Wavelet-Based Signal Analysis of a Vehicle Crash Test With a Fixed Safety Barrier

Hamid Reza Karimi * Kjell G. Robbersmyr **

* Department of Engineering, Faculty of Engineering and Science,
University of Agder, N-4898 Grimstad, Norway, E-mail: hamid.r.karimi@uia.no

** Department of Engineering, Faculty of Engineering and Science,
University of Agder, N-4898 Grimstad, Norway, E-mail: kjell.g.robbersmyr@uia.no

Abstract: This paper deals with the wavelet-based performance analysis of the safety barrier for use in a full-scale test. The test involves a vehicle, a Ford Fiesta, which strikes the safety barrier at a prescribed angle and speed. The vehicle speed before the collision was measured. Vehicle accelerations in three directions at the center of gravity were measured during the collision. The yaw rate was measured with a gyro meter. Using normal speed and high-speed video cameras, the behavior of the safety barrier and the test vehicle during the collision was recorded. Based upon the results obtained, the tested safety barrier, has proved to satisfy the requirements for an impact severity level. By taking into account the Haar wavelets, the property of integral operational matrix is utilized to find an algebraic representation form for calculate of wavelet coefficients of acceleration signals. It is shown that Haar wavelets can construct the acceleration signals well.

Keywords: Wavelet; signal analysis; safety barrier; vehicle crash.

1. INTRODUCTION

Occupant safety during a crash is an important consideration in the design of automobiles. The crash performance of an automobile largely depends on the ability of its structure to absorb the kinetic energy and to maintain the integrity of the occupant compartment. To verify the crash performance of automobiles, extensive testing as well as analysis are needed during the early stages of design [7].

In the last ten years, emphasis on the use of analytical tools in design and crash performance has increased as a result of the rising cost of building prototypes and the shortening of product development cycles. Currently, lumped parameter modeling (LPM) and finite element modeling (FEM) are the most popular analytical tools in modeling the crash performance of an automobile ([1], [2]). The first successful lumped parameter model for the frontal crash of an automobile was developed by Kamal ([13]). In a typical lumped parameter model, used for a frontal crash, the vehicle can be represented as a combination of masses, springs and dampers. The dynamic relationships among the lumped parameters are established using Newton’s laws of motion and then the set of differential equations are solved using numerical integration techniques. The major advantage of this technique is the simplicity of modeling and the low demand on computer resources. The problem with this method is obtaining the values for the lumped parameters, e.g. mass, stiffness, and damping. The current approach is to crush the structural components using a static crusher to get force deflection characteristics. The mass is lumped based on the experience and judgment of the analyst. Usually complicated fixtures and additional parts are attached to the component being tested to achieve the proper end conditions. This adds complexity and cost to the component crush test. Since the early 60s, the finite element method (FEM) has been used extensively for linear stress, deflection and vibration analysis. However, its use in crashworthiness analysis was very limited until a few years ago. The availability of general purpose crash simulation codes like DYNA3D and PAMCRASH, an increased understanding of the plasticity behavior of sheet metal, and increased availability of the computer resources have increased the use of finite element technique in crash simulation during the last few years [10]. The major advantage of an FEM model is its capability to represent geometrical and material details of the structure.

On the other hand, wavelet transform as a new technique for time domain simulations based on the time-frequency localization, or multiresolution property, has been developed into a more and more complete system and found great success in practical engineering problems, such as signal processing, pattern recognition and computational graphics ([8], [12]). Recently, some of the attempts are made in solving surface integral equations, improving the finite difference time domain method, solving linear dif-
The wavelet series representation of the one-dimensional function \( y(t) \) in terms of an orthonormal basis in the interval \([0, 1)\) is given by
\[
y(t) = \sum_{i=0}^{\infty} a_i \psi_i(t) \quad (4)
\]
where \( \psi_i(t) = \psi(2^i t - k) \) for \( i \geq 1 \) and we write \( i = 2^j + k \) for \( j \geq 0 \) and \( 0 \leq k < 2^j \) and also defined \( \psi_0(t) = \psi(t) \). Since it is not realistic to use an infinite number of wavelets to represent the function \( y(t) \), (4) will be terminated at finite terms and we consider the following wavelet representation \( \tilde{y}(t) \) of the function \( y(t) \):
\[
\tilde{y}(t) = \sum_{i=0}^{m-1} a_i \psi_i(t) = a^T \Psi_m(t) \quad (5)
\]
where
\[
a_i = \frac{1}{2} \int_0^1 y(t) \psi_i(t) \, dt. \quad (6)
\]
The approximation error \( \Xi_y(m) := y(t) - \tilde{y}(t) \) depends on the resolution \( m \). Generally, the matrix \( H_m \) can be represented as
\[
H_m := [\Psi_m(t_0), \Psi_m(t_1), \ldots, \Psi_m(t_{m-1})], \quad (7)
\]
where \( \tfrac{1}{m} \leq t_i < \tfrac{i+1}{m} \) and using (5), we get
\[
[y(t_0), y(t_1), \ldots, y(t_{m-1})] = a^T H_m. \quad (8)
\]
For further information see the references [3], [18]-[20].

2.2 Integral Operation Matrix

In the wavelet analysis of dynamical systems, we consider a continuous operator \( \hat{O} \) on the \( L_2(\mathbb{R}) \), then the corresponding discretized operator in the wavelet domain at resolution \( m \) is defined as ([18])
\[
\hat{O}^m = T_m \hat{O} T_m^{-1} \quad (9)
\]
where \( T_m \) is the projection operator on a wavelet basis of proposed resolution. Hence to apply \( \hat{O}^m \) to a function \( y(t) \) means that the result is an approximation (in the multiresolution meaning) of \( \hat{O} y(t) \) and it holds that
\[
\lim_{m \to \infty} \| \hat{O}^m y - \hat{O} y \|_2 = 0, \quad (10)
\]
where the operator \( \hat{O}^m \) can be represented by a matrix \( P_m \).

In this paper, the operator \( \hat{O} \) is considered as integration, so the corresponding matrix \( P_m = < \int_0^t \Psi_m(\tau) \, d\tau, \Psi_m(t) > = \int_0^1 \int_0^t \Psi_m(\tau) \, d\tau \Psi^T_m(t) \) represents the integral operator for wavelets on the interval at the resolution \( m \). Hence the wavelet integral operational matrix \( P_m \) is obtained by
\[
\int_0^t \Psi_m(\tau) \, d\tau = P_m \Psi_m(t). \quad (11)
\]
For Haar functions, the square matrix $P_m$ satisfies a recursive formula ([3], [18]-[20]).

3. VEHICLE KINEMATICS IN A FIXED BARRIER IMPACT

The first and second integrals of the vehicle deceleration, $a(t)$, are shown below. The initial velocity and initial displacements of the vehicle are $v_0$ and $x_0$, respectively.

$$a = \frac{dv}{dt}, \quad dv = a dt, \quad \int_0^t dv = \int_0^t a dt, \quad v = v_0 + \int_0^t a dt \tag{12}$$

$$x = x_0 + \int_0^t \left( v_0 + \int_0^t a dt \right) dt, \tag{13}$$

In the fixed barrier test, vehicle speed is reduced (velocity decreases) by the structural collapse, therefore, the vehicle experiences a deceleration in the forward direction. To study the effect of vehicle deceleration on occupant-restraint performance in a real test, the performance of the safety barrier was determined by performing a full-scale test at Lista Airport [23]. The test involves a vehicle, a Ford Fiesta, which strikes the safety barrier at a prescribed angle and speed. The vehicle speed before the collision was measured. Vehicle accelerations in three directions at the centre of gravity were measured during the collision. The test was video recorded. Using normal speed and high-speed video cameras, the behaviour of the safety barrier and the test vehicle during the collision was recorded.

3.1 Vehicle dimensions

Figure 1 shows the characteristic parameters of the vehicle, and these parameters are listed in Table 1.

Table 1. Vehicle dimensions in [m].

<table>
<thead>
<tr>
<th>Width</th>
<th>Length</th>
<th>Height</th>
<th>Wheel track</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.58</td>
<td>3.56</td>
<td>1.36</td>
<td>1.42</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wheel base</th>
<th>Frontal overhang</th>
<th>Rear overhang</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.28</td>
<td>0.63</td>
<td>0.65</td>
</tr>
</tbody>
</table>

3.2 The position of the center of gravity

To determine the position of the center of gravity each test vehicle was first weighed in a horizontal position using 4 load cells. Then the vehicle was tilted by lifting the front of the vehicle. In both positions the following parameters were recorded:

- $m_1$: wheel load, front left
- $m_2$: wheel load, front right
- $m_3$: wheel load, rear left
- $m_4$: wheel load, rear right
- $m_v$: total load
- $\theta$: tilted angle
- $l$: wheel base

Also, location of the center of gravity above a plane through the wheel centers is

$$CG_Z = \left( \frac{m_3 + m_4}{m_v} \right) l$$

where $m_f$ and $m_b$ are, respectively, front and rear masses in tilted position. Table 2 shows the measured parameters to calculate the center of gravity. The position of the centre of gravity for the test vehicle is measured and the result is listed in Table 3.

Table 2. Measured parameters.

<table>
<thead>
<tr>
<th>$m_1$ [kg]</th>
<th>$m_2$ [kg]</th>
<th>$m_3$ [kg]</th>
<th>$m_4$ [kg]</th>
<th>$m_v$ [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>235</td>
<td>245</td>
<td>182</td>
<td>157</td>
<td>819</td>
</tr>
<tr>
<td>$m_f$ [kg]</td>
<td>$m_b$ [kg]</td>
<td>$d$ [m]</td>
<td>$l$ [m]</td>
<td>$\theta$ [deg]</td>
</tr>
<tr>
<td>443</td>
<td>376</td>
<td>1.71</td>
<td>2.28</td>
<td>22.7</td>
</tr>
</tbody>
</table>

Table 3. The position of the centre of gravity.

<table>
<thead>
<tr>
<th>$CG_X$ [m]</th>
<th>$CG_Y$ [m]</th>
<th>$CG_Z$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.94</td>
<td>0.02</td>
<td>0.50</td>
</tr>
</tbody>
</table>

4. INSTRUMENTATION

During the test, the following data should be determined:

- Acceleration in three directions during and after the impact
- Velocity 6 m/s before the impact point
The damage should be visualized by means of:

- Still pictures
- High speed video film

The observations should establish the base for a performance evaluation. Eight video cameras were used for documentation purposes. These cameras are placed relative to the test item. Two 3-D accelerometers were mounted on a steel bracket close to the vehicle’s centre of gravity. This bracket is fastened by screws to the vehicle chassis. The accelerometer from which the measurements are recorded is a piezoresistive triaxial sensor with accelerometer range: ±1500g. The yaw rate was measured with a gyro instrument with which it is possible to record 1°/msec. Figures 2-4 show the measurements of the 3-D accelerometer in x−, y− and z− directions.

Data from the sensors was fed to an eight channel data logger. The logger has a sampling rate of 10 kHz. The memory is able to store 6,5 sec of data per channel. The impact velocity of the test vehicle was measured with an equipment using two infrared beams. The equipment is produced by Alge Timing and is using Timer S4 and photo cell RL S1c. On the test vehicle a plate with a vertical edge was mounted on the left side of the front bumper. This vertical edge will cut the reflected infrared beams in the timing equipment and thereby give signals for calculation of the speed.

The test vehicle was steered using a guide bolt which followed a guide track in the concrete runway. About 7m before the test vehicle hit the test item the guide bolt was released. Vehicle accelerations at the centre of gravity were measured, and also the yaw rate of the vehicle. These measurements make it possible to calculate the Acceleration Severity Index (ASI), the Theoretical Head Impact Velocity (THIV), the Post-impact Head Deceleration (PHD) value and the yaw rate. The impact speed of the test vehicle was determined. The ASI-, the THIV- and the PHD-values are calculated according to EN 1317-1 clause 6 and clause 7, and the results are shown in Table 4. Using normal speed- and high-speed video cameras, the behavior of the safety barrier and test vehicle during the collision was recorded, see Figures 5-6. The value of ASI corresponds to the requirement for impact severity level B. The THIV- and PHD-values are below the limiting values.

Table 4. The calculation results.

<table>
<thead>
<tr>
<th></th>
<th>ASI</th>
<th>THIV</th>
<th>PHD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.28</td>
<td>29.9</td>
<td>7.8</td>
</tr>
</tbody>
</table>

5. WAVELET-BASED SIGNAL ANALYSIS

This section attempts to show the effectiveness of the wavelet technique to represent the measured signals of the test. By choosing the resolution level $j = 7$ (or $m = 2^8$) and expansion of the acceleration signal $x(t)$, $v(t)$, $a(t)$ in (12)-(13) by Haar wavelets, we have $x(t) = X\Psi_m(t)$, $v(t) =$ and

\[
V\Psi_m(t) = V_0\Psi_m(t) + \int_0^t A\Psi_m(\tau) d\tau = V_0\Psi_m(t) + AP_m\Psi_m(t)
\]
Constituting the Haar wavelet properties in (14)-(15), a seven-level wavelet decomposition of the measured x-acceleration signal \( (a_x) \) is performed and the results, i.e. the approximation signal \( (a_7) \) and the detail signals \( (d_1-d_7) \) at the resolution level 7, are depicted in Figures 7-14. One advantage of using these multilevel decomposition is that we can zoom in easily on any part of the signals and examine it in greater detail. Using the approximation signal \( (a_1) \) and the detail signal \( (d_4) \) at the resolution level 1 by Haar wavelets, Figure 15 compares the constructed

\[
X \Psi_m(t) = X_0 \Psi_m(t) + \int_0^t V_0 \Psi_m(\tau) d\tau + \int_0^t A \Psi_m(\tau) d\tau dt,
\]

\[
= X_0 \Psi_m(t) + V_0 P_m \Psi_m(t) + A P_m^2 \Psi_m(t) \quad \text{(15)}
\]
Fig. 15. The constructed signal $a_j(t)$ (solid line) at the resolution level 1 with the real signal (dashed line). signal $a_j(t)$ (solid line) with the real signal (dashed line). It is noted that the approximation error between those curves in Figure 15 is decreasing when the resolution level $j$ increases. The results in Figures 7–15 show the capability of the Haar wavelets to reconstruct the measured signals well.

6. CONCLUSIONS

This paper studied the wavelet-based performance analysis of the safety barrier for use in a full-scale test. Based upon the results obtained, the tested safety barrier has proved to satisfy the requirements for an impact severity level. By taking into account the Haar wavelets, the property of integral operational matrix was utilized to find an algebraic representation form for calculate of wavelet coefficients of acceleration signals. It was shown that Haar wavelets can construct the acceleration signals well.

REFERENCES