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MODAL ANALYSIS OF A HUMAN HEAD IMPACT SIMULATOR

1. INTRODUCTION

The United States Department of Transportation regulates automotive vehicle designs in order to reduce the likelihood of human injury [1]. For example, the motor vehicle safety standard no. 222 has been issued for school bus seating and crash protection [2]. To evaluate compliance with this standard, a contactable vehicle surface is impacted from any direction at 6·7 m/s by a human head form. It is a rigid surface comprised of two hemispherical shapes as shown in Figure 1 with total equivalent weight of 5·227 kg

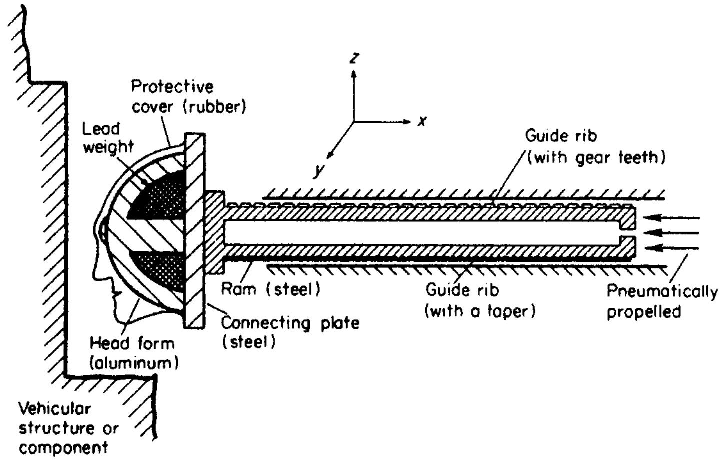

Figure 1. Human head impact simulator. It is mounted at the end of a pneumatically propelled ram. Thus the impact device consists of the following components: head form, protective cover, plate and ram. Note that there is only one pair of guide ribs.

(corresponding roughly to a child's head). An accelerometer is mounted at the center of gravity along the axis passing through the centers of two hemispheres. The axial acceleration, $a(t)$ (in g), must be such that

$$\left[\frac{1}{(t_2-t_1)}\int_{t_1}^{t_2} a(t)\,\mathrm{d}t\right]^{2\cdot 5}(t_2-t_1)\leq 1000, \qquad (1)$$

where t_1 and t_2 are any two points in time (in s), during the impact. Only the rigid body acceleration is to be measured and hence the standard requires that the head simulator must not exhibit any resonant frequency below 3000 Hz [2]. The objective of this study was to verify that this was the case for a *particular test device* through experimental and computational modal analyses. Also, we were interested in comparing the lowest natural frequency of the head form to available cadaver and skull data [3–7].

2. MODAL ANALYSIS

2.1. *Experiment*

The various components of the simulator except the protective cover were placed on a foam pad or suspended on elastic cords, to simulate free–free boundary conditions,

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for experimental determination of natural frequencies and mode shapes over 0–5 kHz frequency range. The same experiment was repeated for the assembled device except for the protective cover. Overall, 16 observation points were chosen for transverse (in the *y* and *z* directions) and longitudinal modes (along the *x* direction). The natural frequency results are given in Figure 2. Other details including associated mode shapes are documented in reference [8].

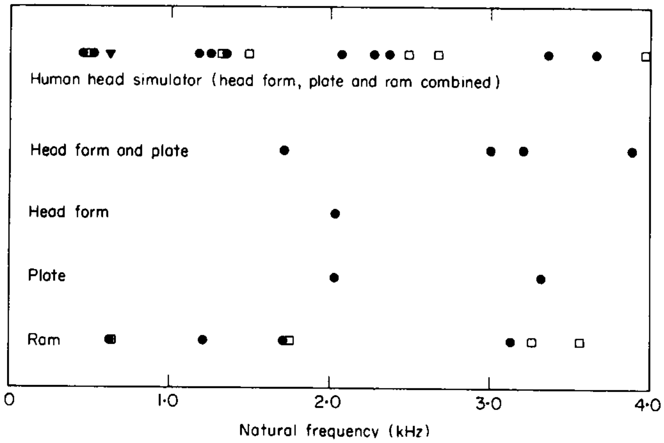

Figure 2. Natural frequency spectrum of the human head simulator and its various components. Experiment: ●; finite element analysis: □; closed form analytical solution: ▼.

2.2. *Finite element analysis*

A detailed model of the free–free ram was developed with a beam element being used for the eigenvalue and eigenvector solution over 0–5 kHz range; however, the guide ribs were not included in the model. This model was re-run with a lumped mass (corresponding to the head form and plate) at one end. Again, the natural frequency results are summarized in Figure 2.

2.3. *Analytical solution*

An attempt was made to predict the lowest natural frequency of the assembled simulator by treating it as a beam with a lumped mass and with a free end; the guide ribs and other geometry changes were not included [9]. This value is also given in Figure 2.

3. RESULTS

Figure 2 shows a comparison between measured and computed natural frequencies; excellent agreement is evident. Comparisons with similar agreement have also been made for the mode shapes [8]. The discrepancies between experiment and analysis are due to the following reasons: (i) torsional natural frequencies and modes were not measured but were included in the analysis; (ii) the guide ribs have been ignored in the analysis. Because of these ribs, the natural frequencies of bending vibrations are different for the *y* and *z* directions. For example, the first natural frequency of bending vibration is 468 Hz for the *y* direction and 525 Hz for the *z* direction; the corresponding finite element analysis prediction is 475 Hz, and the closed form analytic solution is 625 Hz. The measured results show a similar pairing of natural frequencies at the higher modes of vibration.

Our experimental and computational modal analysis results demonstrate that there are a number of natural frequencies below the specified limit of 3000 Hz [2]. The lower frequencies are mostly due to the dynamics of the ram, as shown in Figure 2, and the higher natural frequencies are due to the ram, plate and head form dynamics. Based on these results, we conclude that the accelerometer signal, acquired to verify equation (1), could be contaminated by the presence of these natural frequencies, especially by the first bending mode of the ram. We are currently evaluating the degree of contamination in the accelerometer direction (x) due to the bending modes along the y and z directions for the *particular test device*. This contamination (if any) could seriously affect the reliability of the measured data. It should be pointed out that the same ram and the propelling mechanism is also used for knee and pelvic form impactors. To remedy this problem, we are currently studying the following options: (i) fabricate the ram out of a composite material—this should raise natural frequencies but it may not be able to carry dynamic loads; (ii) redesign the pneumatic system and ram, or (iii) develop a measurement methodology which will eliminate or reduce the effect of device dynamics for a *particular test device*.

Finally, we compare the first natural frequency of the head form with available cadaver and skull data in Table 1. This comparison suggests that the head form does not simulate the human head dynamics, and hence injury-mechanisms resulting from localized deformations are not included in the current safety standards [2]. We recommend further research in this area.

TABLE 1

Comparison of first natural frequency of head form with cadaver, skull and human volunteer data [3–7]

	Cadaver	Human volunteer	Human skull	Head form [2]
First natural frequency (Hz)	166 [6]	313±7% [5]	1385 [7]	2037
	313 [5]		1641 [7]	
	360 [4]		1800 [3]	

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