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# APPLICATION OF THE SECOND GENERATION WAVELET TRANSFORM FOR PAVEMENT PREVENTIVE MAINTENANCE

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**Abstract:** This study proposes the use of the Second-generation Wavelet Transform (SWT) for pavement preventive maintenance. New wavelet filters in the SWT are biorthogonal wavelet filters containing free parameters. This method is adopted to determine free parameters based on some training signals, which contain the localized road distress. Using free parameters, it is comparatively easier to determine an optimal basis function. Application of the filters to Training signals effectively leads to the detection of the characteristic points of the road surface. SWT was applied to the vertical acceleration of a vehicle on the road surface. When the form of the input data and the studied waveform of a free parameter were similar, a close-up of the output ingredient was taken. When form differed, it was not detected as a feature point. This is considered to be a very important factor when designing WT for use in pavement preventive maintenance.

**Key Words:** Second-generation wavelet transform, Training signals, Free parameters, Road surface characteristics, Pavement preventive maintenance

## 1. INTRODUCTION

A paved road surface is a civil engineering structure that touches a vehicle directly through its tires. Since the road surface unevenness affects the drive of a vehicle, the performance of the road surface should be maintained at a good level. In recent years, following increases in traffic volume and increases in both the size and speed of vehicles, social requirements for road surface conditions have become strict in Japan. The safety and comfort of the drive are a special concern. Therefore, to maintain paved road surfaces efficiently and effectively, research in evaluating the unevenness on road surfaces has become essential, and many studies results on this topic have been reported worldwide in recent years.

As a means of detecting unevenness existing locally on road surfaces, the Wavelet Transform (WT), which can simultaneously discriminate information on uneven spots and frequency (or wavelength), have attracted much attention. WT is a calculation method that uses a wavelet called the basis function, to detect a component similar to the basis function as found in analytical data (such as unevenness of the road surface). One of the major benefits of WT is its quick operating speed, since the same algorithm of decomposition and recomposition is used in all calculation processes; therefore, WT has been used in many engineering fields.

For the calculation of WT, a basis function customized to obtain results for analytical purposes must be used. For example, to detect corrugation, the basis function must be specialized for detecting corrugation. Although the typical basis function formulated by a mathematician is bundled in the program of the commercially available WT, no functions specific to the analysis of paved road surface conditions are included. Therefore, the basis function for the evaluation of paved road surface conditions must be formulated. The formulation of the basis function is difficult, however, since certain conditions (such as a moment condition) must be satisfied. Although WT attracts much attention as a detection and evaluation tool of road surface unevenness, it has not yet been progressed enough to use in the actual field.

As a remarkable way of solving this problem, Sweldens (1996) published the Lifting Scheme method, in which the function to learn a characteristic point was added to the conventional WT. Furthermore, Takano *et al.* (1999) published a study in which the Lifting Scheme method was summarized systematically as the Second-generation Wavelet Transform (SWT), and then applied to the field of information discovery science. Optimization processing for the basis function in detecting a characteristic component was significantly improved by using SWT.

In the field of pavement engineering, authors have performed fundamental examinations in applying SWT to the detection of characteristically uneven points on the road surface; they have reported that SWT was an effective tool in formulating the basis function for road surface management. Therefore, SWT can be applied as a preventive maintenance tool to detect “signs” of unevenness, such as damage on the road surface within periodically measured sections. If the principle of maintenance is to be preventive rather than corrective, SWT can be used effectively as a tool to bring about pavement preventive maintenance.

In Japan, since there is no legal standard related to the measurement of paved road surface unevenness, the road surface unevenness on an ordinary road (except highways) is measured only two times: during post-completion/post-installation inspection, and whenever there is serious damage. There is no concept of pavement preventive maintenance on an ordinary road in Japan. Therefore, the actual status of the performance of the paved-road surface is not grasped at this time.

Thus in this study, a road administrator used a SUV vehicle fitted with a vertical accelerator on the unsprung mass to patrol the road and measure vertical acceleration caused by the unevenness in the road surface. As a result, data required for analytic purpose were captured when SWT was applied to the process of such detection, and the results are outlined below.

## 2. PROPERTIES OF THE SECOND GENERATION WAVELET TRANSFORM

### 2.1 Overview of the Second Generation Wavelet Transform

Let $c_l^1$ denote a signal with time parameter $l$. Using multi-resolution analysis in the WT, the signal $c_l^1$ can be broke down into low frequency and high frequency components:

$$\hat{c}_k^0 = \sum_l \tilde{h}_{k,l}^{old} c_l^1 \tag{1}$$

$$\hat{d}_m^0 = \sum_l \tilde{g}_{m,l}^{old} c_l^1 \tag{2}$$

Where, $\hat{c}_k^0$ : Low frequency component
$\hat{d}_m^0$ : High frequency component
$\tilde{h}_{k,l}^{old}$ : Old type of low frequency decomposition filter
$\tilde{g}_{m,l}^{old}$ : Old type of High frequency decomposition filter
$l$ : Time parameter (Frequency parameter)
$k$ : Position parameter (low frequency)
$m$ : Position parameter (high frequency)

Conversely, we can reconstruct the original signal $c_l^1$ from the low frequency and high frequency components $\hat{c}_k^0$ and $\hat{d}_m^0$ by the formula:

$$c_l^1 = \sum_k h_{k,l}^{old} \hat{c}_k^0 + \sum_m g_{m,l}^{old} \hat{d}_m^0 \tag{3}$$

Where, $h_{k,l}^{old}$ : Old type of low frequency reconstruction filter
$g_{m,l}^{old}$ : Old type of high frequency reconstruction filter

These filters are subject to the following conditions. They are called biorthogonal conditions:

$$\begin{gathered}\sum_l h_{k,l}^{old}\, \tilde{h}_{k',l}^{old} = \delta_{kk'}, \quad \sum_l g_{m,l}^{old}\, \tilde{h}_{k,l}^{old} = 0, \\ \sum_l h_{k,l}^{old}\, \tilde{g}_{m,l}^{old} = 0, \quad \sum_l g_{m,l}^{old}\, \tilde{g}_{m',l}^{old} = \delta_{mm'}\end{gathered} \tag{4}$$

The SWT is the method that added free parameters $\tilde{s}_{k,m}$ to the WT, and defined as follows:

$$\begin{aligned} h_{k,l} &= h_{k,l}^{old} + \sum_m \tilde{s}_{k,m} g_{m,l}^{old} \\ \tilde{h}_{k,l} &= \tilde{h}_{k,l}^{old} \\ g_{m,l} &= g_{m,l}^{old} \\ \tilde{g}_{m,l} &= \tilde{g}_{m,l}^{old} - \sum_m \tilde{s}_{k,m} \tilde{h}_{k,l}^{old} \end{aligned} \tag{5}$$

Where, $h_{k,l}$ : New type of low frequency reconstruction filter
$\tilde{h}_{k,l}$ : New type of low frequency decomposition filter
$g_{m,l}$ : New type of high frequency reconstruction filter
$\tilde{g}_{m,l}$ : New type of high frequency decomposition filter
$\tilde{s}_{k,m}$ : Free parameters

SWT can create a new filter that is suitable for a signal by free parameters. The biorthogonal conditions are as follows:

$$\begin{aligned}&\sum_l h_{k,l}\,\tilde{h}_{k',l}=\delta_{kk'}, && \sum_l g_{m,l}\,\tilde{h}_{k,l}=0,\\ &\sum_l h_{k,l}\,\tilde{g}_{m,l}=0, && \sum_l g_{m,l}\,\tilde{g}_{m',l}=\delta_{mm'}\end{aligned} \tag{6}$$

## 2.2 Detection of characteristic point and training of free parameters

As for the new type of high frequency decomposition filter, High frequency component $d_m^0$ on the characteristic point of a signal is adjusted to 0 by free parameters.

When subtracting the absolute value of $d_m^0$ from the absolute value of $\hat{d}_m^0$ in the WT, the value is small at the points that are different from the characteristic point, while it remains almost the same at the point similar to the characteristic point. The SWT can easily detect the point of the characteristic point by using this formula.

$$I_m=\left|\hat{d}_m^0\right|-\left|d_m^0\right| \tag{7}$$

Where, $I_m$: Difference between $\left|\hat{d}_m^0\right|$ and $\left|d_m^0\right|$

Where, $d_m^0$ is computed by (8).

$$\begin{aligned}d_m^0&=\sum_l \tilde{g}_{m,l}\,c_l^1\\ &=\sum_l\left(\tilde{g}_{m,l}^{old}-\sum_k \tilde{s}_{k,m}\,\tilde{h}_{k,l}^{old}\right)c_l^1\\ &=\hat{d}_m^0-\sum_k \hat{c}_k^0\,\tilde{s}_{k,m}\end{aligned} \tag{8}$$

As $d_m^0$ is zero at the characteristic point,

$$d_m^0=\hat{d}_m^0-\sum_k \hat{c}_k^0\,\tilde{s}_{k,m}=0 \tag{9}$$

For $\tilde{s}_{k,m}$, the efficient method is to prepare $v=2n$ of training signals (TS) with characteristic point:

$$\begin{aligned}&\sum_{k=m-n}^{m+n}\hat{c}_k^{0,v}\,\tilde{s}_{k,m}-\hat{d}_m^{0,v}=0, \quad v=1,2,\ldots,2n\\ &\hat{c}_k^{0,v}=\sum_l \tilde{h}_{k,l}^{old}\,c_l^{1,v}\ ,\ \hat{d}_m^{0,v}=\sum_l \tilde{g}_{m,l}^{old}\,c_l^{1,v}\end{aligned} \tag{10}$$

The equation is a condition that the summation of the $\tilde{g}_{m,l}$ is zero, that is,

$$\sum_l \tilde{g}_{m,l} = \sum_l \left( \tilde{g}^{old}_{m,l} - \sum_{k=m-n}^{m+n} \tilde{s}_{k,m} \, \tilde{h}^{old}_{k,l} \right) = 0$$

Since $\tilde{g}^{old}_{m,l}$ satisfy $\sum_l \tilde{g}^{old}_{m,l} = 0$ and $\sum_l \tilde{h}^{old}_{m,l} = const.$, this condition is equivalent to (11).

$$\sum_{k=m-n}^{m+n} \tilde{s}_{k,m} = 0 \tag{11}$$

Writing (10) and (11) in the matrix form,

$$\begin{bmatrix} \hat{c}^{0,1}_{m-n} & \hat{c}^{0,1}_{m-n+1} & \cdot & \cdot & \hat{c}^{0,1}_{m+n} \\ \hat{c}^{0,2}_{m-n} & \hat{c}^{0,2}_{m-n+1} & \cdot & \cdot & \hat{c}^{0,2}_{m+n} \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \hat{c}^{0,2n}_{m-n} & \hat{c}^{0,2n}_{m-n+1} & \cdot & \cdot & \hat{c}^{0,2n}_{m+n} \\ 1 & 1 & \cdot & \cdot & 1 \end{bmatrix} \begin{bmatrix} \tilde{s}_{m-n,m} \\ \tilde{s}_{m-n+1,m} \\ \cdot \\ \tilde{s}_{m+n-1,m} \\ \tilde{s}_{m+n,m} \end{bmatrix} = \begin{bmatrix} \hat{d}^{0,1}_m \\ \hat{d}^{0,2}_m \\ \cdot \\ \hat{d}^{0,2n}_m \\ 0 \end{bmatrix} \tag{12}$$

### 2.3 Procedure To Detect Characteristic Point

The procedure to detect characteristic point can be summarized as follows:

1) Compute $\hat{d}^0_m$ by (2)
2) Train $\tilde{s}_{k,m}$ by (12)
3) Compute $d^0_m$ by (8)
4) Compute $I_m$ by (7)
5) Find the characteristic point

## 3. DETECTION OF CHARACTERISTIC ROAD SURFACE UNEVENNESS USING VERTICAL ACCELERATION

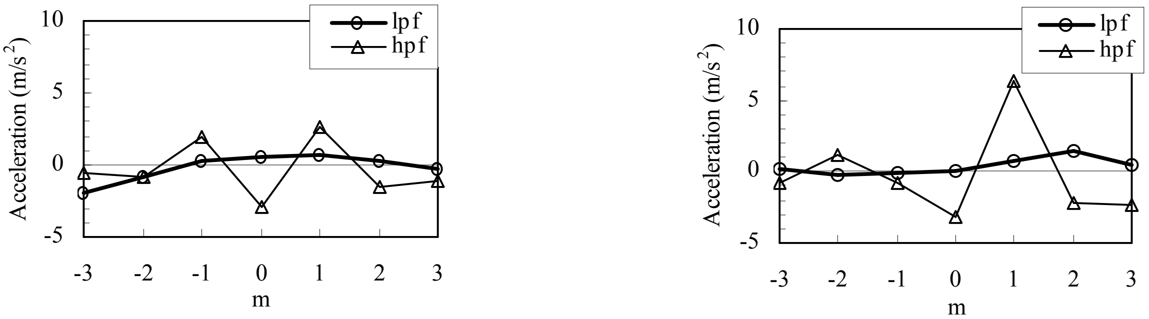
The point of characteristic road surface unevenness should be measured by a profiler that purpose is to measure such traits. However, measuring unevenness is not easy, on account of the great deal of labor required for traffic control and the measurement itself. In this regard, vertical acceleration measurements on a patrol vehicle using the commercially available sensor are sufficient in detecting the characteristics of road surface unevenness within the speed limits of an ordinary road, even though it is a simple measurement system. Moreover, the method of presuming the true profile of the road surface from the vertical acceleration data is also devised. Therefore, this method is able to take into account vehicle movement and road surface management; in terms of traffic engineering, it is interesting from the viewpoint of analyzing the interaction between the vehicle and the road surface.

In this study, several characteristic uneven points on the road surface were detected using the vertical acceleration sensor installed on the unsprung mass in the patrol vehicle, and a free parameter was obtained from those uneven points (or training signals, hereafter referred to as "TS") by SWT, and from the similar points as these uneven points are detected from other vertical acceleration data. In addition, N = 4 and N = 6 are configured as the number of TS, since 2*n pieces of TS are required, and the detection performances are compared.

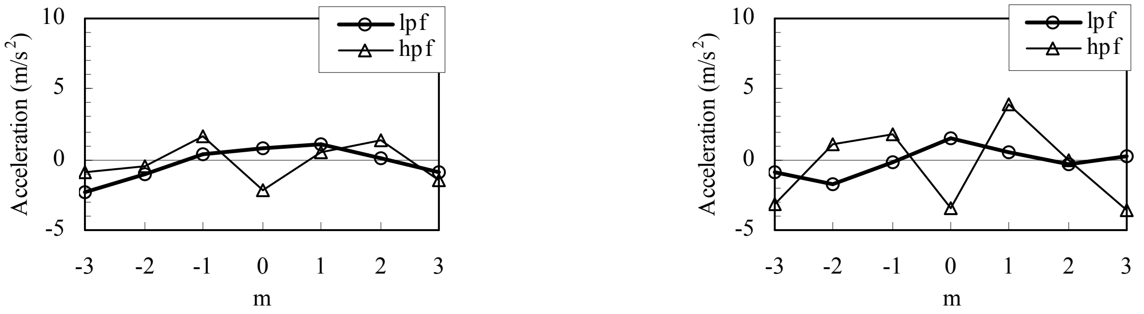
### (1) Learning the free parameter

The model waveform configured, as TS are the slightly damaged block pavements. TS are shown in Figure 1. In this figure, lpf denotes a low-frequency component and hpf denotes a high-frequency component.

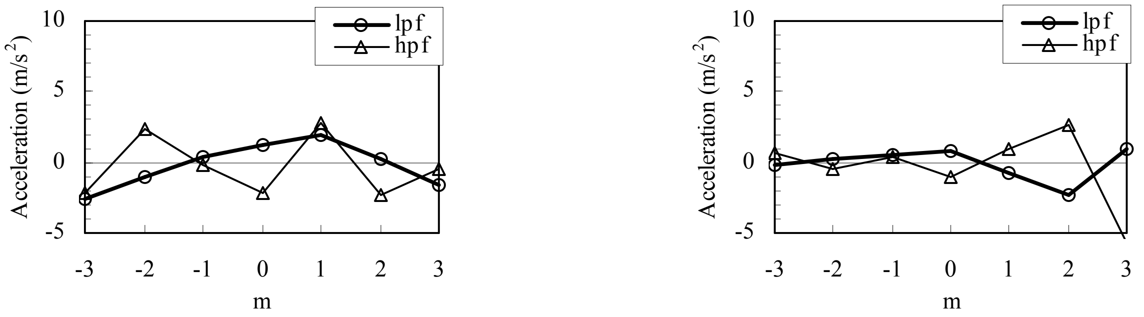
For the configuration of N = 4, the data for five points, including two points before and after the characteristic point m in waveform (a) - (d), are used. Similarly, for the configuration of N= 6, the data for seven points, including three points before and after the characteristic point



(a) No.1 (b) No.2



(c) No.3 (d) No.4



(e) No.5 (f) No.6

Figure 1. Training Signals (TS)

Table 1. The Result of Free Parameters $\tilde{s}_{k,m}$

| k | $\tilde{s}_{k,m}$(N=4) | $\tilde{s}_{k,m}$(N=6) |
|---|---|---|
| m-3 | --- | 0.003 |
| m-2 | 3.839 | 3.499 |
| m-1 | -3.485 | -1.091 |
| m | -0.008 | 4.766 |
| m+1 | 2.920 | -5.310 |
| m+2 | -3.266 | 2.197 |
| m+3 | --- | -4.063 |

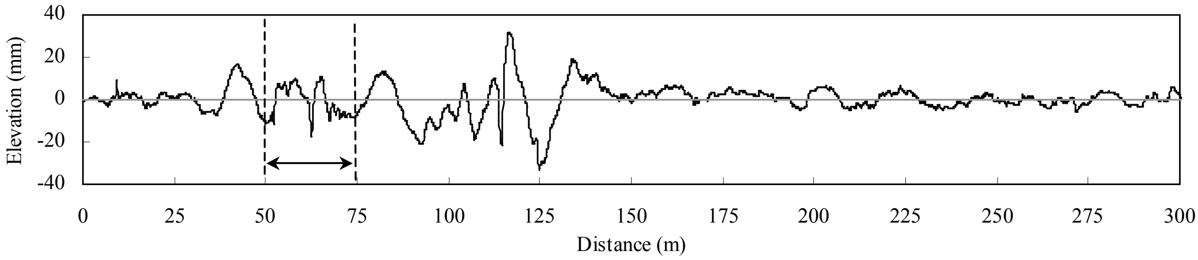


Figure 2. Road Surface Waveform

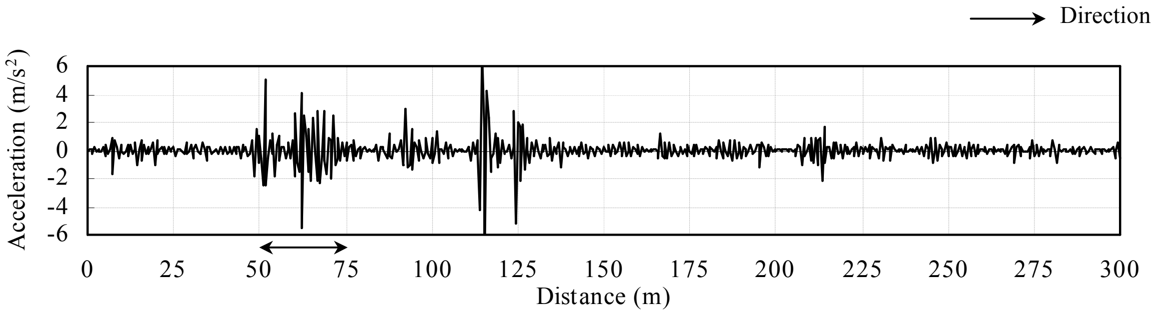
m in waveform (a) - (f), are used. As shown in formula (12) , it is necessary to expand the learning data section (point), along with the increase of TS number.

Table 1 shows the learning data $\tilde{s}_{k,m}$. Here, Spline N = 2 is used as the basis function, and on the basis of this basis function, the weighting process to extract the characteristic point is performed by $\tilde{s}_{k,m}$.

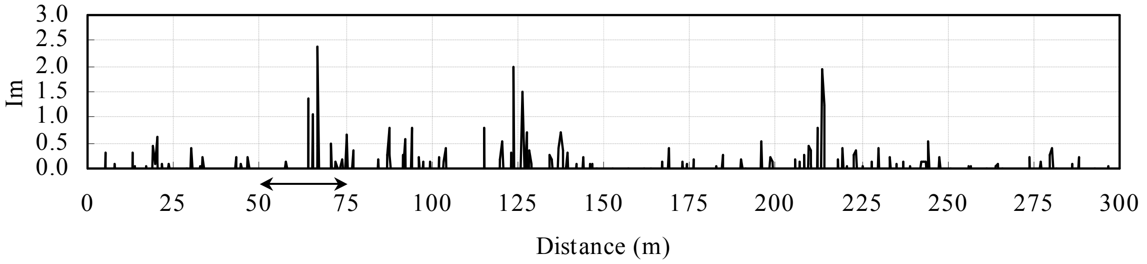
(2) Detection and detection performance of characteristic road-surface unevenness

After $\tilde{s}_{k,m}$ is obtained, characteristic road surface unevenness is detectable using the method described in heading 2. In this section, the block pavement is detected from the vertical acceleration data of the unsprung mass of the vehicle, measured on the disaster prevention road on a riverbed (full length: 300 m, IRI = 5 mm/m) in Japan. Figure 2 shows the road surface data. And Figure 3 (a) is the original waveform used for analysis.

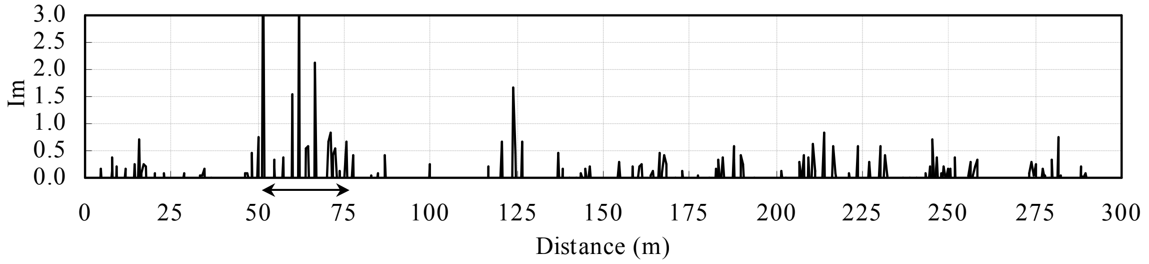
The block pavement exists in the section, between 50 and 75 m from the starting point, as shown in a dotted frame in the figure. This block pavement is not repaired sufficiently in comparison to ordinary roads, and its unevenness is considerable. Usually, the amount of unevenness on block pavement appears to be large in comparison to other asphalt pavement, since unevenness on the asphalt pavement of this road is equally large; if there is no prior information such as experience in this case, it is difficult to discriminate this section as the block pavement. Therefore, in this research, in order to increase the efficiency of the road patrol in the future and to remove conventional empiricism from the selection of the “right places to study,” the section showing the characteristic road surface unevenness is detected using SWT.



(a) Original Waveform



(b) Detection Results of the Characteristic Point (TS N=4)



(c) Detection Results of the Characteristic Point (TS N=6)

Figure 3. Detection of the Characteristic Point

The detection results of the characteristic point when the number of TS is configured as N= 4 is shown in Figure 3 (b). Here, a larger Im value indicates a higher correlation with the point of TS (i.e., slightly damaged block pavement) that has been studied.

In the case of N = 4, although some areas in the section of the block pavement having large amplitude are detected, the detection performance is not satisfactory. Moreover, other sections with large amplitude have been detected to be similar to the block pavement.

The detection result when N = 6 is configured as the number of TS is shown in Figure 3 (c). In comparison to the case of N = 4, although a place 125 m from the starting point was accidentally detected, improvement to the detection performance in the section of the block pavement was confirmed. The proportion of components in this section among the total number of detected components is shown in Figure 4. In the case of N = 6 (which is the example used in this study), the places having the value beyond Im = 0.7 can be specified as the block pavement section with a probability of 50% or more. As mentioned above, it can be

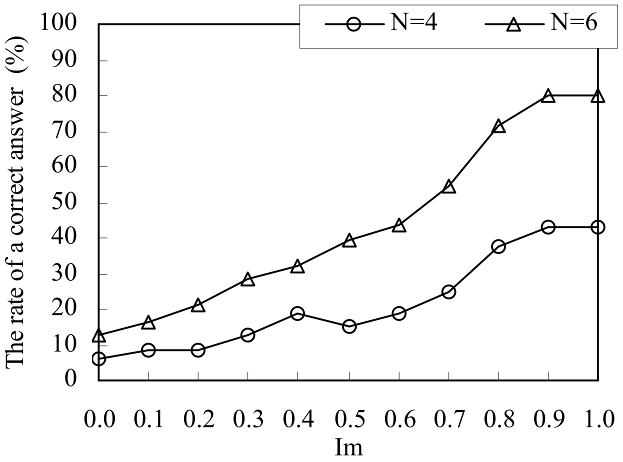


Figure 4. The Proportion of Components in This Section Among the Total Number of Detected Components

considered that the detection performance of characteristic data improves along with an increase of the number of learning TS. However, on the other hand, the learning distance section of TS is the cause of variation in each waveform of TS. Because of this, many components of noise appear on the level with the low value of Im, shown in Figure 3 (c). Therefore, the number of TS and the length of the learning section must be configured appropriately, according to the purpose behind the detection.

## 4. APPLICATION TO PAVEMENT PREVENTIVE MAINTENANCE

The maintenance of pavement should be, basically, an activity that aims to maintain the safety, comfort, and economic efficiency satisfied by the pavement; it should be carried out according to a predetermined plan. Therefore, in order to implement maintenance activities efficiently and effectively, prediction and analysis technology suitable for the purpose at hand is essential. The technical ability to measure the road surface unevenness improves very rapidly, along with the development of computer technology; however, since the number of road surface condition survey vehicles introduced to the site is not sufficient for these purposes, Pavement Management System (PMS) does not at this time fully function from the viewpoint of life-cycle analysis. An understanding of pavement conditions depends upon the provision of a daily road patrol. Furthermore, since qualitative evaluations by inspectors depend upon their skills, it is difficult to create a database in which objectivity, reliability and a standardization of terms can be found. That is, the instruction of the repair according to the result of an accurate monitor of the deterioration situation of pavements is difficult in a present road pavement maintenance management system.

In the near future in Japan, when the proportion of actively-used roads exceeding 20 or 30 years of age has rapidly increased, the need for a full-scale road maintenance system will be evident. The deterioration of civil engineering structures (pavement is included) occurs quickly. Therefore, the road administrator on these roads will have to be aware of the performance of the road at all times. In the situation that sufficient public investments or maintenance money cannot be expected, to maintain the service level of current roads and to use them effectively, it is necessary to capture data concerning their conditions with the passage of time, and to carry out suitable maintenance initiatives based on a predetermined plan. In such a case, removing a doubtful spot before uneven points, including road surface damage becomes large, is imperative. Therefore, from this point forward, it is necessary to detect those initial "signs" that eventually lead to large road-surface unevenness, rather than detecting road surface unevenness when it is too great and hence expensive and time-consuming to repair. Such is the essence of proactive rather than reactive road surface maintenance management, and it is a favored field for the application of SWT.

When TS is specified, a data bank that records the following four kinds of data is necessary; road unevenness, behavior of vehicles, maintenance work records, and traffic. Therefore, when TS is first specified, time is required. In addition, the first specification of analytical data used as TS requires a lot of work. However, once TS is determined and its compatibility with site data is proven, the detection of characteristically uneven areas can be performed automatically. At that point, SWT could finally contribute to minimizing the overall costs of road surface maintenance.

## 5. CONCLUSION

This study proposed a preventive maintenance method based on SWT that detects characteristic unevenness of road surfaces, from the vertical acceleration generated on a road patrol vehicle. Since road patrol vehicles that perform routine inspections are used as measurement vehicles in this method, data accumulation over time can take place without excessive investigators expense or time. The road maintenance in many advanced nations has changed greatly from the construction type to the maintenance management type. And now, the technology that is used to investigate and evaluate road performance more accurately is needed. Since SWT is considered an effective tool in response to this need, we will continue to study the optimization of TS for purposes of road management.

## REFERENCES

Kawamura,A., Shimeno,S., Himeno,K., Komatsubara,A. and Hagiwara, T. (1999) Study on Application of the Multiresolution Analysis to Road Profile Evaluation. **Proceedings of the 3rd International Symposium on the Environmental Impact of Road Unevenness**, PIARC, Porto, Portugal, 121-132, March 1999.

Shirakawa, T, Kawamura,A. and Nakatsuji,T. (2004) Basic study on the road roughness detection method using the second-generation wavelet transform. **Proceedings of 5th Symposium on Pavement Surface Characteristics Roads and Airports (SURF2004)**, PIARC, Toronto, Canada, 1-10(CD-ROM), June 2004.

Sweldens,W.(1996) The lifting scheme - A custom design construction of biorthogonal wavelets –, **Journal of Applied and Computational Harmonic Analysis**, **Vol.3, No.2**, 186-200.

Takano,S., Minamoto,T., Arimura,H., Niijima,K., Iyemori,T. and Araki,T. (1999) Automatic detection of geomagnetic sudden commencement using lifting wavelet filters, **Proceedings of the 2nd International Conference on Discovery Science**, Waseda University, Japan, 242-251, December 1999.