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Accuracy Enhancement of Reflection Signals in Impact Echo Test

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Abstract

A majority of infrastructures has been deteriorated over time. Therefore, it is very important to verify the quality of construction, and the level of structural deterioration in existing structures, to ensure their safety and functionality. Many researchers have studied non-destructive testing (NDT) methods to identify structural problems in existing structures. The impact echo technique is one of the widely used NDT techniques. The impact echo technique has several inherent problems, including the difficulties in P-wave velocity evaluation due to inhomogeneous concrete properties, deterioration of evaluation accuracy where multiple reflection boundaries exist, and the influence of the receiver location in evaluating the thickness of the tested structures.

Therefore, the objective of this paper is to propose an enhanced impact echo technique that can reduce the aforementioned problems and develop a Virtual Instrument for the application via a thickness evaluation technique which has same technical background to find deterioration in concrete structures. In the proposed impact echo technique, transfer function from dual channel system analysis is used, and coherence is improved to achieve reliable data. Also an averaged signal -ensemble- is used to achieve more reliable results. From the analysis of transfer function, the thickness is effectively identified.

Keywords : impact echo test, flaws, concrete slabs, transfer function, virtual instrument

1. Introduction

Vast majority of concrete structures have deteriorated over time. Therefore, there is a growing need for developing efficient procedures for the evaluation of the safety and serviceability of damaged concrete structures due to deterioration. Without nondestructive testing (NDT) methods, it is often very difficult to assess the damage of concrete structures, particularly when the damaged area is very small, or the area is in the interior of the structure.

When impact is applied to a structure, the stress waves caused by the applied impact are passed through the structure with certain velocity, and the applied velocity of wave stresses can be related to the density, Poisson's ratio, dynamic modulus of elasticity and the effective dimension of the tested concrete member. Many researchers have studied NDT methods to identify structural problems in existing structures.

There are various types of available NDT techniques, depending on the types of stress wave techniques and analysis methods used. The impact echo technique is one of the widely used NDT techniques. It uses P wave reflection from the boundary such as defect, crack and end of structures. However, the impact echo technique has several inherent problems, including the difficulties in the evaluation of P-wave velocity due to inhomogeneous concrete properties, deterioration of evaluation accuracy where multiple reflection boundaries exist, and the influence of the receiver location in evaluating the distance to a defect and the thickness of the tested structures.

If the input force and the response of member are known, transfer function from 2 channel system analysis can be used, and coherence can be improved to obtain more reliable data. Also, output signals can be analyzed from input signals without being influenced by noises or unwanted signals due to other structural characteristics. In addition, an averaged signal -ensemble- can be used to achieve more reliable results. Therefore, the objective of this paper is to propose a modified impact echo method to reduce the

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aforementioned problems using the transfer function and develop a virtual instrument to measure and analyze data using Labview language.

2. Modeling of impact generated stress wave

In an impact testing, stress waves can be generated by mechanical impact. Among the important parameters that characterize the impact are the duration(contact time) of the impact, the diameter of the sphere, and the kinetic energy of the sphere at impact. A practical analysis of wave motion in plate can be helped by the evaluation of the force histories.

The equation of structural motion can be specified in terms of partial differential equations, and the contact force is directly related to the particle velocity at the location of the applied impact. A classical solution for the contact of two elastic bodies was developed by Hertz (1895). Because this theory takes into account the curvature of the contacting surface, it results in a nonlinear contact law. The force between two spherical masses of radii R_1 and R_2 in contact is described by Eq. (1) when α is approach.

$$F = k\alpha^{3/2} \tag{1}$$

The Hertz law of contact specified in Eq.(1) can now be used directly to the examination of impact when the vibratons produced by the collision can be neglected. From Newton's second law of motion, the impact force acting is given in Eq.(2).

$$F = -m_1\ddot{w}_1 = -m_2\ddot{w}_2 = -\frac{m_1m_2}{m_1+m_2}\ddot{\alpha}\,, \tag{2}$$

where, $\ddot{\alpha} = \ddot{w}_1 + \ddot{w}_2$, $m_1, m_2 = mass$,
$w_1, w_2 = displacement$

Substituting Eq.(2) into Eq.(1), and integrating Eq.(2) with initial conditions yields Eq. (3) and (4).

$$\frac{m_1m_2}{m_1+m_2}\ddot{\alpha} = -k_2\alpha^{\frac{3}{2}} \text{ or } \ddot{\alpha} = -\mathrm{k}_1\mathrm{k}_2\alpha^{\frac{3}{2}} \tag{3}$$

$$\text{with } k_1 = \frac{m_1+m_2}{m_1m_2}\,,\quad \frac{1}{2}(\dot{\alpha}^2 - \mathrm{v}_0{}^2) = -\frac{2}{5}\mathrm{k}_1\mathrm{k}_2\alpha^{\frac{5}{2}} \tag{4}$$

where, v_0 : initial relative velocity

The maximum compression α_m, specified in Eq.(5), occurs at $\dot{\alpha} = 0$.

$$\alpha_m = \left[\frac{5v_0{}^2}{4k_1k_2}\right]^{2/5} \tag{5}$$

By integrating the contact duration, Eq.(4), τ is determined as shown in Eq.(6).

$$\tau = 2\int_0^{\frac{\tau}{2}}\mathrm{d}t = 2\int_0^{\alpha_m}\frac{\mathrm{d}\alpha}{\sqrt{\mathrm{v}_0{}^2 - \frac{4}{5}\mathrm{k}_1\mathrm{k}_2\alpha^{5/2}}} = \frac{2\alpha_m}{\mathrm{v}_0}\int_0^1\frac{\mathrm{d}Z}{\sqrt{1-Z^{5/2}}}$$

$$= \frac{4}{5}\sqrt{\pi}\frac{\Gamma(\frac{2}{5})}{\Gamma(\frac{9}{10})}\frac{\alpha_m}{\mathrm{v}_0} = 2.9432\frac{\alpha_m}{\mathrm{v}_0} = \frac{2.9432}{\mathrm{v}_0{}^{\frac{1}{5}}}\left[\frac{5}{4\mathrm{k}_1\mathrm{k}_2}\right]^{2/5} \tag{6}$$

where, Γ : Gamma function $\quad Z = \frac{\alpha}{\alpha_m}$

The general relation between α and t is expressed as Eq.(7) through the elliptic integral.

$$\mathrm{t} = \int_0^{\alpha}\frac{\mathrm{d}\alpha}{\mathrm{v}_0{}^2 - \frac{4}{5}\mathrm{k}_1\mathrm{k}_2\alpha^{5/2}} \tag{7}$$

A reasonable approximation of Eq.(7) is developed in Eq.(8) , and the force-time relation is then approximated in Eq.(9).

$$\alpha = \alpha_m \sin\frac{1.0684\mathrm{v}_0\mathrm{t}}{\alpha_m} \tag{8}$$

$$f(t) = \frac{1.140v_0{}^2}{k_1\alpha_m}\sin\frac{1.0684v_0t}{\alpha_m}\,,\quad 0 \le t \le \frac{\pi\alpha_m}{1.0684v_0} \tag{9}$$

$$f(t) = 0\,,\quad t > \frac{\pi\alpha_m}{1.0684\mathrm{v}_0}$$

The variation of impact force with time is represented by a half sine curve using Fourier transform. The middle equation of Eq. (9) can be described as Eq. (10).

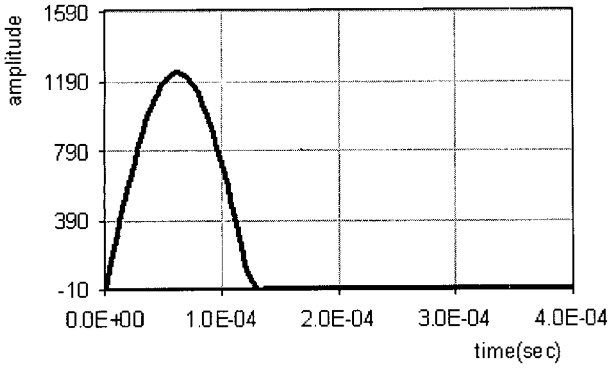
$$F\{f(t)\} = A\int_0^{\pi/\bar{\omega}}\frac{1}{2j}(e^{j\bar{\omega}t} - e^{-j\bar{\omega}t})e^{-j\omega t}dt$$

$$= \frac{A\bar{\omega}}{\bar{\omega}^2 - \omega^2}(1 + \cos\frac{\pi\omega}{\bar{\omega}} - j\sin\frac{\pi\omega}{\bar{\omega}}) \tag{10}$$

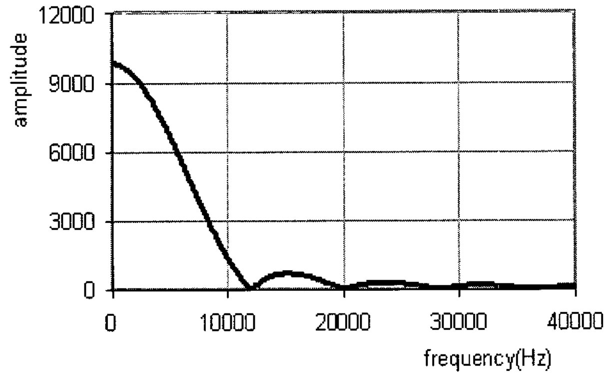
Since the amplitude $\mathrm{A}=1.140v_0{}^2/k_1\alpha_m$ and contact time is $\mathrm{t_c}=\pi\alpha_m/1.0684v_0$, the impact force can be developed in the form of both time and frequency domains shown in Fig. 1.

3. Transverse impact of a mass on plates

The transverse impact of mass on a thin plate of uniform depth 2b has been examined according to the classical theory of plates(Karas K, Raman C.V., Tillett J.P.A., Zener C), when the principal mode of motion of the plate consists of flexural vibrations, the longitudinal stresses and vibrations being neglected. The plate displacement is dependent upon two space coordinates which will be designated by x and y.



(a) Impact force in time domain



(b) Impact force in frequency domain

Fig. 1 Impact force in time and frequency domain

The term $w_1(c)$ represents the displacement of the plate at the impact point $c(x_0, y_0)$ due to the concentrated contact force $F(t)$. The differential equation for the forced vibration of a plate under the action of time-dependent load of surface density $\overline{W}(x,y,t)$ is given by Eq.(11)

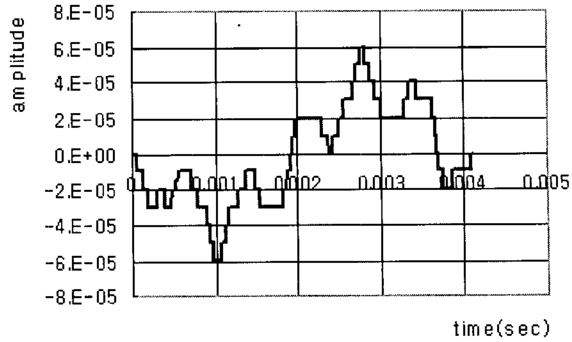
$$D\nabla^4 w_1 + 2\rho b\frac{\partial^2 b w_1}{\partial t^2} = \overline{W} \quad \text{where,} \quad D = \frac{2b^3 E}{3(1-\mu^2)} \qquad (11)$$

For a collision, the loading function is specialized to point contact force $F(t)$, and the solution of Eq.(11) in a simple integral expression is shown in Eq.(12),

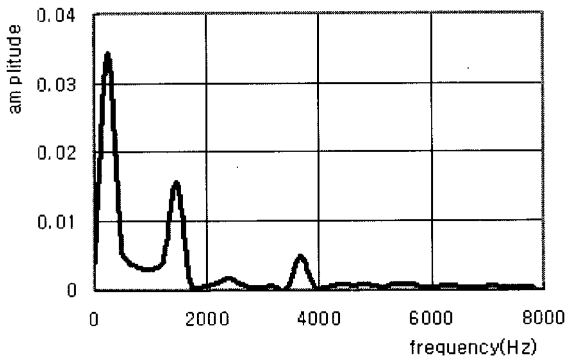
$$w_1(x_0, y_0, t) = \frac{1}{2b\rho}\sum_{i=1}^{\infty}\sum_{k=1}^{\infty}\frac{(\sin\frac{i\pi x}{m}\sin\frac{k\pi x}{n})^2}{w_{ik}\frac{mn}{4}}\int_0^t F(\overline{\tau})\sin\omega_{ik}(t-\overline{\tau})d\overline{\tau}$$

$$= \frac{1}{16b^2}\left[\frac{3(1-\mu^2)}{\rho E}\right]^{\frac{1}{2}}\int_0^t F(t)dt \qquad (12)$$

Fig. 2 shows the typical results of calculations utilizing Eq.(12) for the case when a steel sphere strikes a concrete with an initial velocity, and the velocity and acceleration can be calculated by differentiation.



(a) Deflection in time domain



(b) Deflection in frequency domain

Fig. 2 Typical central deflection of a simply supported concrete

4. Impact echo test and transfer function

If a signal A(t) is an input signal from impact hammer, and B(t) is an output signal from accelerometer, the Fourier transform of each signal in time domain will be $S_A(j\omega)$ and $S_B(j\omega)$, respectively, in frequency domain with complex values. If the auto spectrum of each signal and cross spectrum are $G_{AA}(\omega)$, $G_{BB}(\omega)$, $G_{BA}(\omega)$ respectively, coherence of two signals can be represented as Eq. (13).

$$\overline{\gamma}_{BA}^2(\omega) = \frac{|\overline{G_{BA}(\omega)}|^2}{\overline{G_{AA}(\omega)} \bullet \overline{G_{BB}(\omega)}}, \quad 0 \le \overline{\gamma}_{BA}^2(\omega) \le 1 \qquad (13)$$

In this paper, the transfer function from dual channel system analysis is used to prevent possible errors such as noises or unwanted signals due to other structural sources. In addition, an averaged signal -ensemble- is used to achieve more reliable results. The Eq.(14) is an equation expressed for the transfer function normalized the output signal with input signal, and a traveling time and frequency from surface to defects or bottom in impact echo test can be obtained from the transfer function with the same procedures in the impact echo test.

$$TF_{mag} = H(\omega) = \frac{S_B(j\omega)}{S_A(j\omega)} = \frac{S_B(j\omega)\bullet S_A(j\omega)^*}{S_A(j\omega)\bullet S_A(j\omega)} = \frac{S_B(j\omega)\bullet S_B(j\omega)^*}{S_A(j\omega)\bullet S_B(j\omega)}$$

$$= \frac{\overline{G_{BA}(\omega)}}{G_{AA}(\omega)} = \frac{\overline{G_{BB}(\omega)}}{G_{AB}(\omega)} \qquad (14)$$

Using a general commercial language, Labview4, a useful tool is developed, as shown Fig. 3. Using this tool, the Fourie transform, cross spectrum, phase angle, coherence and the transfer function can be easily calculated. From the Fourier transform window, both the ellapsed time in high frequency from surface to defect or other surface and the natural frequency of structure in lower frequency can be evaluated. But in this study, only higher frequency part is used to evaluate the thickness of structures. From the dual channel analysis window, coherence and the transfer function can be checked.

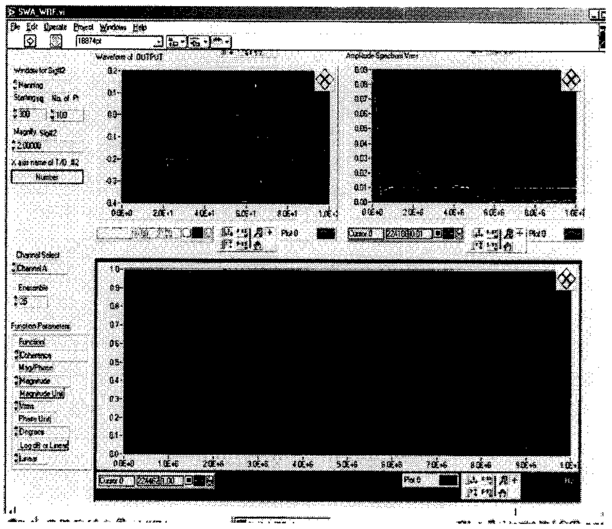


Fig. 3 Program for FFT and T/F

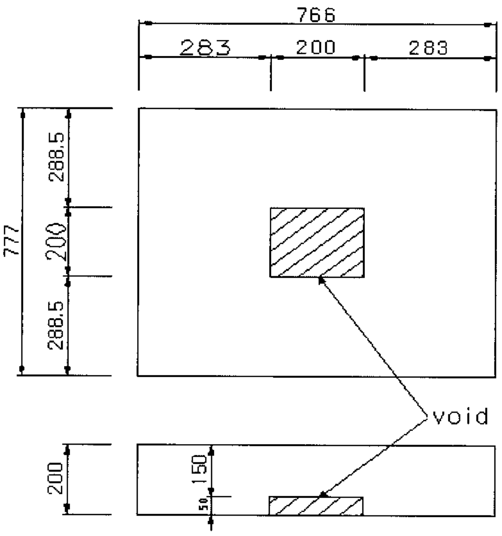


Fig. 4 Layout of slab specimen (unit : mm)

5. Impact test

A slab shown in Fig. 4 is used for impact tests, and the material properties are listed in Table 1. And the reliability of this test can be found from Table 1 and wave velocity measurement from PUNDIT and impact echo method.

Travelling frequencies of wave in concrete slab are found as Table 2 using impact echo method(IEM) and modified impact echo method(MIEM), and Fig. 5 shows a typical response of slab in frequency domain and an averaged frequency response function between impact and response point. And traveling frequency in MIEM could be found more easily without difficulty than in IEM. Averaged P wave velocity is measured 3,539 $m/\sec$ and 3,742 $m/\sec$ using impact echo test and pundit respectively in sound part of slab, since different kinds of center frequencies were used. That means there were resolution difference and traveling ability of wave in the inhomogeneous of concrete slab.

Fig. 6 shows the estimated thicknesses using IEM and MIEM in cross sections along to east-west and south-north direction with 7cm interval. From the test data there is 6~7% error in IEM and 0.1~5.3% error in MIEM. And the travelling frequency can be found more distinctly shown as Fig. 5 by using MIEM than using IEM because MIEM signal is normalized by input signal. MIEM's averaged signal can aviod complication due to multiple reflections and give more exact results.

Table 1 Material properties of the concrete slab

Compressive strength (MPa)	Density of concrete (kg/m^3)	Modulus of elasticity (GPa)		Dynamic modulus of elasticity (GPa)	
		ACI 318-02	$f-\varepsilon$ curve	PUNDIT test	$f-\varepsilon$ curve
21.3	2,316	22.1	21.7	27.4	26.6

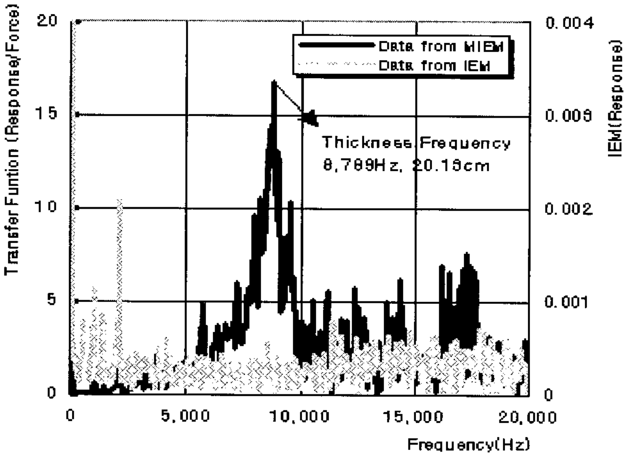


Fig.5 An Example of Ttpical response for test specimen

Table 2 Travelling frequencies of wave using MIEM

Location (x,y)	Travelling frequency (Hz)	Estimated thickness (cm)	Error (%)
(3.5,3.5)	8.545	20.71	3.6
(3.5,10.5)	8.447	20.95	4.7
(3.5,17.5)	8.545	20.71	3.6
(3.5,24.5)	8.447	20.95	4.7
(3.5,31.5)	8.740	20.25	1.2
(3.5,38.5)	8.545	20.71	3.6
(3.5,45.5)	8.789	20.13	0.6
(3.5,52.5)	8.740	20.25	1.2
(3.5,59.5)	8.887	19.91	0.4
(3.5,66.5)	9.033	19.59	2.1
(10.5,3.5)	8.740	20.25	1.2
(10.5,10.5)	8.447	20.95	4.7
(10.5,17.5)	8.789	20.13	0.6
(10.5,24.5)	8.447	20.95	4.7
(10.5,31.5)	8.643	20.47	2.3
(10.5,38.5)	8.789	20.13	0.6
(10.5,45.5)	8.545	20.71	3.5
(10.5,52.5)	8.937	19.80	1.0
(10.5,59.5)	8.496	20.83	4.1
(10.5,66.5)	8.936	19.80	1.0
(17.5,3.5)	8.545	20.71	3.5
(17.5,10.5)	8.740	20.25	1.2
(17.5,17.5)	8.691	20.36	1.8
(17.5,24.5)	8.643	20.47	2.3
(17.5,31.5)	8.789	20.13	0.6
(17.5,38.5)	8.789	20.13	0.6
(17.5,45.5)	8.594	20.59	2.9
(17.5,52.5)	8.691	20.36	1.8
(17.5,59.5)	8.740	20.25	1.2
(17.5,66.5)	8.545	20.25	1.2
(24.5,10.5)	8.691	20.36	1.8
(24.5,17.5)	8.691	20.36	1.8
(24.5,24.5)	8.984	19.70	1.5
(24.5,31.5)	8.740	20.25	1.2
(24.5,38.5)	8.887	19.91	0.5
(24.5,45.5)	8.789	20.13	0.6
(24.5,52.5)	8.691	20.36	1.8
(24.5,59.5)	9.180	19.28	3.7
(31.5,10.5)	8.936	19.80	1.0
(31.5,17.5)	8.789	20.13	0.6
(31.5,24.5)	8.838	20.02	0.1
(31.5,31.5)	11.914	14.85	1.0
(31.5,38.5)	11.572	15.29	1.9
(31.5,45.5)	9.033	19.59	2.1
(31.5,52.5)	9.033	19.59	2.1
(31.5,59.5)	8.887	19.91	0.5
(38.5,10.5)	8.936	19.80	1.0
(38.5,17.5)	8.789	20.13	0.6
(38.5,24.5)	8.643	20.47	2.3
(38.5,31.5)	12.109	14.61	2.7
(38.5,38.5)	12.042	14.69	2.1
(38.5,45.5)	8.642	20.48	2.4

Table 2 Travelling frequencies of wave using MIEM (continued)

Location (x,y)	Travelling frequency (Hz)	Thickness (cm)	Error (%)
(38.5,52.5)	8.887	19.91	0.5
(38.5,59.5)	8.545	20.71	3.5
(45.5,10.5)	8.594	20.59	2.9
(45.5,17.5)	9.082	19.48	2.7
(45.5,24.5)	8.691	20.36	1.8
(45.5,31.5)	8.643	20.47	2.3
(45.5,38.5)	8.691	20.36	1.8
(45.5,45.5)	8.691	20.36	1.8
(45.5,52.5)	9.082	19.48	2.7
(45.5,59.5)	8.887	19.91	0.5
(52.5,3.5)	8984	19.70	1.5
(52.5,10.5)	8838	20.02	0.1
(52.5,17.5)	8643	20.47	2.3
(52.5,24.5)	8643	20.47	2.3
(52.5,31.5)	9082	19.48	2.7
(52.5,38.5)	8887	19.91	0.5
(52.5,45.5)	8838	20.02	0.1
(52.5,52.5)	8887	19.91	0.5
(52.5,59.5)	8936	19.80	1.0
(52.5,66.5)	8936	19.80	1.0
(59.5,3.5)	8887	19.91	0.5
(59.5,10.5)	8447	20.95	4.7
(59.5,17.5)	8691	20.36	1.8
(59.5,24.5)	8643	20.47	2.3
(59.5,31.5)	8594	20.59	2.9
(59.5,38.5)	8740	20.25	1.2
(59.5,45.5)	8691	20.36	1.8
(59.5,52.5)	8.398	21.07	5.3
(59.5,59.5)	8.594	20.59	2.9
(59.5,66.5)	8.398	21.07	5.3
(66.5,3.5)	8.789	20.13	0.6
(66.5,10.5)	8.691	20.36	1.8
(66.5,17.5)	8.936	19.80	1.0
(66.5,24.5)	8.740	20.25	1.2
(66.5,31.5)	8.789	20.13	0.6
(66.5,38.5)	8.740	20.25	1.2
(66.5,45.5)	8.740	20.25	1.2
(66.5,52.5)	8.789	20.13	0.6
(66.5,59.5)	8.887	19.91	0.5
(66.5,66.5)	8.887	19.91	0.5

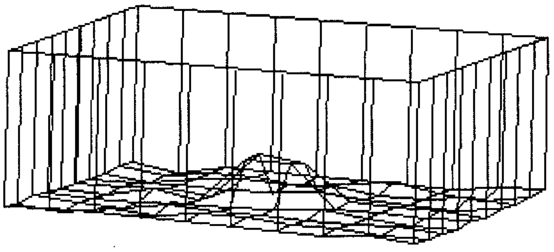


Fig.6 Estimated slab thickness profiles using T/F

6. Comparisons

The modified impact echo method using transfer function can result in a better result of assessment without much consumption of time and money. The thicknesses of concrete slab can be detected using high frequency part with the maximum error of 5.3 %.

From the normalization of response signal with input force signal, complication due to indistinct small signals around traveling frequency can be reduced as shown Fig. 5. And noise and unwanted signals can be distinguished by coherence, and averaged signals from reliable source are used. And Labview program for this makes easier measurements and analysis of reflect waves from the boundaries.

7. Conclusions

The test method described in this paper on concrete slab can be used with such good reasons.

1) The modified impact echo method using transfer function can have the distinctiveness of results by normalizing the response signal with force signal.
2) The coherence can be used to find the noise and unwanted signals and more reliable data can be selected.
3) Averaged signal is helpful to find more exact thickness frequency.
4) Labview program developed for modified impact echo method makes procedures easy.

Acknowledgment

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