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Development of elevator-use, popular-type seismic-wave-energy-sensing earthquake detector

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ABSTRACT: Acceleration-type earthquake detectors are generally used in operation control systems serving elevators etc. in the event of earthquakes. Although such detectors operate fairly well in ordinary buildings, they often do not in tall buildings, and in skyscrapers in particular. We have already developed seismic-wave-energy-sensing earthquake detectors designed to sense the maximum wave energy in close correlation with seismic intensity, and have applied them in the elevators of superhigh-rise buildings. Recently, for application in lower buildings at lower costs, we have developed a popular-type seismic-wave-energy-sensing earthquake detector.

1 INTRODUCTION

To minimize damage due to earthquakes, elevators are provided with operation control systems for use in the event of earthquakes.

Among earthquake detectors which give commands to such operation control systems, acceleration-type earthquake detectors designed to operate on seismic accelerations are mostly used, and they operate fairly well in the elevators of ordinary buildings, but often fails to operate well particularly in superhigh-rise buildings.

Under these circumstances, we made a thorough review of earthquake detectors, and successfully developed the world's first seismic-wave-energy-sensing earthquake detector, which was applied in the elevators of superhigh-rise buildings.

Such seismic-wave-energy-sensing earthquake detectors were too expensive for application in lower buildings. Consequently, we further developed low-priced versions of such detectors. This paper discusses this development together with the principles of such detectors.

2 OPERATIONS AND PROBLEMS OF CONVENTIONAL ACCELERATION-TYPE EARTHQUAKE DETECTORS USED IN THE ELEVATORS OF SUPERHIGH-RISE BUILDINGS

Table 1 shows operation control during an earthquake for an elevator of building A, a representative superhigh-rise building in Tokyo.

In the Central Japan Sea Earthquakes on May 26, 1983, as shown in Table 2, the top floor of this building showed as large a quake as ±10cm, 0.2Hz. Such a large quake might possibly cause the movable cables (tail cords) for transmitting signals and power to elevator cars to quake in resonance at an amplitude of about ±2m, resulting in an accident. In this respect, operation control in the event of earthquakes should have been activated, but in reality it was not activated because the quake acceleration did not reach 30 Gal.

Table 1. Operational control during earthquakes for building A

Low acceleration sensing	High acceleration sensing
Set level: 30 Gal	Set level: 60 Gal
Stops at the nearest floor for 10 minutes and returns to normal operation.	Stops at the nearest floor and suspends service. After inspection, returns to normal operation.

Table 2. Situation during earthquakes of building A

	Situation of quake	Situation of control
May 26, 1983 Top floor	0.2Hz ±16 Gal ±10cm	It was necessary to be controlled; however, operational control was not applied.
August 8, 1983 Top floor	(3Hz, ±30 Gal, ±0.08cm)→(0.2Hz, ±1.6 Gal, ±1cm)	Operational control was unnecessarily applied.
Pit in hostway (Usually slight quake)	50Hz ±13 Gal ±0.13μm	—

In the Western Kanagawa Earthquakes on August 8, 1983, the quake did not affect the top floor of the same building so much as to bring the elevators to a stop, but the quake acceleration reached 30 Gal, which was detected by acceleration-type earthquake detectors, causing operation control to be activated.

Thus, the reliability of conventional earthquake detectors designed only to detect acceleration is limited when they are applied in superhigh-rise buildings.

3 SEISMIC-WAVE-ENERGY-TYPE EARTHQUAKE DETECTORS

According to the definition of seismic scales of the Meteorological Agency of Japan, when buildings start to be damaged, the seismic scale is rated V.

The guidelines for antiseismic design and installations of elevators established under the supervision of the Ministry of Construction in Japan state that on the JMA seismic scale of V, elevator cars be brought to a stop at the nearest floors under operation control in linkage with earthquake detectors.

Conventionally, to detect this seismic intensity, a correlation between acceleration and seismic intensity has been used, but studies by Katsumata, Ichikawa, etc. show that this correlation is not very reliable.

Upon making studies on the correlations between seismic intensity and various physical properties, Takagi (1969) reported that seismic intensity is most clearly correlated with the maximum seismic wave energy.

Thus, we sought a method for obtaining the maximum of seismic wave energy easily.

As far as energy is concerned, there is no need to take the P-wave into consideration. So, we will deal only with the S-wave below.

As shown in Fig. 1, in the half period after an S-wave reaches a small area dS, the S-wave runs forward by half its wavelength $\lambda/2$.

Being a transversal wave, the S-wave has a quake displacement y normal to its travelling direction. Differentiating y with time t yields quake velocity υ_y at the point.

If the wave energy in the volume $dS\cdot(\lambda/2)$ is W, it is the maximum seismic wave energy acting in one direction, and is given by

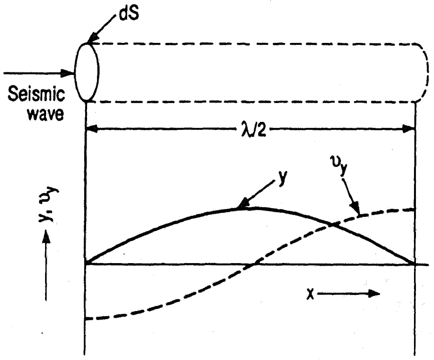

Figure 1. Situation of seismic S-wave

$$W = dS\cdot\left(\frac{\lambda}{2}\right)\cdot \frac{1}{(T/2)}\int_0^{T/2}\left\{\frac{1}{2}\rho\left(\frac{dy}{dt}\right)^2 + \frac{1}{2}\mu\left(\frac{dy}{dx}\right)^2\right\}\cdot dt \qquad (1)$$

where T: period of earthquake, ρ: mass per unit volume of medium, and μ: rigidity of medium.

Let us assume that quake displacement y is given by

$$y = D\cdot\sin 2\pi ft \qquad (2)$$

where f is quake frequency (= 1/T). If the travelling speed of the S-wave is υ_S, it is given by

$$\upsilon_s = dx/dt = \sqrt{\mu/\rho} \qquad (3)$$

Putting these into equation (1), we have

$$W = \pi^2\cdot ds\cdot\sqrt{\mu\cdot\rho}\,(D^2/T) \qquad (4)$$

If a point is determined, W can be obtained from D^2/T, because $\pi^2\cdot dS\cdot\sqrt{\mu\cdot\rho}$ is nearly constant. On the other hand, period T cannot be known unless it lapses by more than one cycle.

Furthermore, even if period T is obtained, calculation or division D^2/T is so troublesome that the equipment would be complicated and expensive.

Thus, we sought a method for obtaining maximum W of seismic wave energy easily. If the product of quake displacement y and quake velocity υ_y is e_t, it is given by

$$\begin{aligned} e_t &= y\cdot\upsilon_y = D\cdot\sin 2\pi ft\cdot\{(2\pi fD)\cdot\cos 2\pi ft\} \\ &= \pi(D^2/T)\cdot\sin 4\pi ft \\ &= e\cdot\sin 4\pi ft \end{aligned} \qquad (5)$$

where e is the amplitude of e_t, which is given by

$$e = \pi\cdot(D^2/T) = (\pi\cdot\sqrt{\mu\cdot\rho}\cdot dS)^{-1}\cdot W \qquad (6)$$

Since $(\pi\cdot\sqrt{\mu\cdot\rho}\cdot dS)^{-1}$ is almost constant if a point is determined, e is proportional to W. This is why e was named the coefficient of seismic wave energy. In practice, as control signals can be generated in comparison with e_t, e_t can also be considered a coefficient of seismic wave energy.

The coefficients of seismic wave energy can be obtained with the circuit shown in Fig. 2. The coefficient of seismic wave energy in a given direction on a plane can be obtained by obtaining and summing the coefficients of seismic wave energies in two orthogonal directions on a plane. The seismic-wave-energy-sensing earthquake detector is designed to give a control signal by comparing the values thus obtained with the reference value in a comparator.

Kawasumi reported on the relation between

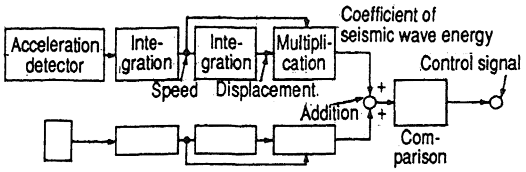

Figure 2. Block diagram of seismic-wave-energy-sensing-type earthquake detector

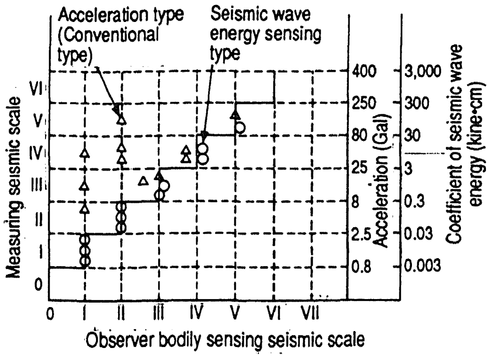

Figure 3. Simulation results of Matsushiro earthquake swarm

Table 3. Comparison of physical quantities corresponding to seismic intensity

Intensity scale of JMA	0	I	II	III	IV	V	VI	VII
Coef. of seismic-wave energy (kine•cm)	0 to 0.003	0.003 to 0.03	0.03 to 0.3	0.3 to 3	3 to 30	30 to 300	300 to 3000	3000 to ∞
Acceleration (Gal)	0 to 0.8	0.8 to 2.5	2.5 to 8	8 to 25	25 to 80	80 to 250	250 to 400	400 to ∞

acceleration and the JMA seismic scale. For the relation between seismic wave energy coefficient and seismic intensity, we determined the values shown in Table 3 from the results of studies by Takagi (1969) etc. Fig. 3 shows the results of a test with Matsushiro Series Earthquakes. The coefficients of seismic wave energy are closer to seismic intensities.

4 COMPARISON OF OPERATION CONTROL FOR ELEVATORS DURING EARTHQUAKES

If the seismic intensity obtained from its relation with acceleration in Table 3 and that obtained from its seismic wave energy coefficient are called acceleration seismic intensity and wave energy seismic intensity respectively, the acceleration seismic intensity for superhigh-rise building A in the Central Japan Sea Earthquakes on May 26, 1983 was III, while the wave energy seismic intensity for the same was V, as shown in Table 4. Again, while the acceleration seismic intensity for the same building on August 8, 1983 was IV, the wave energy seismic intensity for the same was III. *The actual quake of building A and the effect of* the elevators nearly agree with the wave energy seismic intensity.

Table 4. Acceleration seismic intensity and wave-energy seismic intensity measured at building A

	Situation of quake	Acceler-ation intensity scale	Wave energy intensity scale
May 26, 1983 Top floor	0.2Hz ±16 Gal ±10cm	III	V
August 8, 1983 Top floor	(3Hz, ±30 Gal, ±0.08cm)→(0.2Hz, ±1.6 Gal, ±1cm)	IV→I	II→III
Pit in hostway (Usually slight quake)	50Hz ±13 Gal ±0.13μm	III	0

For other superhigh-rise buildings, similar results were obtained as shown in Table 5. Thus, the seismic-wave-energy-sensing earthquake detector is expected to operate properly with all earthquakes.

From the results obtained thus far, continuing our study on what detection level and what operation control during earthquakes should be selected if the seismic-wave-energy-sensing earthquake detector was employed, we decided to take Table 6 as the standard.

Table 5. Actuation status of earthquake detectors installed in superhigh-rise buildings

	Acceleration sensing	Energy sensing
Large-magnitude earthquakes with distant hypocenters requiring controlled elevator operations	X (No detector actuation obseved)	O (Detector actuated)
Small-magnitude earthquakes with nearby hypocenters not requiring controlled elevator operation	X (Detector actuated in certain cases)	O (Detector not actuated)
Large-magnitude earthquakes with nearby hypocenters requiring controlled elevator operations	O (Detector actuated)	O (Detector actuated)

NOTE: O denotes appropriate detector functioning
X denotes inappropriate functioning

Table 6. Operational control during earthquakes using seismic-wave-energy-sensing-type earthquake detector

Seismic wave energy coefficient	Wave energy intensity scale	Operational control command during earthquakes
[0, 10 kine•cm)	[0, 4.5)	Normal operation
[10, 30 kine•cm)	[4.5, 5.0)	Stop at nearby floor and automatic reset to normal operation after 3 minutes
[30, 100 kine•cm)	[5.0, 5.5)	Stop at nearby floor and automatic reset to normal operation after 10 minutes
[100 kine•cm or over	[5.5 or over	Emergency stop

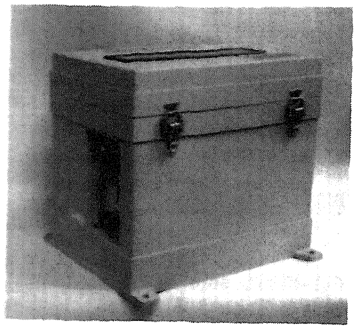

Figure 4. Popular-type seismic-wave-energy-sensing earthquake detector

5 POPULAR-TYPE SEISMIC-WAVE-ENERGY-SENSING EARTHQUAKE DETECTOR

As described above, it is evident that the seismic-wave-energy-sensing earthquake detector can detect quakes that can rock buildings and cause damage to elevators. This has been proved not only by the results of tests but also theoretically.

However, such detectors already in service are rather complicated and expensive, and are mainly employed in superhigh-rise buildings.

Superhigh-rise buildings generally have a flexible structure, and in a strong wind like a typhoon, they quake a lot, occasionally causing seismic-wave-energy-sensing earthquake detectors to be activated. This is a characteristic of seismic-wave-energy-sensing earthquake detectors. As quakes due to earthquakes differ from quakes due to strong winds, different operation control systems must be employed for them.

While quakes due to earthquakes change rapidly and are rather short, quakes due to strong winds change rather slowly and last long. Thus, for buildings taller than 120m and subjected to strong winds, a system designed to discriminate whether building quakes are due to earthquakes or due to strong winds has been developed and employed. If a building quakes at a level between 1 kine•cm and 9.9 kine•cm once or more per 1 min and this condition continues for more than 10 min, which can never be due to earthquakes, the system ascribes them to strong winds and gives a strong-wind signal. With quakes [10–30 kine•cm), for example, the maximum speed of the elevators is limited to 210 m/min. If an earthquake occurs during operation control for strong winds, the small-quake detector installed on the ground detects it and switches operation control for strong winds to operation control for earthquakes, which will be switched back to operation control for strong winds when the earthquake ceases.

With popular-type seismic-wave-energy-sensing earthquake detectors intended for buildings not taller than 120m, there seems to be no need to employ operation control for strong winds. Thus, we decided to omit this function from popular-type models.

For the acceleration-type detector of the present system, we also employed a compact and lightweight model instead of the conventional rather large ones.

To obtain velocity and displacement by integrating the output of the accelerator, we decided to employ a so-called lattice filter and an IC used in the CPU on a time-sharing control basis, while omitting the conventional linear amplifier.

As a result, the completed system as shown in Fig. 4, compared with conventional models, was reduced in volume to about 10%, in price to 50%, and was designed to be installed more easily.

6 CONCLUSION

Now, we have outlined the popular-type seismic-wave-energy-sensing earthquake detector. At present, this model is in experimental service. It is expected to find wide applications in buildings not taller than 120m.

REFERENCES

Onoda, Y. & Ikeda, E. 1971. *Trans. IEE of Japan*, Vol. 107-C, No. 10, pp. 947–954.

Onoda, Y. & Ikeda, E. 1988. *9th World Conf. on Earthquake Engineering Proceedings*, Vol. VII, pp. 661–666.

Takagi, S. 1969. *Papers in Meteorology ana Geophysics*, Vol. 20, No. 1, pp. 79–89.