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Walking Stability using Portable Acceleration Measurement System

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***Abstract*— It is important that we analyze walking stability of physically unimpaired persons as one aspect of preventive medicine. There are many cases of unstable walking even if people think they are in good health. It is considered that if they continue to walk unstably, this may cause lower-back pain or knee pain; this burden also exerts bad influences upon other physical parts. We assessed walking stability, quantitatively, using an acceleration measurement system. Using this system, we measured the acceleration displacement at the COG of a normal walking subject and evaluated walking stability quantitatively. The center of gravity (COG) plays an important role in evaluation of stability for both standing posture and walking. By using the seasonal adjustment model it was possible to predict the periodic fluctuations observed, decomposing the original data into factors representing stability and instability. We assessed walking stability, quantitatively, using the ratio of the variance of the noise component vs. the variance of periodic component. This study provides useful information for understanding walking systems in preventive medicine and rehabilitative medicine.**

***Keywords*— Walking stability, Acceleration measurement system, Seasonal adjustment model, Preventive medicine**

I. Introduction

Patients with walking disorders are diagnosed by orthopedics and a rehabilitation course in a hospital, but the walking of physically unimpaired persons is not diagnosed. It is considered that if they continue to walk unstably, this may cause lower-back pain or knee pain; this burden also exerts bad influences upon other physical parts [1,2]. So it is important that we analyze walking stability of physically unimpaired persons as one aspect of preventive medicine. Studies of walking motion by gyro sensors and acceleration sensors worn by the patient have measured head, trunk and lower-back displacement, and the relationships among the three joints of hemiparetic patients [3,4]. Some Analyses of walking improvement in patients with foot problems or lower-back pain have also been reported [5].

In the present study, we used a portable acceleration measurement system consisting of a small, light-weight acceleration sensor connected to a small wristwatch-type computer. This system does not cause much discomfort to the subjects. Using this system, we measured the acceleration at the center of gravity (COG) of normal subjects and analyzed their walking stability. This system was also used in our previous work [6]. The COG plays an important role in analysis of walking stability for both standing posture and walking movement.

According to the previous studies, we know that walking movement is the result of a regular pattern of movement and that the central pattern generator is located in the spinal cord. The central pattern generator makes walking rhythmic by stimuli from the mesencephalic locomotor region of the mesencephalon. The cerebellum receives both information from the mesencephalic locomotor region and feedback information from the arms and legs, and that constitutes the internal model of walking movement. Many joints in the body are involved in walking, through interacting feedback mechanisms, and act in cooperation. According to the previous studies, due to impairment of the control mechanism in patients with lower-back pain and lower-limb disease, the rhythm of the movements of the lower-back and knee joints becomes unstable. As a result, some disorder occurs in the feedback relations of the movement in each part and also in the movement of COG. In addition, for physically unimpaired persons who do not show any painful symptoms, it is known that the periodic walking rhythm worsens because of lifestyle-related diseases and various other causes.

Therefore, in this study, we observed the periodic walking rhythm of the COG of each normal subject, and by using the seasonal adjustment model [7,8,9] it was possible to predict the periodic change and to analyze stability, which was hard to estimate from the original data. At first, in the preliminary experiment, we analyzed walking stability, quantitatively, for the same subjects wearing normal shoes and slippers, while they walked in the same corridor of a university building. Next, we analyzed the walking stability of different subjects, also quantitatively, with shoes which they wear every day.

II. Methods

A. Portable Acceleration Measurement System

This system consists of an Acceleration Sensor (Japan Aviation Electronics Industry, Ltd.), a small wristwatch-type computer, and rechargeable lithium batteries (which supply electrical power to the sensor). When the switch was turned on, the acceleration was recorded into the small wristwatch-type computer (WPC) at 30Hz. A person can walk everywhere naturally using this system. Batteries were held in a waist pouch, attached a wide belt.

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B. Experimental Procedure

In a preliminary experiment, three normal subjects were measured for acceleration of COG while walking wearing every day their shoes and slippers. Next, four other normal subjects were measured for acceleration of COG while walking in their every day shoes. The WPC was attached to the wrist of the subjects, and the batteries were placed in a pouch attached around the subjects' waist. The acceleration sensor was attached to the subjects' COG. A strong, broad, elastic pouch-type belt was attached to the subjects' waist, and an acceleration sensor was attached to the COG. When the switch was turned on, the acceleration of the COG was recorded by the WPC. This analysis was conducted in the corridor of a university building, over a walking distance of 10m. Walking speed was normal for each subject. There were five repetitions of each trial.

C. Data analysis method

The seasonal adjustment model [7,8,9] is an analysis of the time series data that repeats a similar pattern in every period of time. In our study, noting the periodicity in the original data, we used the seasonal adjustment model to predict periodic fluctuations. The original data are first decomposed into a periodic (seasonal) component and a noise component, which we think of stable and unstable element, respectively. Next, we quantified the walking stability, using the ratio of the variance of these two components. In this study, we analyzed acceleration displacement in its most important direction, the pitch direction. In the seasonal adjustment model, the time-series data y_n are expressed as the sum of three components, namely the trend component t_n, the seasonal component s_n, and the observation noise component w_n:

$$y_n = t_n + s_n + w_n \qquad (1)$$

where the trend component t_n and the seasonal component s_n, respectively, are modeled as follows:

$$\Delta^k t_n = \varepsilon_n \qquad (2)$$

$$\sum_{i=0}^{p-1} s_{n-i} = \eta_n \qquad (3)$$

Here Δ represents the first temporal difference operator defined as $\Delta t_n = t_n - t_{n-1}$. The variables $w_n, \varepsilon_n, \eta_n$ are the stochastic disturbance, the distribution of which is assumed to be Gaussian. Since each subject walked a straight line in our experiment, we could not see a clear trend in the original data. Therefore we ignored the trend component in the above model.

This leads to the following seasonal adjustment model, using the state-space representation (matrix representation);

The period of the seasonal component equals to 15 or 16 (p=15 or 16). The state vector x_n can be estimated by using the Kalman filter algorithm [7,8,9,10]. Initial state vectors and the variance of Gaussian noise w_n, η_n were estimated by the maximum likelihood method.

$$x_n = Fx_{n-1} + Gv_n \quad v_n \sim N(0, \tau^2) \quad \text{System model} \qquad (4)$$

$$y_n = Hx_n + w_n \quad w_n \sim N(0, \sigma^2) \quad \text{Observation model} \qquad (5)$$

where the state vector is defined by

$$x_n = (s_n, s_{n-1}, \cdots, s_{n-p+2})^t$$

and (6)

$$F = \begin{bmatrix} -1 & -1 & -1 & \cdots & -1 \\ 1 & 0 & 0 & \cdots & 0 \\ 0 & \cdot & \cdot & & \cdot \\ \cdot & & \cdot & & \cdot \\ \cdot & & & \cdot & \cdot \\ 0 & \cdot & \cdot & \cdot\ 1 & 0 \end{bmatrix}, \quad G = \begin{bmatrix} 1 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{bmatrix} \qquad (7)$$

$$H = [1\ 0\ 0 \cdots 0]$$

III. Results and Discussion

A. Same subjects walking in normal, flat shoes versus slippers

First we evaluated the walking stability of normal subjects, quantitatively, comparing normal, flat shoes to slippers. Figures 1a-3b show the data for three subjects wearing normal, flat shoes while walking compared to slippers. The top graph in each figure shows a section of the original measurement of acceleration displacement of the subject's COG in the pitch direction while walking. We looked at periodicity as the factor representing stability. Using the seasonal adjustment model, the original data can be decomposed into a periodic component (seasonal component) and a noise component, which are, respectively, the factor representing stability and instability. The trend component is omitted because it is constant for each subject. In the graphs, acceleration (m/sec^2) is shown on the Y axis and time (1/30sec) on the X axis. The middle graph in each of the figures is each subject's seasonal component. Each middle graph was decomposed into a rhythmic pattern that had a rhythm peculiar to each subject. According to previous studies [1], patients with lower-limb disease and even physically unimpaired persons with unbalanced posture do not show a rhythmic walking pattern. Therefore, it was thought that the rhythmic, periodic walking pattern of each middle graph was useful as an index of each subject's stability. The noise component at the bottom of each figure shows the rest of the trend and seasonal component that was subtracted from the original data. Comparing the graphs of the subjects wearing normal shoes vs. slippers, we see that the noise component was greater, in all subjects, when they were wearing slippers. Each subject reported that walking was more difficult while wearing slippers than while wearing normal shoes.

B. Subjects wearing every day shoes while walking (different subjects from A)

Figures 4 – 7 show the data for four subjects (different subjects from *A*)) walking while wearing their every day shoes. These graphs also show the original data decomposed into a periodic component and a noise component, using the seasonal adjustment model. The trend component is again omitted, because there was a constant value for each subject. Each middle graph was decomposed into a rhythmic pattern that had a rhythm peculiar to each subject. The noise component is very different for each subject, perhaps because the type of shoes was not the same for each. Some wore mules (medium heel) and some wore sneakers. We analyzed walking stability, quantitatively, using the ratio of the variance of the noise component vs. the variance of the seasonal component (walking characteristic).

Table 1 shows the noise component vs. seasonal component for the four normal subjects (subjects D, E, F and G) while walking in their every day shoes. There were five repetitions of each trial, and the data are expressed as mean and standard deviation (SD). This table shows that the ratio of the variances of noise component vs. seasonal component is lined up in ascending order. This order can be considered as the order of stability.

IV. CONCLUSION

In this study, we have extracted the periodic rhythm of each subject by adapting the seasonal adjustment model. It was understood that the ratio of disorder of periodic rhythm (noise component) to regular periodic rhythm, which is peculiar to each subject (seasonal component), showed each subject's walking stability. If this analysis of walking balance is checked regularly, it will suggest one of evaluations of present walking stability. The results are useful for understanding walking systems in preventive medicine and rehabilitative medicine.

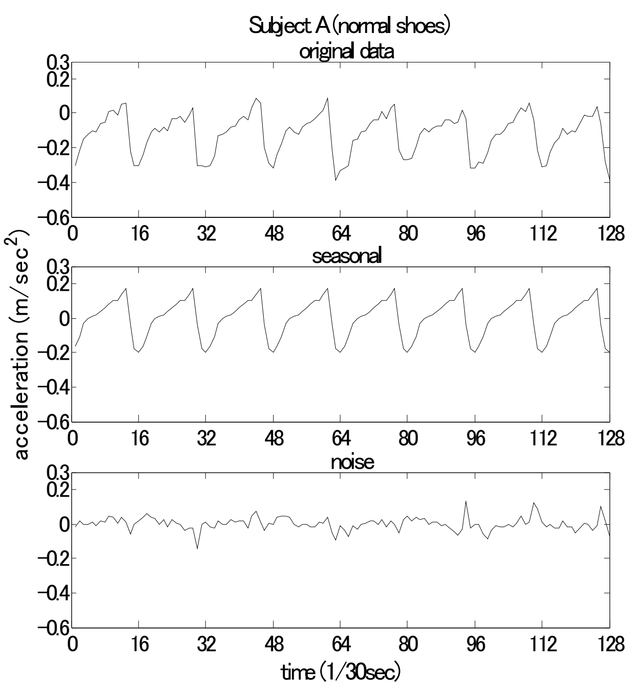

Figure 1a Acceleration displacement of Subject A walking while wearing normal, flat shoes

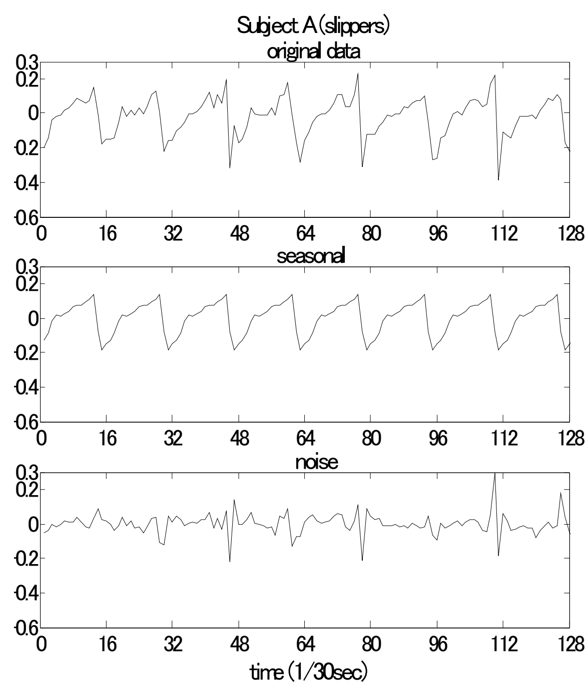

Figure 1b Acceleration displacement of Subject A walking while wearing slippers

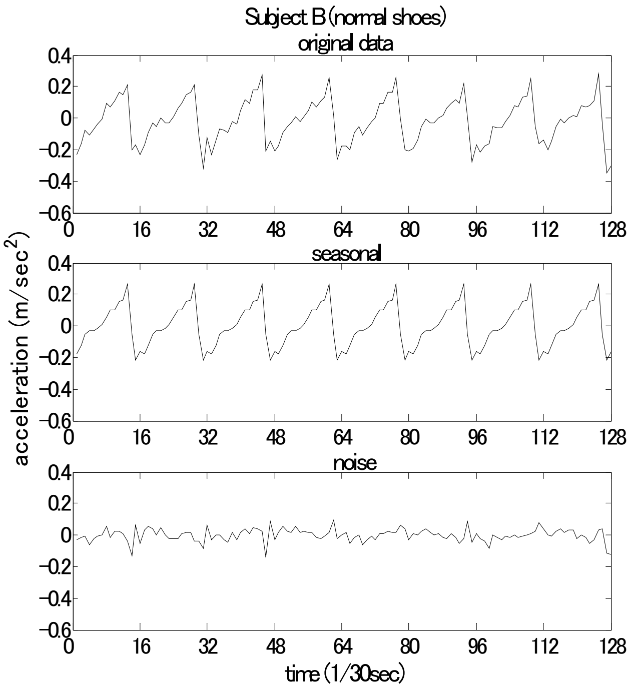

Figure 2a Acceleration displacement of Subject B walking while wearing normal, flat shoes

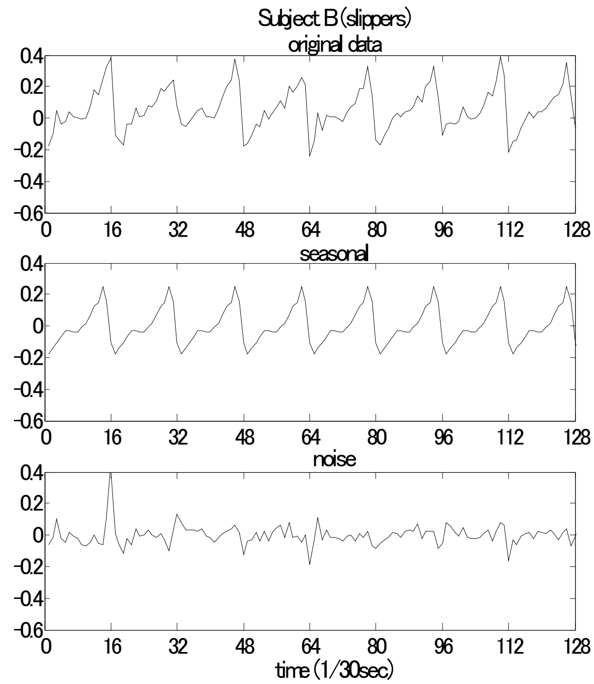

Figure 2b Acceleration displacement of Subject B walking while wearing slippers

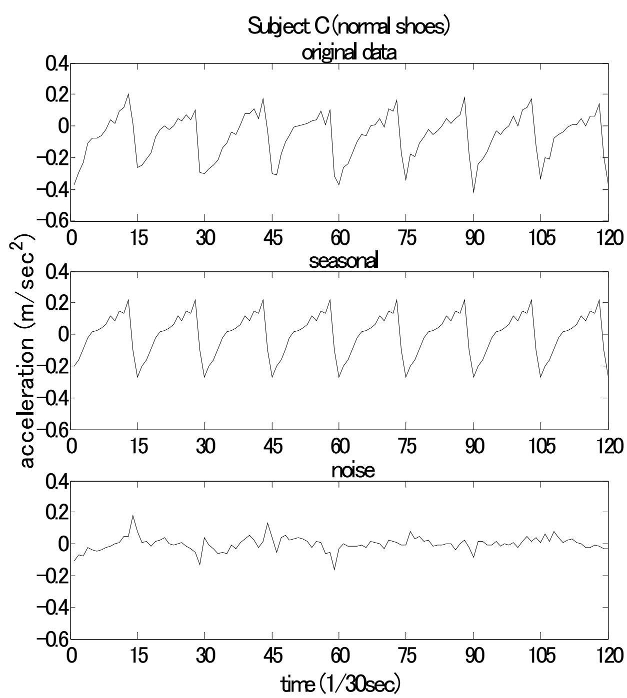

Figure 3a Acceleration displacement of Subject C walking while wearing normal, flat shoes

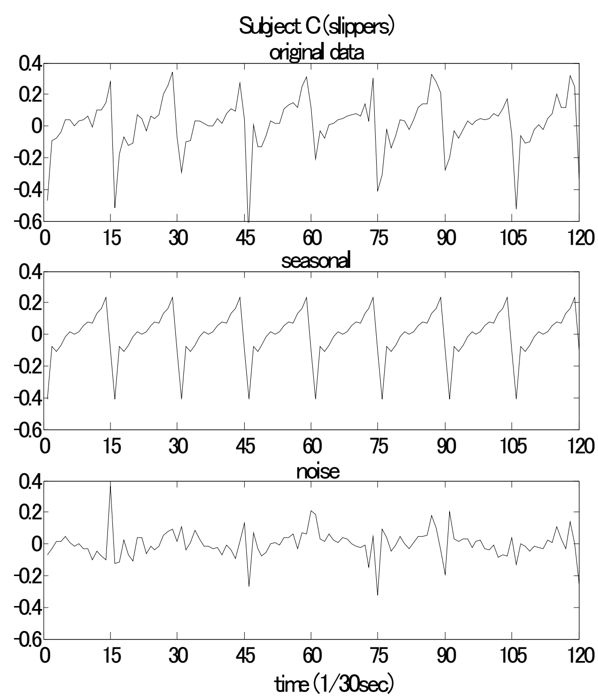

Figure 3b Acceleration displacement of Subject C walking while wearing slippers

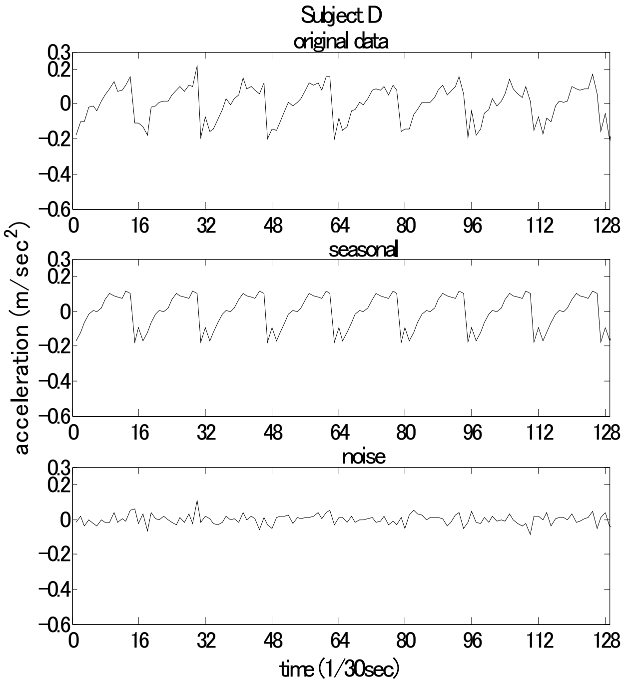

Fig. 4 Acceleration displacement of Subject D walking while wearing every day shoes

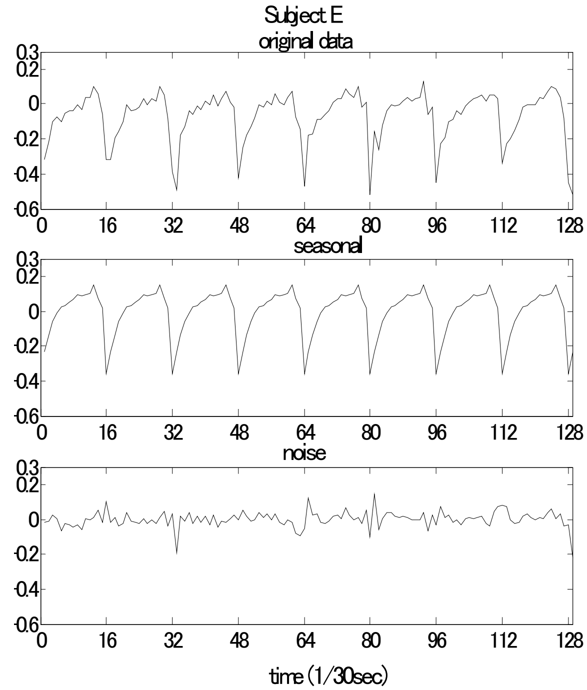

Fig.5 Acceleration displacement of Subject E walking while wearing every day shoes

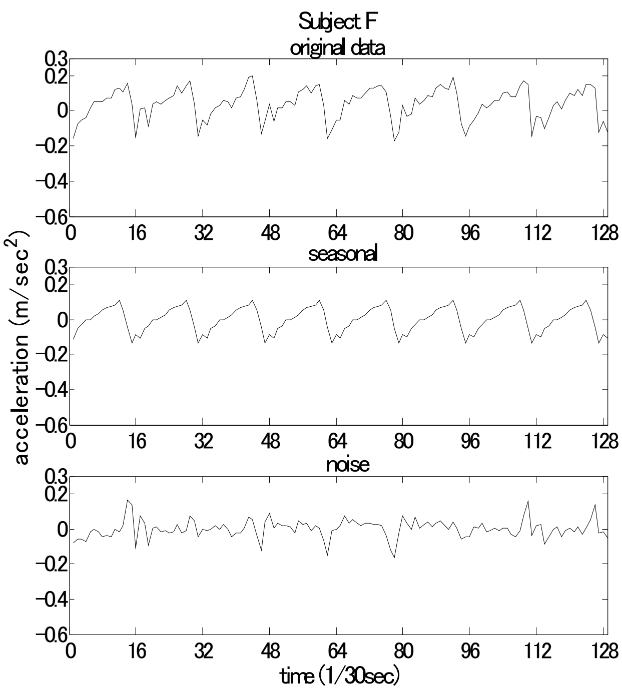

Fig. 6 Acceleration displacement of Subject F walking while wearing every day shoes

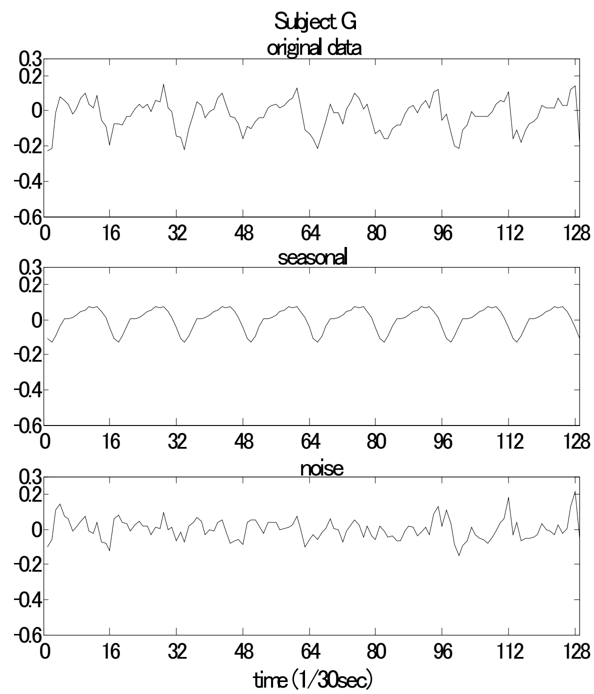

Fig.7 Acceleration displacement of Subject G walking while wearing every day shoes

TABLE 1

Walking While Wearing Every Day Shoes
The Ratio of the Variance of Noise vs.
The Variance of Seasonal Component

Subject	subject D	subject E	subject F	subject G
Mean var(n)/var(s)	0.0893	0.1150	0.5116	0.8621
SD	0.0027	0.0016	0.0157	0.0010

Mean and SD of 5 trials
var(n)/var(s) : variance of noise / variance of seasonal

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