TONNAGE SIGNATURE ANALYSIS USING THE HAAR TRANSFORM

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ABSTRACT

The force exerted by the press during a stamping or forming operation offers a convenient and accurate signal for process monitoring. Different statistical methods based on thresholding have been proposed in the past for the analysis of the tonnage signatures. The orthogonal Haar transform (used for data compression) is presented here as an alternative approach which is computationally efficient and ideal for on-line fault detection schemes. This paper introduces the properties of the Haar transform relevant to this application with several case studies drawn from the autobody stamping industry.

INTRODUCTION

The three-dimensional forming of sheet metal imparts the final shape on the finished product by matched dies under considerable pressure. A separate binder ring is used to regulate the flow of material as the inner punch stretches the material over the lower die. Both the blank holder force (BHF) generated by the binder ring and the punch tonnage have significant impact on the quality of the part produced.

The tonnage forces, in particular the BHF, are sensitive to changes in a number of process variables [Ahmetoglu2, *et al.* (1992)], [Siekirt (1986)]. These process variables fall broadly into three categories: (i) material properties, (ii) die set variables, and (iii) press variables. Tonnage signatures are altered either directly by changes in these process variables or indirectly through occurrences of splits, wrinkles or slugs during the drawing stage.

Tonnage monitoring systems are used to monitor peak loads and variation in tonnage as a function of time, ram position or crank angle [Carabbio (1993)], [Clark, *et al.* (1991)]. However, the detection schemes available thus far depend on thresholding to detect the occurrence of a fault. Upper and lower control limits are used to establish an acceptable operating range around a desired template signal. Any excursion beyond these thresholds will trigger a fault alarm.

More robust detection schemes have been developed by [Martinez and Bortfeld (1987)] and [Seem and Knussmann (1994)] which are based on the deviation of tonnage signatures from a desired template. The data fall into acceptable or unacceptable classes. These techniques were used to detect workpiece fracture and die wear.

All these methods, however, do not provide any fault isolation capability. The standard (diagnostic) procedure following a fault alarm is to shut down the press and "eyeball" the signatures for some quick answers. This is not only an off-line procedure but also one which success rate (of diagnostic) is highly dependent on the experience and skill of the attendent technician.

This paper presents an alternative approach to the fault detection problem using the Haar transform. The extension to fault isolation comes naturally with sufficient training data. While the more familiar orthogonal Fourier transform (which uses complex exponentials as its basis functions) is ideal for sinusoidal narrow-band signals, the Haar transform is especially well-suited to represent spectrally wide-band signals

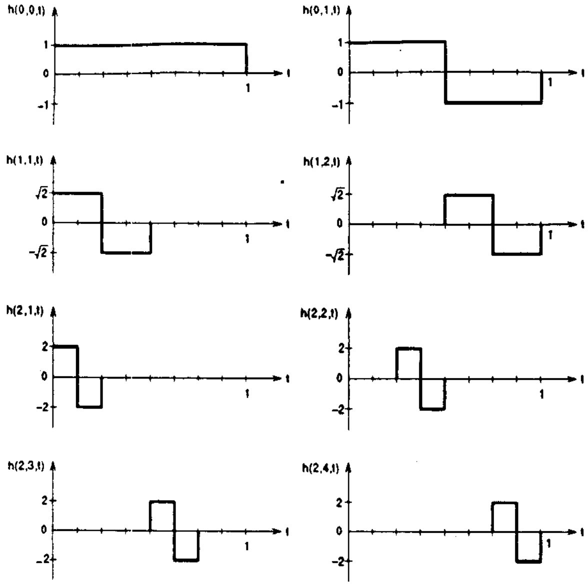

FIGURE 1: CONTINUOUS HAAR FUNCTION FOR n=8 SUBINTERVALS.

[Mikhael and Ramaswamy (1992)], as in this case. The Haar transform is also the most efficient algorithm in terms of computational speed and memory usage.

The fundamental definition and properties of the Haar functions are given in Section II. The applications of the Haar transform to the detection problem in the stamping process are discussed in the section titled *Applications.*

HAAR FUNCTIONS

The Haar transform is a member of a class of nonsinusoidal orthogonal functions [Ahmed and Rao (1975)]. It consists of rectangular waves distinguished by a parameter called sequency which is a generalization of frequency. The *set* of continuous Haar functions {h(n,m,t)} is periodic, orthonormal and complete, and was proposed by Alfred Haar in 1910. The Haar orthonormal sequence is defined on the closed interval [0,1] and can be generated by the recurring relation (1):

$$h(0,0,t) = 1, \; t \in [0,1)$$
$$h(r,m,t) = \begin{cases} 2^{r/2}, & \frac{m-1}{2^r} \le t < \frac{m-1/2}{2^r} \\ -2^{r/2}, & \frac{m-1/2}{2^r} \le t < \frac{m}{2^r} \\ 0, & elsewhere \; \forall \; t \in [0,1) \end{cases} \tag{1}$$

where $0 \le r < log_2 n$ (n = number of subintervals in [0,1)) and $1 \le m \le 2^r$.

The first eight Haar functions are shown in Fig. 1. Points of discontinuity are defined as the average of the limits approached from both sides of the discontinuity.

The Haar functions form a complete orthonormal basis of $L^2[0,1]$, the space of functions $f(t)$ that are defined over the interval [0,1] with $f^2(t)$ integrable in the Lebesque sense [Shore (1973)]. The function $f(t)$ can be expressed as an infinite series of Haar functions:

$$f(t) = \sum_{n=0}^{\infty} \sum_{m=0}^{2^n-1} c_n^m \, h(n,m,t) \tag{2}$$

where

$$c_n^m = \int_0^1 f(t)\, h(n,m,t)\, dt \tag{3}$$

In practice the function $f(t)$ is approximated by the partial sum $S_N(t)$ which contains 2^N terms :

$$S_N = \sum_{n=1}^{N} \sum_{m=0}^{2^n-1} c_n^m \, h(n,m,t) \tag{4}$$

In other words, in the expansion of $f(x)$, $S_N(x)$ is a step function with 2^N steps, with the value of $S_N(x)$ at each step equal to the mean value of $f(x)$ within the step interval. The coefficient, c_n^m, is simply proportional to the difference between two adjacent steps of $S_N(x)$ at $x = (2m-1)/2^n$. It can be shown that S_N is the best approximation of $f(x)$ in the mean-square-error sense when it is a step function of 2^N equal steps.

The corresponding discrete Haar functions are obtained by sampling the continuous Haar functions in Fig. 1 at the middle of each subinterval to produce an array:

$$H(3) = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 \\ \sqrt{2} & \sqrt{2} & -\sqrt{2} & -\sqrt{2} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sqrt{2} & \sqrt{2} & -\sqrt{2} & -\sqrt{2} \\ 2 & -2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & -2 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2 & -2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 2 & -2 \end{bmatrix}$$

The discrete Haar transform array is generally denoted by $H(N)$ where $N = log_2 n$ and n is the number of discrete data points. Each row of $H(N)$ is a discrete Haar function obtained by sampling the corresponding continuous Haar function, h(r,m,t).

If $[X] = [x(0)\, x(1)\, x(2) \ldots x(n-1)]$ is a sequence of n discrete points, then the corresponding Haar coefficients, $[C] = [c(0)\, c(1)\, c(2) \ldots c(n-1)]$ for the Haar basis are related by the transform pair:

$$[X] = [C]\,[H(N)]$$
$$x(i) = \sum_{k=0}^{n-1} c(k)\hbar(k,i) \tag{5}$$

and

$$[C] = [X]\,[H(N)]^{-1}$$
$$c(i) = \sum_{k=0}^{n-1} x(k)\hbar^{-1}(k,i) \tag{6}$$

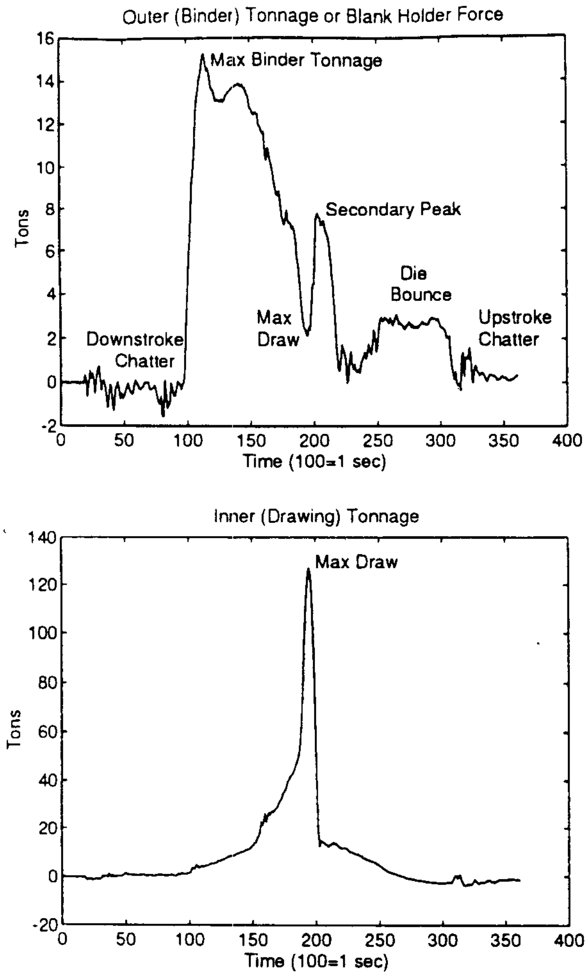

FIGURE 2: TYPICAL DRAW PRESS SIGNATURE.

where $h(i,j)$ and $h^{-1}(i,j)$ are the (i,j)th elements of $H(N)$ and $H(N)^{-1}$ respectively.

The Haar transform can be done in $(2n-2)$ additions and subtractions and is less than the $n\log_2 n$ multiplications in the case of the fast Fourier transform.

APPLICATIONS

Tonnage signals from a HELM monitoring system were recorded with a TEAC RD145 DAT recorder. The location of the strain gage transducers vary with the type of the press. A typical signature showing the various segments of the BHF and inner tonnage is shown in Fig. 2.

Under normal operating conditions, the Haar coefficients for successive cycles follow a normal Gaussian distribution, with very small variance. Fault sensitive coefficients are identified from training data and tracked during a production run. The $\pm 3\sigma$ limits have been used to set the thresholds for fault alarm in most cases. However, the selection of thresholds is purely subjective and depends on several factors including the age and condition of the press which affects the repeatability of the process. The absence of quantitative measures in this paper is intentional as the purpose here is to demonstrate the methodology and not to establish operating limits for the stamping process; the reason being that each *press-die-material-stamping speed* combination produces a unique signature [Carabbio (1993)]. Furthermore, the correct choice of Haar detectors will set new *maxima* and *minima* in the presence of an offending signature (Fig. 8).

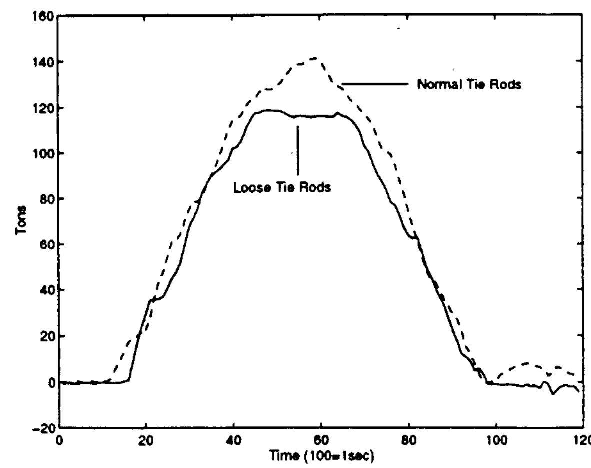

FIGURE 3: SIGNATURE FOR NORMAL/LOOSE TIE ROD.

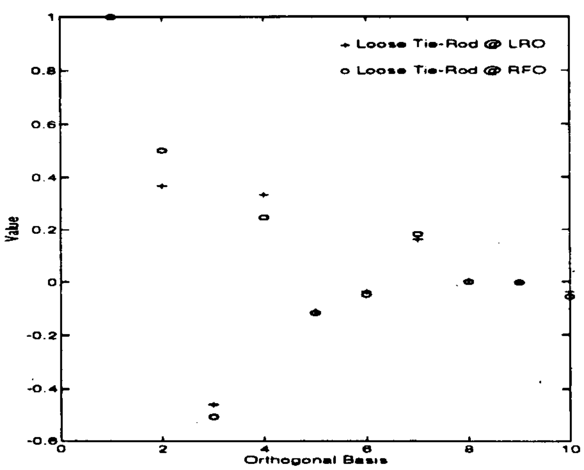

FIGURE 4: HAAR COEFFICIENTS VARY WITH TIE ROD CONDITION.

The detection of four process faults using the Haar transform will be discussed in the following paragraphs. These are based on case studies conducted at an autobody stamping plant.

Loose Tie Rods

In straight-side presses, the crown and bed are connected to the uprights by tie rods which hold the uprights in compression. The tie rods must be equally prestressed for the press to operate normally. The crown separates from the uprights at about 200% of press capacity and any loads above this is absorbed by the tie rods.

When this happens, the uprights are no longer in compression and the strain gages of the tonnage monitors remain in maximum extension over the period of separation during the highest point of the forming cycle. The tonnage signature has a flat top or is said to "plateau out" at the maximum tonnage as shown in Fig. 3.

Fig. 4 shows the shift in the values of selected (normalized) Haar coefficients when this occurs. The separation between the two sets of coefficients is directly proportional to the extent of the problem.

Non-parallelism

Unlike one and two point slides (the number of connections supporting the slide), parallelism of slide to bolster of a four point slide may be forced. Forcing parallelism during die contact is one of the major causes for poor part quality and also detrimental to die life and press integrity. Fortunately, the forcing action shows up clearly in the tonnage signature and can be easily rectified if detected early in its appearance. A correlation between the corner tonnages will indicate a rocking motion between "opposing" corners as shown in Fig. 5. Here, the different degrees of parallelism (before and after the links were adjusted) are reflected by a corresponding shift in the 1st, 3rd and 4th Haar coefficients (Fig 6). The deterioration in condition can be monitored by tracking the trajectories of these coefficients over time.

Spurious Faults

Spurious faults are extremely difficult to detect without continuous on-line monitoring. They are highly nonstationary and random and usually associated with the initial stages of component failure. In this example, a cycle with a fault (Fig. 7) was inserted in a train of 60 successive cycles of the press.

The 6th and 12th coefficients displayed the largest change at the fault cycle. The trajectories of these two coefficients are plotted in Fig. 8.

Slugs

Splits usually occur during the drawing stage due to a variety of causes. In extreme cases, pieces of the blank material around the split may break off and lodge themselves in the die. These "slugs" in turn produce splits and surface defects in the next blank.

Fig. 9 shows a train of pulses from the tonnage monitors leading from a normal operation (cycle n) to the discovery of a slug at the end of (cycle (n+2)). Only the region

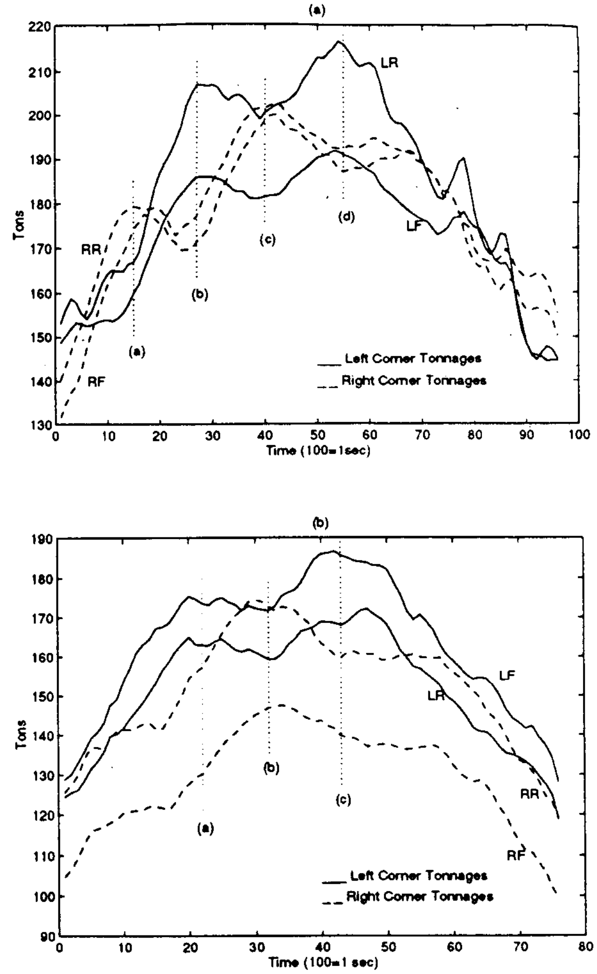

FIGURE 5: PARALLELISM (a) BEFORE, AND (b) AFTER LINK ADJUSTMENT.

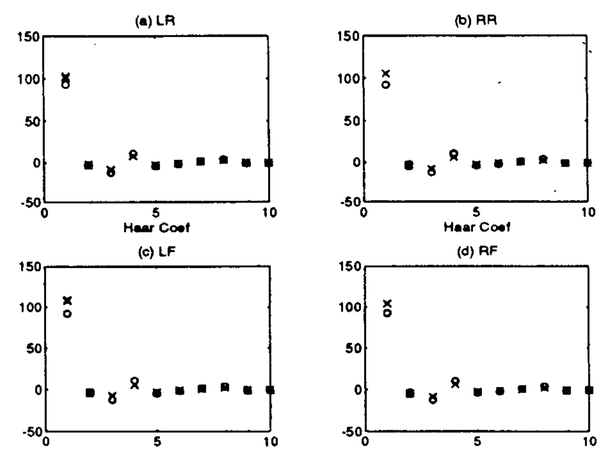

FIGURE 6: HAAR COEFFICIENTS (x) BEFORE, AND (o) AFTER LINK ADJUSTMENT.

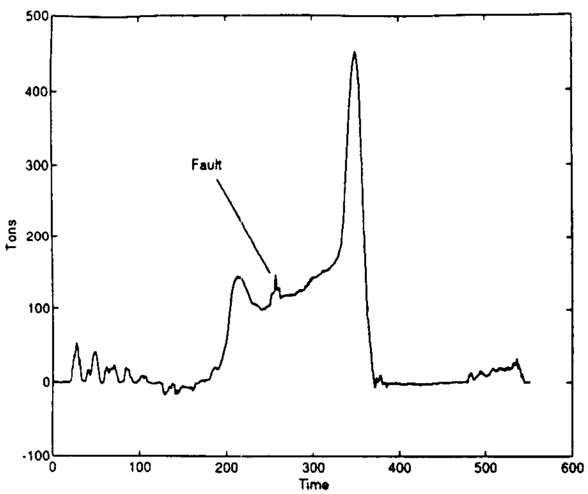

FIGURE 7: FAULT SIGNATURE.

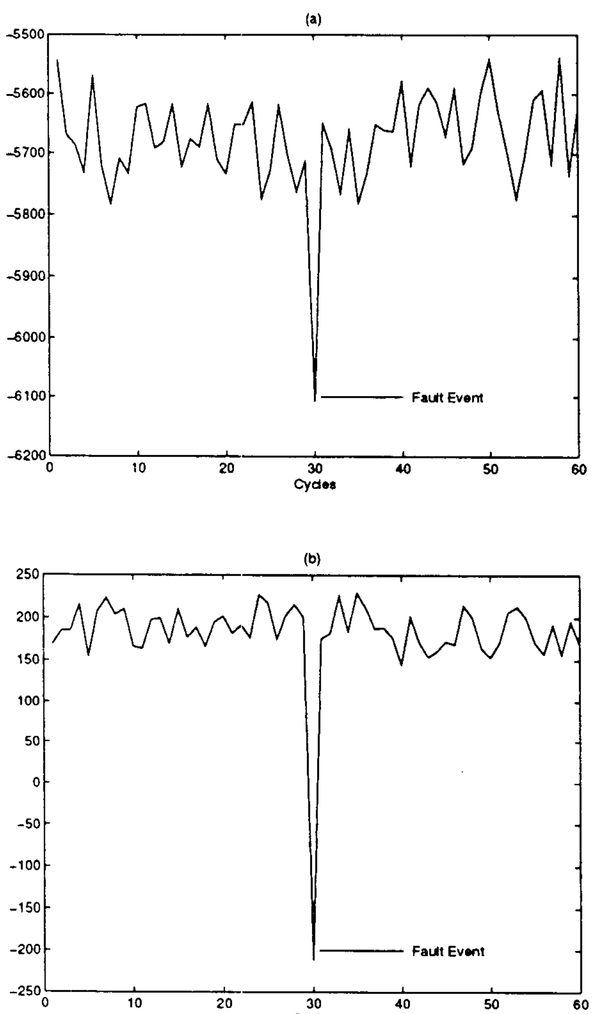

FIGURE 8: TRAJECTORY OF THE (a) 6th AND (b) 12th HAAR COEFFICIENTS.

around the secondary peak was affected by this anomaly. The corresponding Haar coefficients were computed for these signals and a plot of the lowest 10 coefficients shown in Fig. 10.

CONCLUSION

The application of the Haar transform to the analysis of tonnage signals encountered in the stamping industry was discussed. The nature of the normal and fault signatures lend themselves as ideal candidates for the Haar transform. In contrast with conventional methods that are dependent on peak tonnage measurements, the Haar approach is not compromised by the relative magnitude or distance of the faults from the peak tonnage.

The computational efficiency of the Haar coefficients makes it ideal for real-time process monitoring.

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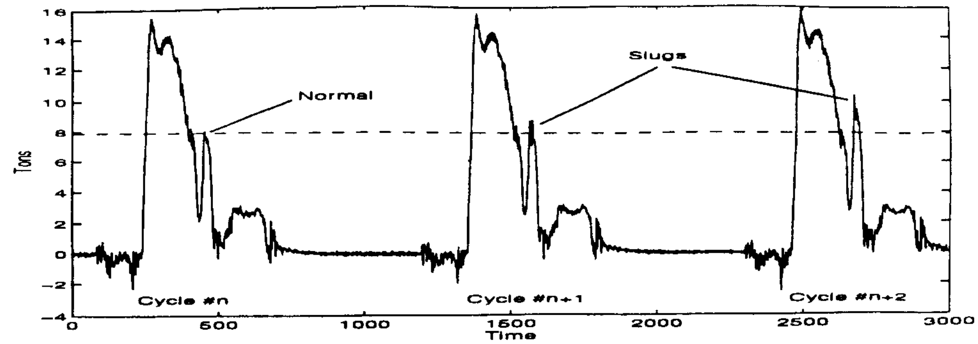

FIGURE 9: TRAIN OF PULSES LEADING TO A SLUG.

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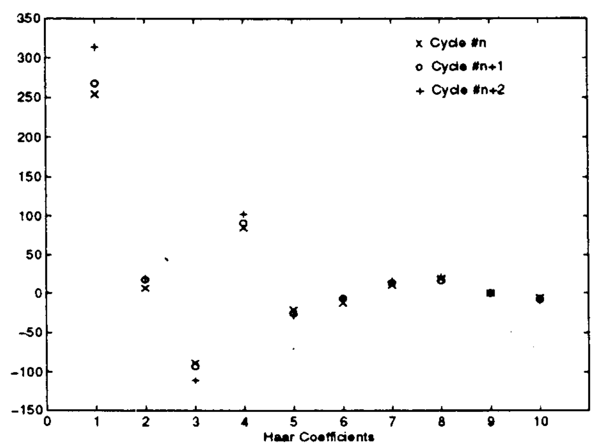

FIGURE 10: HAAR COEFFICIENTS AFFECTED BY THE SLUG.