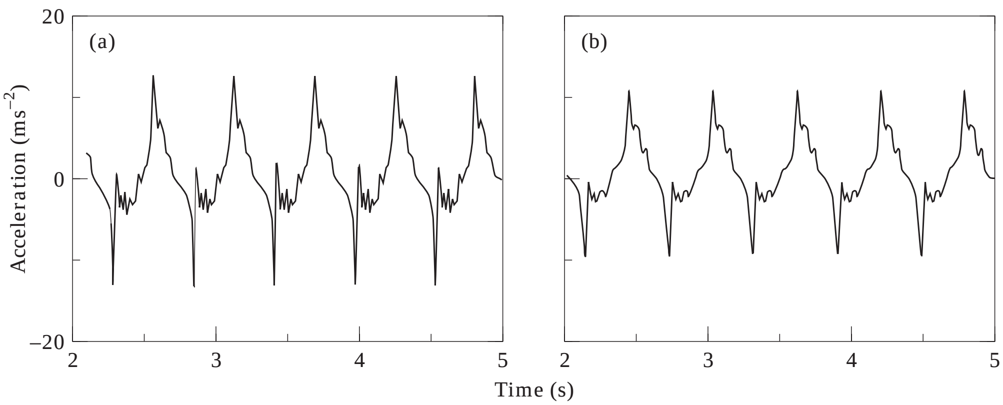

Figure 1. Vibration on top of suspension: (a) with only bottom buffer and (b) with both top and bottom buffers.

vibration dose values were the same. These top end-stop impacts can therefore be expected to cause the driver similar discomfort to that caused by the bottom end-stop impacts.

A pair of 10 mm by 8 mm by 4 mm cuboid buffers was made for the top buffers. The top buffers had the equivalent vertical thickness and approximately the same equivalent vertical stiffness as the original bottom buffers. The suspension seat was tested with both top and bottom buffers as well as with bottom buffers only. The acceleration time histories on top of the suspension, with and without the top buffers, when using the same input magnitude are shown in Figure 1. It can be seen that the peak-peak acceleration caused by end-stop impacts was greatly reduced by fixing top buffers to the seat suspension. As a result, the *VDV* ratio showed a reduction relative to when using only bottom buffers (see Figure 2). This indicates that under these test conditions the severity of end-stop impacts in a suspension seat with only bottom buffers can be reduced by adding top buffers to the suspension mechanism.

It may be seen that with an input magnitude of 0·6 ms^{-2} r.m.s., the *VDV* ratio when using both top and bottom buffers was slightly greater than when using only bottom buffers. This may be attributed to the shortening of the suspension travel due to the inclusion of the top buffers. This will tend to increase the probability of end-stop impacts arising from low input magnitudes. The optimization of the buffers should include a

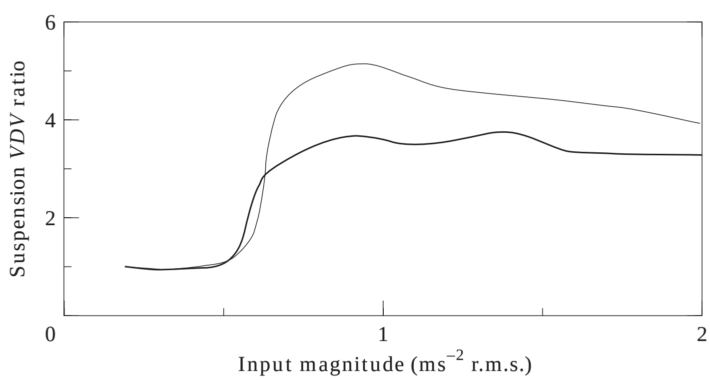

Figure 2. Effect of top buffers on suspension *VDV* ratio, Key: ——, with bottom and top buffers; ——, with bottom buffers only.

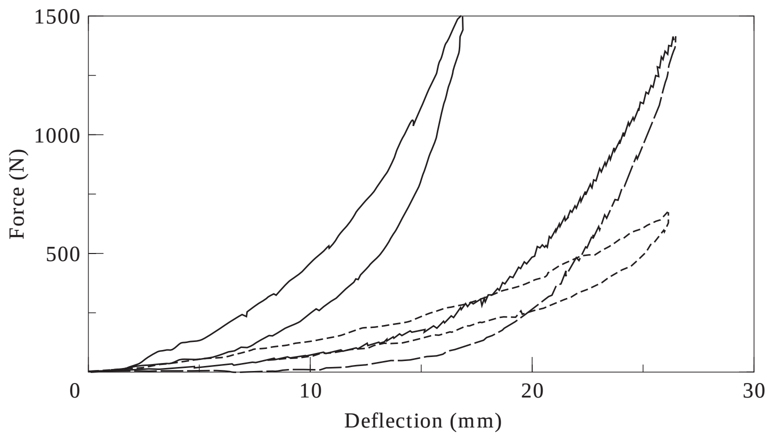

Figure 3. Force-deflection characteristics of buffers B, (· · · ·), A (——), and O (▬▬).

consideration of the trade-off between the reduced magnitude of severe shocks and the increased probability of lower magnitude shocks. Alternatively, the suspension stroke must be increased.

For the seat suspension without top buffers, the data show that the bottom buffer stiffness was less critical, since severe impacts always occurred when the suspension sprung mass hit the top end-stop, and these impacts formed the main part of the vibration dose value. For some seats with a damper, top end-stop impacts may be less likely than bottom end-stop impacts because of asymmetric characteristics of the damper, the rebound damping coefficient tends to be higher than the compression damping coefficient. The fixing of top buffers may then not be as essential as they are for seat suspensions without a damper, where the top and bottom end-stop impacts occur with equal probability as in the case of the present suspension seat.

4.2. INFLUENCE OF BUFFER FORCE–DEFLECTION CHARACTERISTICS

The suspension seat was tested with the pair of top buffers as described above, and with two additional pairs of bottom buffers A and B. The force–deflection characteristics of buffers A and B, and that of the original buffers (referred to as buffer O) are shown in Figure 3. The buffers exhibited strong non-linear progressively hardening force–deflection characteristics. The stiffness was low with low deflection, but it increased to a high value when the buffer had a large deflection. Hysteresis was observed for all three pairs of buffer, indicating that the buffers possessed damping.

The original buffers had the highest initial stiffness and the highest stiffness gradient. This made them the stiffest of the three pairs of buffers. Buffer A had the lowest stiffness of the three buffers at low deflection and a medium stiffness gradient when the deflection increased. Buffer B had a medium stiffness at low deflection and the lowest stiffness gradient over the entire range of deflection. It behaved more like a linear spring with medium stiffness. Of course, further applied force can also compress buffer B to its limit of deformation and this will cause progressively hardening force-deflection characteristics, similar to the other two pairs of buffers.

Figure 4 shows the VDV ratios with the three pairs of bottom buffers. At low input magnitudes (around 0·6 ms^{-2} r.m.s.), buffer A produced the lowest VDV, ratio, buffer B a medium VDV ratio, and buffer O the highest VDV ratio. This is in the same order as their stiffnesses at low deflection (see Figure 3), and indicates that lower buffer stiffness

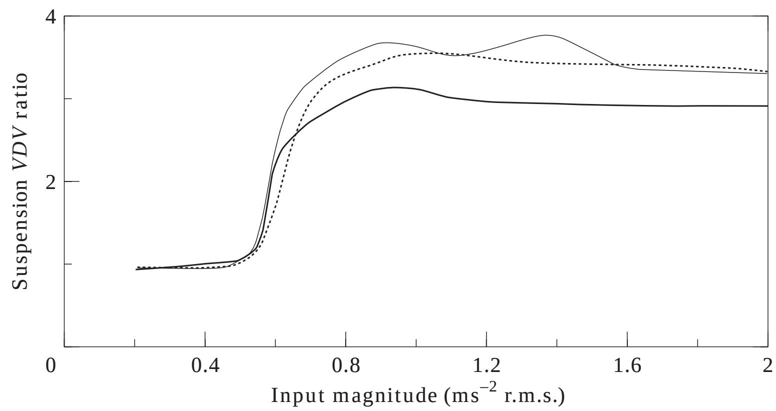

Figure 4. Effect of buffer force–deflection characteristics on suspension *VDV* ratio. Key: ——, buffer *O*; · · · · , buffer *A*; ━━, buffer *B*.

(i.e., softer buffers) can result in less severe end-stop impacts with low input magnitudes. At high input magnitudes (higher than 0·8 ms^{-2} r.m.s.), buffer *B* produced the lowest *VDV* ratios, while buffer *A* produced *VDV* ratios similar to, but a little lower than, those of buffer *O*. This arises from the similar high stiffness in buffers *A* and *O* at the large deflections caused by the greater excitation magnitude. The buffer *B* provided better performance than the original buffers, because they were not compressed to their high stiffness stage within the range of excitation magnitudes tested.

The results suggest that the sizes and shapes of buffers, and the way that buffers are fixed to a suspension mechanism, should be such that they have a nearly linear medium stiffness over a large deflection. The buffers should be designed such that, with likely vehicle motions, the buffers will not be compressed to their high stiffness stage, as was the case for the original buffer *O* and with buffer *A*. This could be realised with thick buffers having a medium stiffness. However, thick buffers will shorten the suspension travel and increase the probability of end-stop impacts. The thickness of buffers thus involves a compromise and needs optimisation.

4.3. EFFECT OF BUFFER DAMPING

It is tempting to optimize suspension damping so that it is most effective in isolating steady state vibration. High damping in the suspension would reduce the probability and the severity of end-stop impacts, but the vibration isolation performance of the suspension seat would be compromised. Buffer damping would dissipate vibration energy so as to reduce the severity of end-stop impacts without affecting the steady state vibration isolation performance. In a simulation study, the effect of buffer damping has been investigated by using a two-degree-of-freedom human-seat model and assuming that the buffers possess viscous damping and have dual-linear stiffness characteristics [9]. The buffer damping was shown to have a significant effect on suspension seat end-stop impacts, similar to the effect of suspension damping.

Figure 5 shows the predicted *VDV* ratios with different buffer damping during excitation at various magnitudes. The *VDV* ratios have been calculated without frequency weighting. Increased buffer damping significantly reduces the *VDV* ratio (i.e., the severity of end-stop impacts), over a range of damping coefficients from 0–400 Nsm^{-1}. However, a very high buffer damping coefficient (for example 800 Nsm^{-1}) results in high magnitude impacts, similar to the increased severity with a high buffer stiffness.

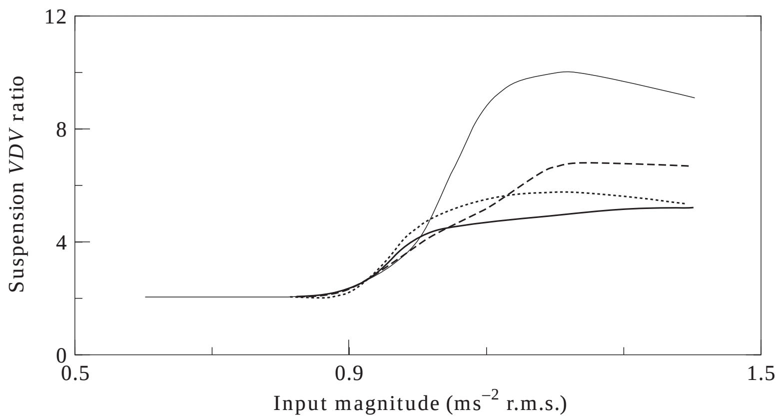

Figure 5. Effect of buffer damping on suspension VDV ratio (adapted from reference [9]). Key for damping (Ns/m): ——, 0; - - - -, 200; ▬▬, 400; · · · ·, 800.

A third pair of buffers, A', was made from a so-called high damping rubber material. Buffer A' had similar force–deflection characteristics to buffer A, but the "high damping" produced slightly higher hysteresis than for buffer A. The VDV ratios for buffer A' were tested at different magnitudes and compared with those for buffer A. There was no significant difference between the VDV ratios. This may be attributed to the insignificant differences in the damping characteristics of the two materials. Current rubber materials do not normally provide as much damping as that used in the simulation study for which the results are illustrated in Figure 5, so the potential for rubber buffer damping to reduce the severity of suspension seat end-stop impacts is limited. However, high "end-stop" damping might be provided by other materials or some passive devices.

Actively controlled devices, whose damping increases shortly prior to a potential end-stop impact, might provide sufficiently high damping to prevent severe end-stop impacts. The feasibility of this approach has been demonstrated by using an actively controlled electrorheological fluid damper responding to a simple control policy,

$$c = \left\{ \begin{matrix} c_{high}, & |d| \geqslant d_{th} \\ c_{low}, & |d| < d_{th} \end{matrix} \right\},$$

where d_{th} is the pre-set threshold of relative suspension displacement, c_{high} is the high damping coefficient applied when end-stop impacts are likely to occur and c_{low} is the low damping coefficient for isolating steady state vibration. Wu and Griffin [11] investigated the effect of the displacement threshold d_{th} and the high damping coefficient c_{high} on the severity of end-stop impacts with both sinusoidal and random acceleration excitations.

5. CONCLUSIONS

The severity of suspension seat end-stop impacts may be reduced by fixing top buffers to suspension seats with only bottom buffers. The end-stop impact performance of suspension seats can be further improved by selecting rubber buffers with optimum force-deflection characteristics. It was found that thick buffers with linear medium stiffness provided the least severe end-stop impacts. Buffers with too low stiffness, or too high stiffness at low deflection and quickly increasing stiffness at large deflection, will cause unnecessarily severe end-stop impacts. Buffer damping would dissipate vibration energy and thus reduce the occurrence of severe end-stop impacts. However, current rubber materials do not provide the high damping required. Alternative materials or active or passive devices may provide the required damping.

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