Development of an Optimized Seat Cushion Design Methodology

ABSTRACT

Seat cushions for high-performance aircraft are typically selected for their ability to meet stringent specifications. One of the major criteria is the safety performance during an ejection. To address the design goals of cushion and material selection, a computational modeling method was developed that accounts for component and subsystem testing, component and subsystem modeling, validation criteria and, finally, theoretical application. This method is then demonstrated on designing a seat cushion that has optimized safety properties for an ACESII ejection seat.

INTRODUCTION

Chronic back pain in military pilots is a significant problem. It may be caused by any combination of the following factors: aircraft vibration, pilot posture during aircraft control, pilot muscle fatigue, cockpit ergonomics, and the pilot's general physical fitness and medical history. High-technology improvements in occupant comfort have limited application to military aircraft seats, especially ejection seats, as they are an integral part of an aircraft life support system. The introduction of any complicated system or additional parts to enhance comfort would require extensive integration and qualification efforts at considerable cost. Therefore, the solutions for comfort that can be quickly and cheaply implemented are desired.

Long-term sitting comfort may be enhanced by a new or improved seat cushion. However, some seat cushions have been shown to amplify the acceleration transmitted to the torso of the aircrew member if they have not been designed properly [1]. Any item introduced to an ejection seat and located between the seat pan and the gluteal region of the pilot must not compromise the existing risk of spinal injury which is limited by the human tolerance to the fracture of the lumbar vertebra. As more resources are applied to improving seat cushion comfort, the performance of a cushion for the prevention and reduction of spinal injuries (the safety performance) should not be ignored or sacrificed. Therefore, when the comfort performance of a cushion design is assessed, its safety performance must also be evaluated.

The safety performance of a cushion can be measured by certain spinal injury criteria, such as Dynamic Response Index (DRI) [2], or directly by certain occupant response characteristics, such as the peak lumbar load and the peak chest acceleration [3]. The evaluation of the safety performance of ejection seat cushions is conventionally performed using impact tests. A number of vertical deceleration tower (VDT) test studies have been performed at the Air Force Research Laboratory (AFRL) over decades to evaluate several types of ejection seat cushions, including certain designs with comfort improvement [1,4-9]. It should be pointed out that in the previous study [1], some inconsistencies in the lumbar load data were noted.

These VDT tests have typically occurred late in the design cycle when a prototype already existed. The tests were then used to determine if the cushions met the specifications. If a failure occurred, then the cushion would be redesigned and tested again. This typical design-build-test flow could be lengthy and tedious. Fortunately for the manufacturers, they held a wealth of corporate knowledge and would build a cushion they were confident would pass.

Optimization Method

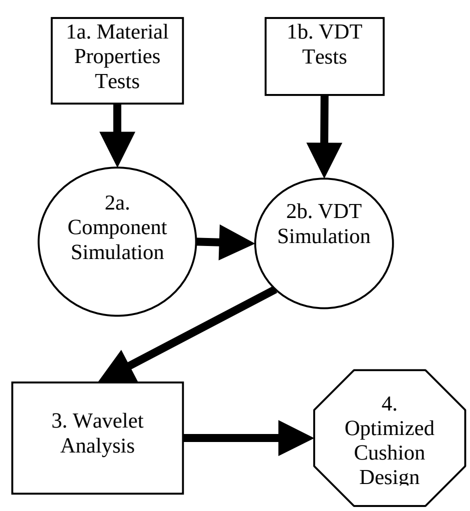


Figure 1. Optimization method flow chart

The process by which a theoretically optimized design can be reached is through the developed four-step method (Figure 1). It should be pointed out that technically there would be a fifth step which would be to build and verify the results, but for purposes of this study the ending point will be the optimized design.

While there is nothing unique about the flow that was chosen, each of these steps is necessary and there can be some cycling between steps. For illustrative purposes this optimization methodology will be applied to the design of an ACESII ejection seat cushion.

1a. Materials Properties Tests

The optimization method relies heavily on computational routines. One of the inputs to these computational routines is information regarding the materials to be used for further testing and simulation. To ensure that a valid baseline simulation of the scenario at hand is validated, current materials must be initially investigated.

There is a wide range of materials available to the cushion designer. Some may be purely elastic but, for purposes of improved crash protection and comfort, more viscoelastic-type foams are being utilized. The properties then become important as the performance of the system will be directly dependent upon their behavior.

As a start, a test program was conducted to measure both the static and dynamic properties of several cushion materials [11]. Cushion material properties were obtained from static and dynamic tests using Instron and Materials Testing System (MTS) facilities. Reaction force, deflection and deflection rate data were collected for each cushion specimen. These data show the differences in the stiffness and damping properties of each specimen tested.

The stiffness and damping properties of an existing ACESII ejection seat cushion, four different Confor™ foam samples, and three different Stimulite™ cover samples were measured in this study. Confor™, an open-celled polyurethane foam, is used in diverse applications such as shock absorption for electronics equipment and cushioning in seating and medical devices. Stimulite™ is a flexible honeycomb cover material made from an extensive variety of thermoplastics and thermoplastic elastomers. The covers are currently used in various commercial seating and padding applications to reduce discomfort. Each of the cushion specimens was tested statically and dynamically with and without each of the covers (Table 1). When the covers were used, they were positioned directly on top of the foam specimens.

Table 1. Test Conditions

Cushions	Covers
2-inch Confor™ C-40, C-42, C-45, C-47	½-inch Stimulite™ soft, medium, firm
Standard 1-inch ACESII	

All tests were conducted with a flat 50 in^2 circular indentor foot connected by means of a swivel joint to the test facility. The fixed impact surface consisted of a 14 x 16-inch rigid aluminum plate. For a detailed test methodology and results see [11]. The cushion materials tested were successfully regressed to yield polynomials that predict the reaction load while accounting for both the deflection and deflection rate (Figures 2 and 3).

1b. VDT Tests

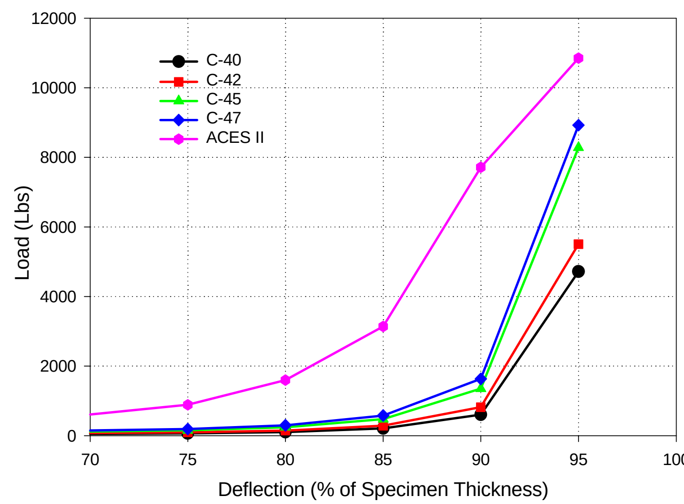


Figure 2. Static Tests of Confor Foam

The AFRL vertical deceleration tower facility (Figure 4) is composed of two vertical rails and a drop carriage. Guided by the rails, the carriage is allowed to enter a free-fall state from a pre-determined drop height. A plunger mounted on the rear of the carriage is guided into a cylinder filled with water located at the base and between the vertical rails. A +Gz acceleration pulse (actually a deceleration pulse) is produced and applied to the carriage when water is displaced from the cylinder by the plunger. The pulse shape is controlled by varying the drop height, which determines the peak acceleration level or G level, and by varying the shape of the plunger, which determines the rise time of the pulse. A carriage-mounted seat is used to restrain a test subject (human or manikin) in an upright seated position. The carriage,

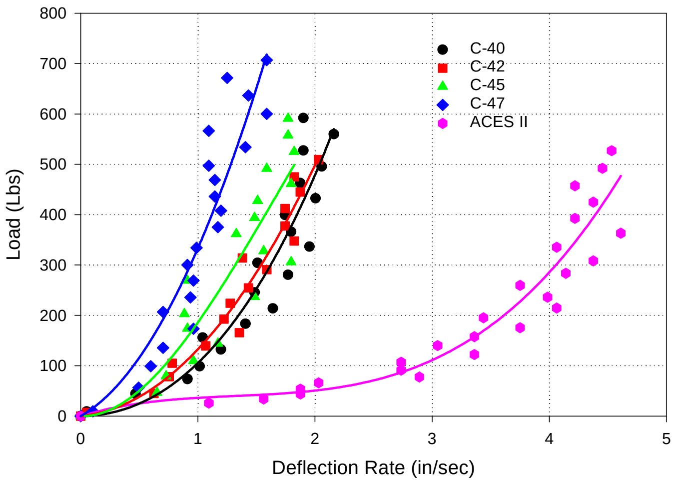


Figure 3. Dynamic Tests of Confor Foam

impact seat, and test subject are instrumented with load cells or accelerometers to collect dynamic response data.

A modified ACESII F-16 ejection seat was used for the tests. The seat back was cut away from the seat and mounted to the VDT carriage so that the seat back tangent plane was vertical. The seat pan was mounted to the horizontal surface of the VDT carriage so that the seat pan was perpendicular to the seat back tangent plane.

Test subjects have ranged from human volunteers of varying anthropometry to several different types of manikins. For this development program, the data from

Figure 4. VDT test set-up

a 50% Hybrid III manikin was used as the occupant in the tests. The manikin was dressed in a standard flight suit and wore an HGU-55/P flight helmet. The manikin was seated in an upright position, centered in the seat, and restrained using the seat's restraint system. A standard double shoulder strap and a lap belt assembly were used as the restraint system for the occupant. The pre-tension levels of the restraint system were 20 ± 5 lbs. Limb restraints were also applied to restrain the motion of the occupant's arms and legs.

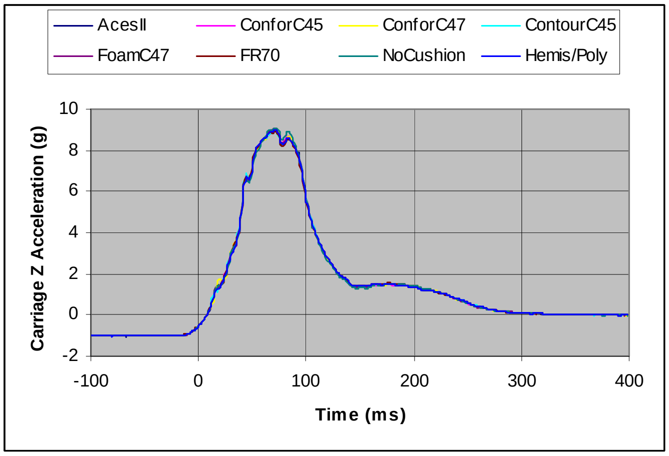
Each cushion was tested at three G-levels: 8, 10, and 12 g ($g = 9.8\,\mathrm{m/s}^2$), which were the nominal amplitudes of the carriage acceleration pulse. The acceleration pulse for the VDT was approximately a half-sine waveform. The accelerations and forces at a number of locations of the test system were recorded, which included the accelerations of the carriage, seat pan, and seat cushion, the forces on the seat pan, and the forces at the restraint system attachment points. The measurements of the occupant responses included the accelerations of the lumbar, chest, and head, and the forces on the femur, lumbar, and head. The data from the tests (Figure 5) can be found in the AFRL/HE Biodynamics Data Bank[1] with the study number of 200203. The test results showed that the repeatability is sound with small variations among the three tests for each cell. The statistical analysis is neither meaningful (as the sample size of three is too small) nor necessary (as the test conditions are well controlled and the random factors are not significant). Therefore, the average of the three tests is used to represent the result for each cell.

For the VDT tests, the acceleration pulse of the carriage is the impact input. It was controlled with respect to its amplitude (peak) and rise-time in the tests. Given the nominal amplitude for each G-level, the actual amplitude has small variations for different cushions.

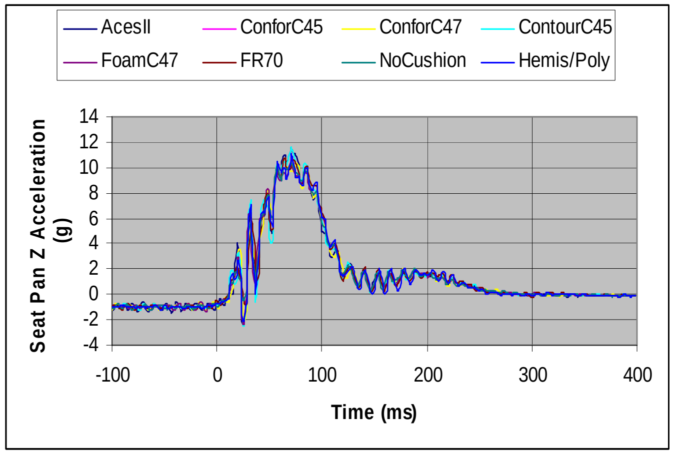
In the vertical deceleration tower tests, the occupant was seated in an upright position. Consequently, the responses in the vertical direction (Z-axis) are dominant as compared to those in the horizontal directions (X- and Y-axis). Therefore, in the following analysis, only vertical responses are considered.

The time histories of the accelerations of the carriage,

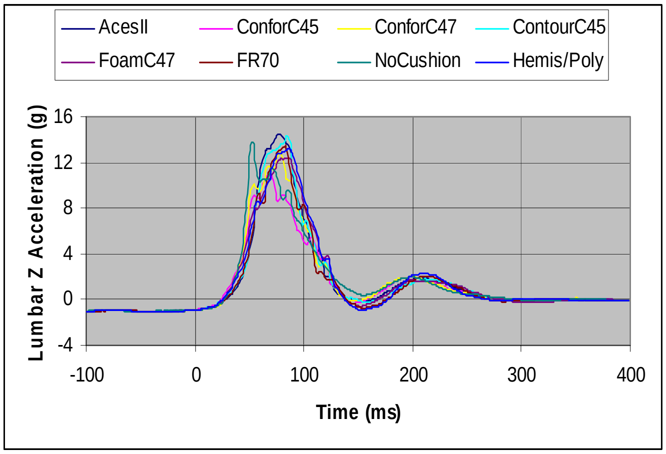
[1] http://www.biodyn.wpafb.af.mil



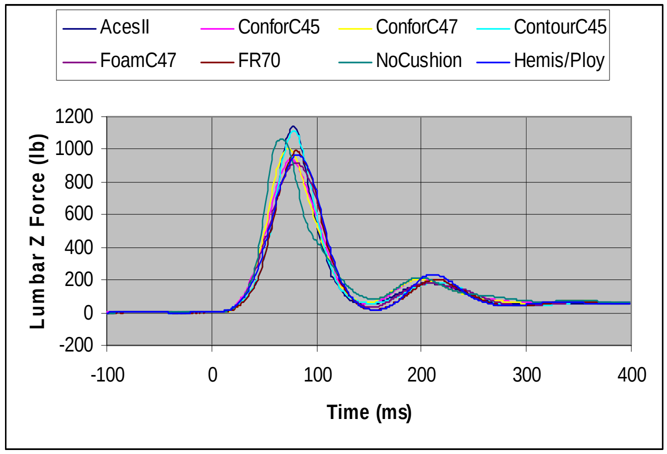
(a) Carriage z acceleration



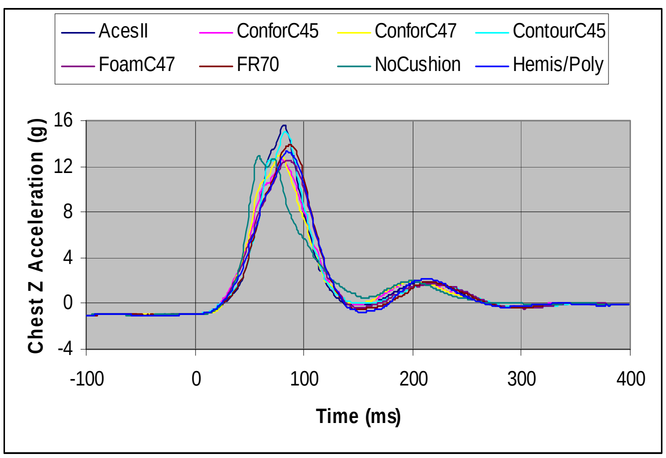
(b) Seat pan z acceleration



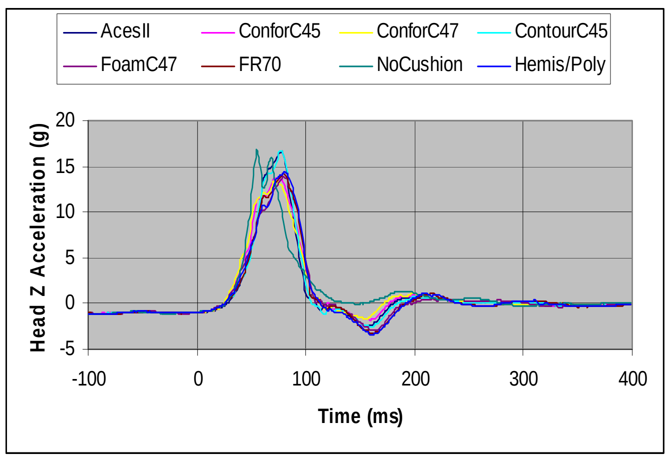
(c) Lumbar z acceleration



(d) Lumbar z force



(e) Chest z acceleration



(f) Head z acceleration

Figure 5. Time histories of accelerations and force for the impact of 10 g

2a. Component Simulation

With the material properties of the cushions measured in step 1a, they need to be put in a usable form for step 2b. While it would be possible to take the data directly into a full simulation, it is much more reasonable to develop a model of the seat cushion and validate this model before full-scale application. In general, the cushion will be modeled as a generic control force (Figure 6), with the rest of the body simplified as a lumped parameter model. This is an oversimplification of the modeling method, but since in this section the cushion is the important parameter, the simplification will suffice until the remaining parts of the model are developed later.

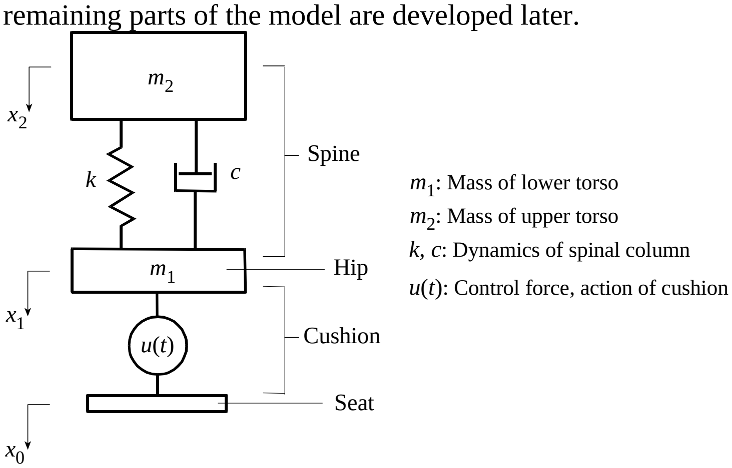


Figure 6. Ejection seat cushion with a two-mass occupant model

For unknown cushion properties, the generic control force will be used. However, for the cases in which the material property behavior has already been measured, the control force can be replaced by the specific form.

Since the cushions of interest here are time–dependent, a quasi-linear visco-elastic model is used [12]

$$F(t) = \int_0^t G(t-\tau)\frac{\partial F_e[\delta(\tau)]}{\partial \delta}\frac{\partial \delta(\tau)}{\partial \tau}d\tau , \qquad (1)$$

where $F(t)$ is the cushion reaction force or contact force, $\delta(t)$ is the cushion deformation or the contact penetration, $G(t)$ with $G(0)=1$ is the normalized reduced relaxation function, and $F_e(\delta)$ with $F_e(0)=0$, a function of δ alone, is referred to as instantaneous elastic reaction force response.

Applying this model to simulate the component tests yields an acceptable level of model validation (Figure 7).

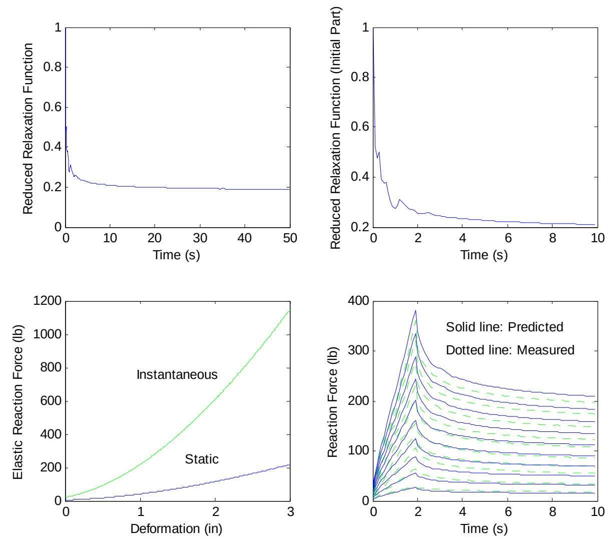


Figure 7. Model identification for C-45 cushion

2b. VDT Simulation

Now, with an acceptable model of the cushion behavior, it is necessary to build a model of the entire test fixture. This model will include the seat geometry, occupant and other features that make up an entire VDT test.

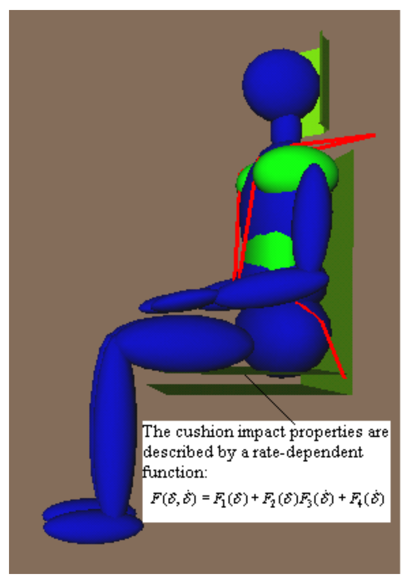


Figure 8. RMB modeling of VDT tests

The ATB [11], a rigid multi-body (RMB) dynamics program, is used to model the VDT tests. This model (Figure 8) consists of 15 segments that represent respective parts of the body, 14 joints that connect segments to each other, four points of the harness belt, and four planes that describe the seat cushion, seat back, seat pan, and headrest, respectively. The interaction between the seat cushion and the occupant is described by the contacts between the seat cushion plane and the occupant. In ATB, the contact between a plane and a body segment is characterized by contact force and penetration. The relationship between the contact force and the penetration depends upon the contact properties defined for that plane. For the contacts between the seat cushion and the occupant, the contact properties depend upon the impact characteristics of the seat cushion. Since, in RMB modeling with ATB, all segments of the occupant body are rigid, the resilience of these segments needs to be taken into account in the impact characteristics of seat cushions.

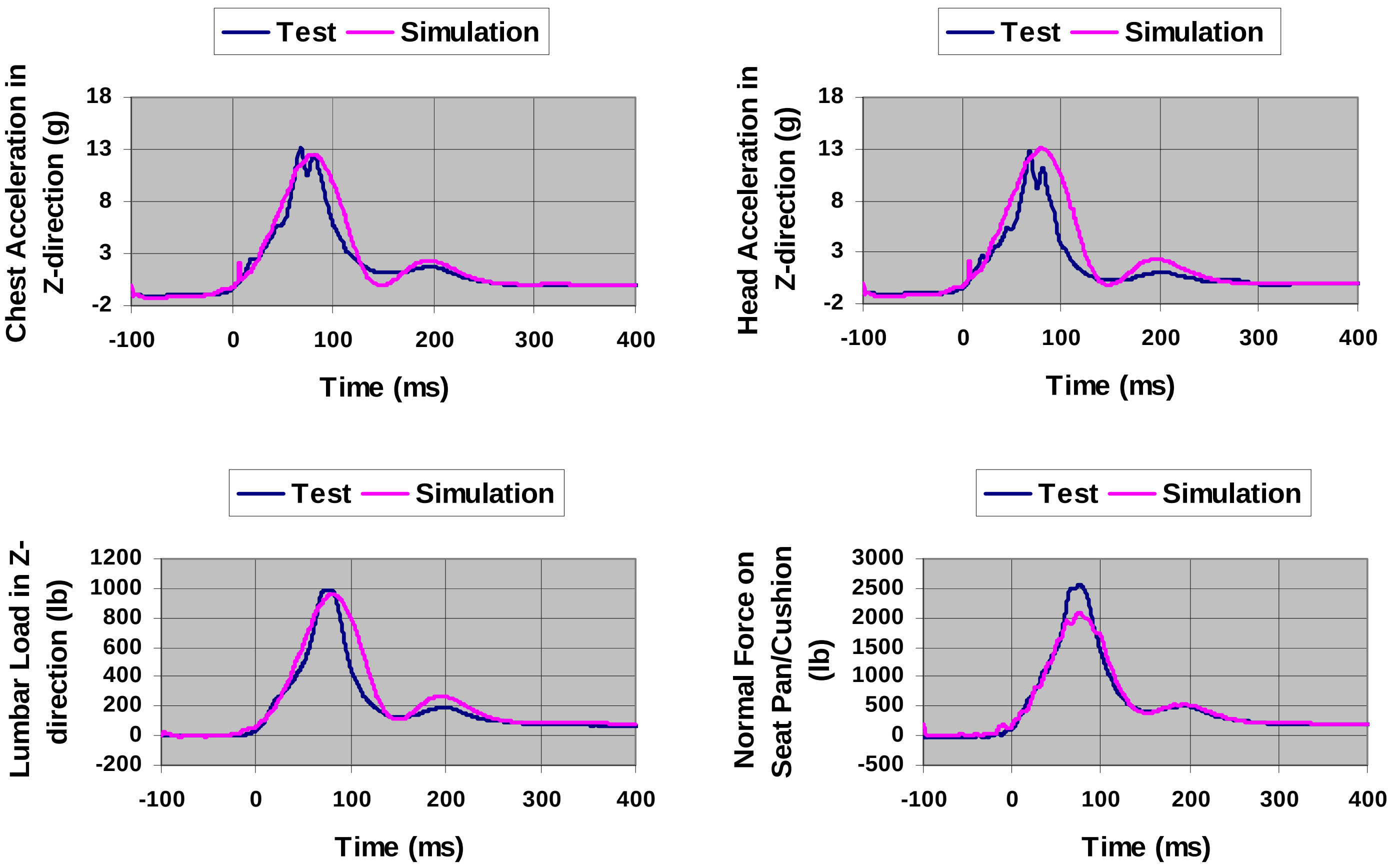


Figure 9. VDT modeling results

Upon applying the initial conditions from the manikin tests with the mechanical properties for the seat system, a simulation was created that represented the testing [13]. Several response parameters of interest were chosen for further analysis (Figure 9). The validity of this model will be discussed in the next section.

3. Wavelet Analysis

With a model now developed and the ability to generate data similar to that resulting from physical testing, the question always arises as to how well the simulation represents the testing. In the case presented here, it can seem trivial to demonstrate that the simulation and the test are representing the same phenomena. However, this is not always the case. There are many instances where there can be slight differences in phasing or amplitude, noise levels can be different, and different data collection and processing techniques can be employed.

For example, in the case of comparing a finite element model of a vehicle to that of an actual crash test [14], the visual data do not readily give an indication of the model validation (Figure 10). If a conventional correlation analysis were performed on these data, a correlation coefficient of 0.77 would be obtained. While this is an average correlation, it does not reveal the true nature of the validity of the simulation.

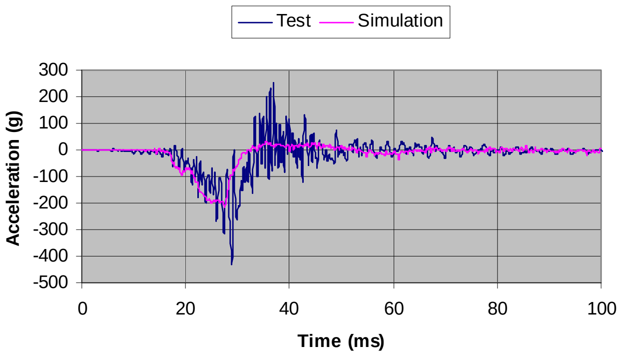


Figure 10. FEM model and test comparison

Recently a new technique has been developed for validating simulations with test data [14-16]. The wavelet methodology has provided an avenue for decomposing signals into their basic properties, such that a comparison of the responses of interest can be conducted.

A visualization of this methodology (Figure 11) demonstrates that the single signal is decomposed into several signals, but each with different properties. This will enable the correlation analysis to be conducted on only the decomposed signals, thus eliminating higher frequency errors and responses that are not of interest.

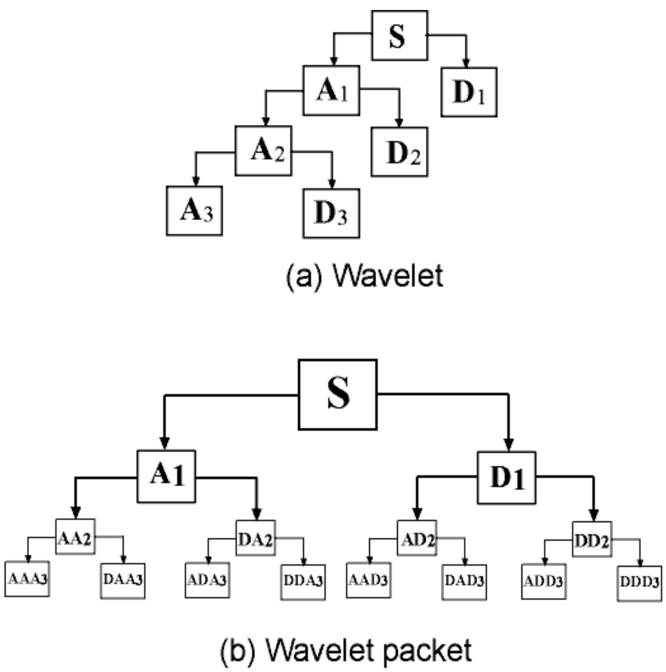


Figure 11. Decomposition in a wavelet basis and a wavelet packet basis

The results of conducting this analysis on the signals represented in Figure 9 will improve the correlation coefficient to 0.87. This demonstrates that the rigid body motion (the approximation or a6) of both the simulation and the test are in good agreement (Figure 12). With the wavelet analysis it is also possible to look at higher order effects of the signal (or the decompositions) which represent the vibratory response of the signal. For the example presented, inspecting d6 demonstrates that the two signals are well correlated for shorter duration time spans. Further decompositions of the signal contain less energy content, as evidenced by their decreasing amplitude. D1 is only a few percent of the approximation (Figure 12). Details to this level can be considered as noise in the system and generally disregarded.

4. Optimized Cushion Design

Now that the computational methodology for simulating VDT tests has been developed and validated, it can now be applied to the development of an optimized seat cushion. The model from section 2b will be employed here, but first some additional requirements will be applied.

This problem can then be formulated as [17]:

$\mathbf{u} = [u_1\, u_2\, \Lambda\, u_N]^T$ = parameters of impact characteristics

$J_i(\mathbf{u})$ = injury criterion to be minimized (2)

$J_k(\mathbf{u})$ = injury criteria to be controlled or bounded

where $i, k \in [1, N]$ and $i \neq k$ where N is the number of injury criteria of concern. Then this parametric optimization problem can be formulated as

Design Variables: $\mathbf{u}$;

Objective Function: min{ $J_i(\mathbf{u})$ }; (3)

Constraints: $J_k(\mathbf{u}) \leq D_k$, and $\mathbf{u}_L \leq \mathbf{u} \leq \mathbf{u}_U$;

where D_k are the prescribed limits on the corresponding injury criteria, and $\mathbf{u}_L$ and $\mathbf{u}_U$ are the lower and upper bounds on the parameters of impact characteristics. Note that this is a feedback control problem in the sense that the force that a safety device exerts on the occupant depends on the motion of the occupant.

This type of problem formulation allows the designer to focus on a specific injury criterion, such as lumbar load or chest acceleration, to be minimized. However, the other response parameters are still bounded such that finding the optimal solution to minimize the one injury criterion does not create an unsafe condition.

One other consideration that must be accounted for is the form of the parameters of interest to be controlled. If the general behavior of the cushion is not known, then a generic control function can be applied. However, if some knowledge exists regarding the types of materials, then this generic control function can be replaced with a polynomial that represents the behavior of the cushion.

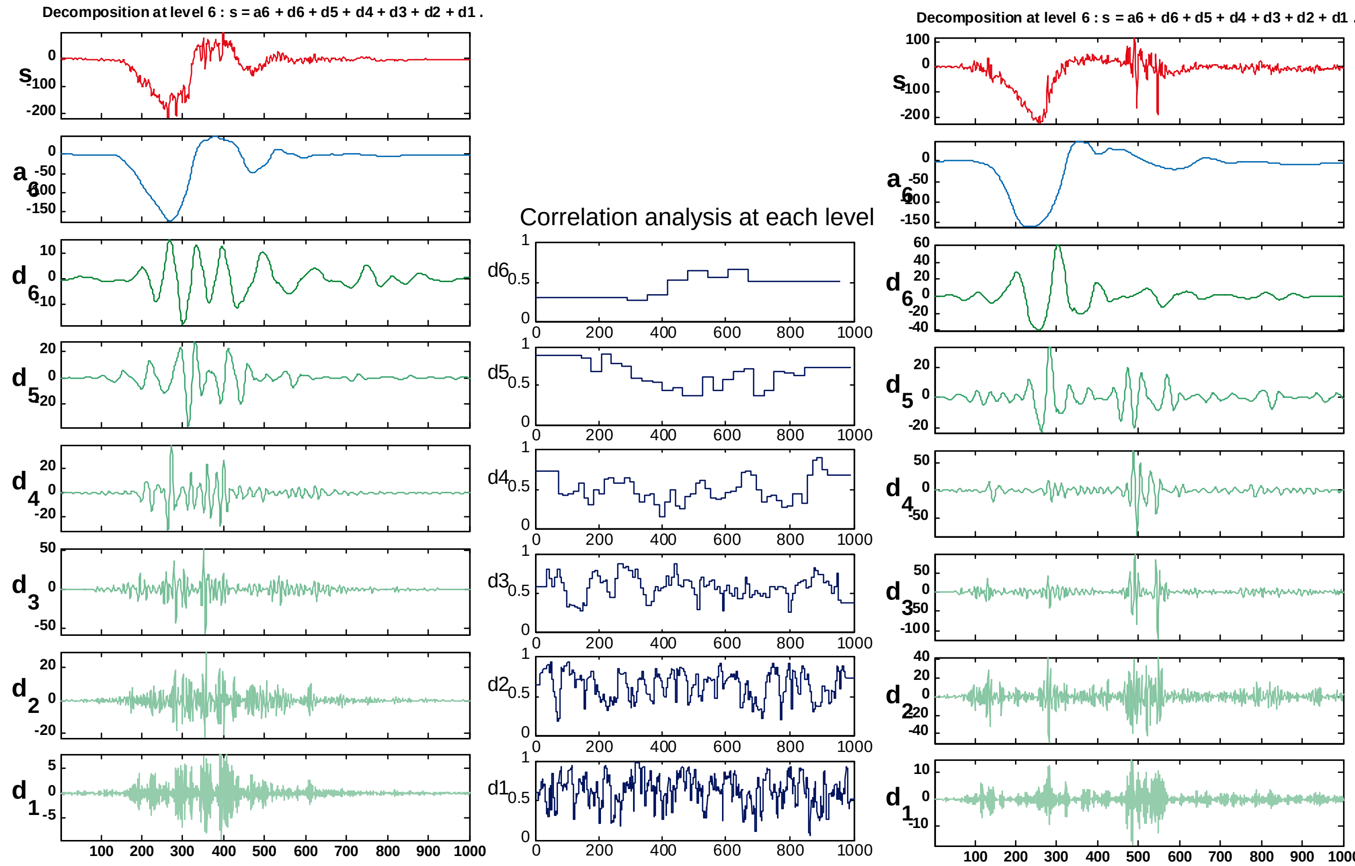


Figure 12. Wavelet analysis demonstrating the signal decomposition

Then it would be the coefficients of the polynomial that will lead to an optimized design.

For the problem at hand, the lumbar load was chosen as the injury criterion to be minimized, and the chest acceleration was bounded to remain below 60 g's. This analysis resulted in approximately a 50% improvement in the peak lumbar load (Figure 13), with similar improvements also seen in the chest acceleration and the reaction force of the cushion and the occupant.

It should be noted that the optimized cushion determined by the analysis does not necessarily have to exist. Rather, the computation gives the properties of the cushion that provide the lowest spinal loads to the given boundary and initial conditions. It is then up to the designer to the select the material that meets the specifications of the optimal design.

DISCUSSION

A six-step procedure for optimizing a system for safety was developed. This method was applied to the design of a seat cushion for ejection seats to minimize spinal loads. This process is comprehensive in that it is a detailed analysis that includes component and full-scale testing as well as component and full-scale modeling with a validation process to assess the quality of the results. While only an overview was presented here, the reader is referred to the references for the details on each step. This process is not unique in that other steps may or may not be needed depending on the particular problem at hand.

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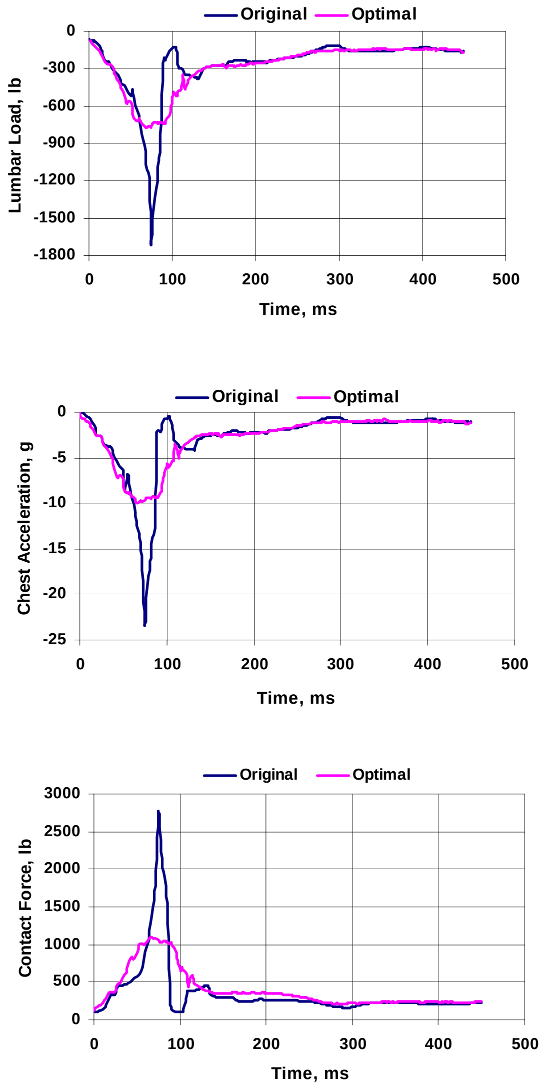

Figure 13. Optimized cushion results

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Biography

Dr. Joseph A. Pellettiere is a mechanical engineer for the Biomechanics Branch, Human Effectiveness Directorate, Air Force Research Laboratory. He has a BS in Biomedical Engineering and an MS in Mechanical Engineering from Case Western Reserve University, and a Ph.D. in Mechanical Engineering from the University of Virginia. His experience is in biomechanics, human simulation and injury, crash protection and prevention using both testing and computational technologies. He currently leads the modeling simulation group in the branch.

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