Effect of Depth and Location of Circumferential Cracks on Natural Frequencies of Rotating Shaft

Dr. Sabah Mohammed Jamel

Professor

Ziad Shakeeb Al-Sarraf — Assistant lecture

Mohammed Najeeb Al-Rawi — Assistant lecture

Mechanical Engineering Department, College of Engineering, Mosul University

Abstract

In this paper, An-Non destructive test procedure was used to study the effect of depth and Location of circumferential cracks on the vibration characteristics of the rotating shafts. The first procedure was to measure the natural frequencies of rotating shaft before renewing circumferential cracks with different dimensions and depths from the bearing of the rotating shaft using (vibration analyzer B & K type 2515) apparatus to analyze the vibrational characteristics during the rotation and comparing it with mathematical analysis using the method of mounting the rotating shaft. Secondly, a crack of certain depth and dimension away from the rotating shaft bearing was made. The measurements of the natural free vibration due to the presence of the crack were carried out. The study took into consideration the diameter and the length of the rotating shaft, beside the measurement of the natural free vibration of the shaft. The practical results showed a decrease in the natural frequencies of rotating shaft when the crack prested. This decrease was more when the crack located in areas near the bearing than was located away from the bearing.

Key Word : Shaft, Crack, Circumferential, Frequency, Depth.

أستلم في 2004/5/1 **قبل في 2005/8/ 28**

lþơĂ!f	Ƨ ŏƧzk!f	ƨdžƧ!f
ƨkƧNj	ƽT!f þĂŋÅ DžþƵ þljƵ ÕzöhƠ!f þþƧk!f	ω_o
ƨkƧNj	ƽT!f þĂŋÅ þljƵ ÕzöhƠ!f þþƧk!f	ω
^{3}Dž/Džƺ‡	Ł5ĆĂ‡!f	ρ
-	þþƧk!f ýdžĆzdž	λ_n
-	LJ ļ ŏÅh Łh ļ lj	ν
^{2}Dž	þÅdžzǂ! Ŏ ư Ƨz!f yƠldž!f Łơć ļ dž	A
Dž̈dž	ƽT!f ƽdžƵ	A
Dž̈dž	þÅdžz!f ƧƠp	**D**
^{2}Dž/LJkĂŏlj	ŁljÅƧdž!f ýdžĆzdž	**E**
^{4}Dž	Łơć ļ dž̈! ŎljĆĂ!f Džƨz!f	I
-	þĆnjŋŮf ƨŏ‡Ƨk ýdžĆzdž	K_t
-	lƧŏƺkdž ƽĆdžƵÜ þĆnjŋŮf ƨŏ‡Ƨk ýdžĆzdž	**Kts , KtL**
Dž̈dž	þÅdžz!f ýÅƠ	**L**
Dž . LJkĂŏlj	ŎFĆljơljŮf Džƨz!f	**M**
LJkĂŏlj	ýzƽ!f þƧ ăÅp	**R_1, R_2**
Dž . LJkĂŏlj	LJfƧÅþ!f DžƨƵ	**T**
Dž̈dž	ƽT!f ‖ dž ļ	t
Dž̈dž	ƽT!f yþÅdž	**X**
-	þÅdžz!f ƧƠp Ĭ!f ƽT!f ƽdžƵ Łh ļ lj	**2a/D**
-	þÅdžz!f ýÅƠ Ĭ!f ƽT!f yþÅdž Łh ļ lj	**x/L**

1. ‖hDŽqƽDŽ‖Ɛ

lþùdžƵŰfÅ LJĆhư!!fÅ ĶĆhkƶ!f LJǫ ŖǫÜ Łŏ ļ þljnj!f ý‡Ćönj!f ýT5 Ŏ5 Ŏ ļ ŏƒƧ!f Yh ļ !f Ƨhkƶk ĶĆ‖Tk!f Ŏù5 ýŏƺTk!f ýŭP Ɛ ηĆƨdž!f ýTƨ!f ‖!Ŗ! Ü LJFĆ‡dž!f LJdž þŏþƶ!f Ŏ5 Łŏ!Ćƶ!f ýĆdžơŰf ýlj Ŏ5 DžþPk ļ k lƧfÅþ!f [1]. źþŋ ĭ ƧÅƧư ĶĆ‖Tk!f Ł Åþơh ƌhljk!f LJĆ5 Ŏ!Ćk!ĆhÅ ƧfƧ ư Ūf LJdž þŏþƶ!f Yh ļ ŏ ĆdžhƧ Łŏ!Ćƶ!f ýĆdžơŰf ĭ þƌk Ŏk!f ŁdžĆnj!f YĆh ļ Ūf LJdž (Unstable) LJƨfÅùkŭ!f Ł!Ćơ Ĭ!ǫ lƧfÅþ!f lþdžZŰf Ư Ƨzk LJǫ ƽÅ‖Tù!f ƌTljk LJD LJ‡džŏÅ . ýdžz!f CĆljÅD Łŏ!Ćƶ!f ĶfƨfƨkNjŮf LJZ ũ ư5 Ü Ćnjŏ5 ĶĆ‖Tk!f ƧÅnjUÅ Ł ÅþơĬ!ǫ .[2] Ćnjŏ5 lƧƛƌdž ŁŏηƧĆP lÅp Ĭ!ǫ lþdžZŰf ‖ lk Ư Ƨzk Łηŏklj ÅD Ķŏŏƨk!f Ł lp ýŭP LJdž LJFĆù‡dž!f Ŏ5 źþŋ Ł!Ćzƽ!f ĶĆŏljlk!f LJdž þzk YÅŏz!f Ƨ T‡! ĶfƨfƨkNjŮf ýŏlơk Ł lŏƧƵ DžfþPk ļ LJǫ Σ ‡zk lƧfÅþ!f ŁdžUljũ! ĶfƨfƨkNjŮf ýŏlơk LJŰ lƧfÅþ!f ŁdžUljũ! Łpć Ƶ!f þŏ!Åk ĶĆƵơdž Ŏ5 ýTƽl! Ł ư Ƨzdž!f Ŏù5 lƧfÅþ!f ŁdžUljŰf ýTƽh ƌhljk!f LJ‡dždž!f LJdž Oh Ţ f ƦR! CfƨηŰf ljRnj! Łŏ‡ŏljĆ‡ŏdž!f f FĆŢP!f Ŏ5 ĶfƧŏźk!f . [4] Łƽl‡dž Ƨŏ ƺÅ Łzŏƨ ļ Ł lƧƵ!f ljRNj LJD LJZ ũ ư5 [3] lƨ‡hdž ýơfƧdž

ĶfƨfƨùkNjŮf ýùlơk Łùŏljlk DžfþPk ļ f ýÅơ Łŏldžz Ł ļ fƧph [5] LJÅƧPcÅ (Adams) Łơh!f DžĆp ƽÅ‖T LJdž ư kk Ŏk!f lƧfÅþ!f Łŏ‡ŏljĆ‡ŏdž!f CfƨηŰf Łdžć lk ļ ă þdž LJŏdžPk Ŏ5 (Łŏ5 ŭkǫŮ) f ơ5 Ł lŏƧƵ Ćnjƽ Ţ Åh CfƨηŰfÅ Łŏlŏlơ!f ƧfƧ ư Ūf LJŏh ƽ5fÅk þÅŋÅ Ĭ!ǫ Łơh!f ý Ţ Åk . ƽÅ‖T!f ljRNj yþfÅdžÅ ƽĆdžZD þŏþơk!Ă .ĆnjljZ ƌhljkdž!f ƧfƧ ư Ūf ĶfR

ǏǐǴZ Ǒlǐơ!f ƽT!f ƨǒƛdk ýĂơ ĦǒƨUlj [6] (Dimarogonas and Massouos) LJǤƛơǤħ!f Σƨþ ĦùljĂƨdž!f ýùdžǤZ ƨǒƛdùk Ħlfƨþ LJZ ű ư5 (Torsion) CfĂk!Ůf Ħ!Ǥơ Ǒ5 ƨfĂþ þĂdžz! Ǒǂ ǒdžǤljǒþ!f ǁ ĂǐǴl!f Ǒùzǒħƀ!f ƨfƨƙNjǩf LJD LJǤƛơǤħ!f ƝkljklfĂ ŮýĂŰf Ǒzǒħƀ!f þþƨk!f ΣǤǒp ýŭP LJdž ƽT!f Ħlƀljdž Ǒ5 ĦǒzpĂdž!f . Ƙfþþƨk!f Dǐǒp Ǒ5 LJǤTllj!f ĦUơŭdž ýŭP LJdž Ǒlǐơ!f ƽT!f þĂηĂħ ƨƛdkǒ CfĂk!Ůf Ħ!Ǥơ Ǒ5 þĂdžz!f DǐǤŮlj! Ǒǂ ǒdžǤljǒþ!f ǁ ĂǐǴl!f ǏǐǴZ ƽT!f ƨǒƛdk [4] (Davis and Mayes) LJǤƛơǤħ!f Σƨþ ű ư5 (Multi- Shaft and Multi- bearing) lþþùzƙdž ýùdžǤơdž ǏùǐǴZ Ƙùhƛdž!fĂ þþùzƙdž! ƨfĂþù!f LJƛħ LJǤƛơǤħ!f ýTĂk .ƒlT LJdžưƙdž!fĂ ƨfĂþ!f þĂdžzǐǴ! ƽT!f Ħlƀljdž Ǒ5 Ǒǂ ǒdžǤljǒþ!f þǤnjηŮf ƨǒƛdk Ħlfƨþ LJZ ĦǒƨǒĂþk!f ĦZƨl!f ǏǐǴZ þdžƙzǒ ƽT!f Ħlƀljdž Ǒ5 CǤljơljŮf DǐƨZ ƨǒƛdk ƘơkĂ ƨfĂþ þĂdžz! Ǒǂ ǒdžǤljǒþ!f ǁ ĂǐǴl!f .ƽT!f ƽdžZ ǏǐǴĂ þĂdžzǐǴ!

Ǒù5 ĦùǒzpĂdž!f ĦljĂƨdž!f Ƙfƨǒƛdk ýĂơ Ħlfƨþ [7] (Rajab and Al-Sabeeh) LJǤƛơǤħ!f ƨηljD ýùǒ!Ǥơk ƨǒĂùƀk ƽǒƨƀ LJZ NldžZĂ ƽT!f ypĂdžħ Ƌhljk!f Ưƨƹ! (Ă+ljǒTĂdžǒk) YĂlj LJdž þĂdžz! ƽT!f Ħlƀljdž .ƽT!f ƨǒþlk! ƒǒ5Ǥ+ þzǒ Ħožǒħƀ Ƙfþþƨk Ħλŭλ ýĂD Ǒ5 ƨǒƺk!f LJD LJǤƛơǤħ!f ƝkljklfĂ Ü Ħǒư ǤǒƨYĂùlj!f LJùdž ƽT LJdžưƙdž ƨfĂþ þĂdžz! ƨfƨƙNjŮf lƨNjǤU [8] (Papadopoulos) ĦơǤħ!f Σƨþ ĦùljĂƨdž!f YǤlùơ! ƘǤ5ĂƽTùdž!f DǐfþPklǤħ ƽTǐǴ! ƒηRĂdžlj ýǒλdžk ƽǒƨƀ LJZ CfĂk!Ůf Ħ!Ǥơ Ǒ5 Ưƨƶkljdž!f ĦǒzpĂdž!f ĦljĂƨdž!f Dǐǒp þǤηǒǫ Ǒ5 LJǒklǒƨƀ!f ƽhǤƀkħ ĦơǤħ!f ƝkljklfĂ .ƒǒǐdžZ ƘǤlǒǐ!f CfƨηǫĂ ǑǒƨUlj ĦǒzpĂdž!f . .ƽT!f ƽdžZĂ ypĂdž ydž Ħožǒħƀ!f Ƙfþþƨk!f LJdž Dǐǒp Ħ ŭλ ýĂD ýǒλdžkĂ þǤηǒǫ Ǒ5 ǁ!RĦĂ ƀlĂ Ǒ5 ƒlT LJdžưƙdž ƨfĂþ þĂdžz! Ƙfƨfƨƙ NjŮf ýǒǐơƙħ [3] (Behera and Parhi) LJǤƛơǤħ!f DǐǤp ýFǤlù!fĂ ƽTù!f ƽdžZ lþǤǒƨ LJD Ħlfƨþ!f ljRNj ýŭP LJdž LJǤƛơǤħ!f Ɲkljklf . (Viscous Mediam) Ɯƨ! . þǤdžPÚf lþǤǒƨĂ ƨfƨƙNjŮf ĦzlĂ Ħηƨơ!f ĦZƨl!f LJǤTlj Ǐ!ǫ ǐþƋk ƜƨǐǴ!f

ýùdžǤơdž DǐfþPklf ydž Ħƽǐ́kPdž ýfĂƀDĂ ƨǤƀpD ƘfĂR lþdžZD DǐfþPklf Dǐk þ15 Ħǒ!Ǥơ!f Ħlfƨþ!f Ǒ5 ǤdžD Ħfþùơǫ yùdž NǒkǒǤnjlj ǤkǐǴǂ Ǒ5 (Bearings) ýdžǤơdž ǏǐǴZ þĂdžz!f Ƙǒħƛk Dǐk Rǫ Ü þĂdžz!f ƨƀp Ylơ ĦZĂLjkdž . ƨfĂþ!f þĂdžz!f þfþkdžf ǏǐǴZ ƽƽ́kPdž ypĂdž Ħλŭλ Ǒ5 Ħǒǐǐơ!f sĂlT lþùdžZŰf Ǒ5 ƘǤllTk!f ƽǤdžZDĂ yþfĂdž LJZ ƋhljkfĂ 2T+!f Ħlfƨþ ĂNj Ü Ħơħ!f fRNj LJdž 2 þnj!f LJǫ Ƙfþþƨùk!f Dǐǒùp Ǒù5 Hǐ́TǤơ!f Ƙfƨǒƺk!f ĦUơŭdž ƽǒƨƀ LJZ Ƙfƨfƨƙ NjŮf ƘǤǒþdž ýǒǐơƙ YĂǐǴlƛħ lƨfĂþ!f DǐǒdžTk Dǐk Rǫ . Ħǒzfƨfƨƙ NjŮf f FǤTP!f ǏǐǴZ lþdžZŰf ljRNj ýfĂƀDĂ ƨǤƀpD ƨǒƛdk Ħlfƨþ LJZ ű ư5 Ü Ħƶǒħƀ!f Dǐk Ǥdž+ . Ħǒƨlj ƝFǤklj ydž ýǒ!Ǥơk!f fRNj ĦljƨǤldžĂ ƨfĂþ!f þĂdžzǐǴ! Ħǒzfƨfƨƙ NjŮf f FǤTP!f ýǒǐơƙ! ǑǐǴdžZ ƜRĂdžlj . ƘfþǤnjη Ůf ƨǒ+ƨk ýdžǤzdž+ ƽT!f Ħlƀljdžƛ lƨλƋdž!f ýdžfĂƶ!f Ưƶƛ Ħlfƨþ

Ǐ TFǐþǁƐ üǐ+ΘĦǁƐ .2

(ω₀) gǿǐƽÉǒǎ gÆŧ3Qǒ ĞƐĦĔGÛǒǎ ğǎǻǻÀǫǒǎ ā ÅÊg 1.2

Ɲùljƶ5 Ü lƨfĂþ!f lþdžZū! Ħǒƨfƨƙ NjŮf f FǤTP!f ǏǐǴZ ƽĂlT!f ypfĂdžĂ ƽǤdžZD ƨǒƛdk Ħlfƨþ ýηŰ ǤùǒƨUlj Dǐǒù!f ljRNj YǤlơ DǐkĂ . ƘǤllTk!f Ħfþơǫ ýhp lþdžZŰf ǁ ǐǴk! Ħožǒħƀ!f Ƙfþþƨk!f Dǐǒp Ħƶƨzdž Yǐ́ƀkǒ Ħƽ́kPdž lþdžZD Ħ ŭλ DǐfþPklf þ15 Ü Ħǒƨfƨƙ NjŮf f FǤTP!f ǏǐǴZ þĂdžz!f ƨƀpĂ ýĂƀ Ljdž ý+ ƨǒƛdk Ħlfƨþ! Ă 500) Ħùƽ́kPdž ypfĂùƀD Ħλŭλ DǐfþPklf Dǐk ƨǤƀpŰf ljRNj Ljdž ƨƀp ý+!Ă (Dǐǐdž 12 Ă 10.5 Ă 8) ƨǤƀpŰf ǁ ù!RĂ Ü [9] (2-1) Ħù!þǤzdž!f DǐfþPkùlf Dǐk Ħožǒħƀ!f Ƙfþþƨk!f ljRNj Ħdžǒp YǤlơ!Ă. (Dǐǐdž 700 Ă 600 þùzħ Ħdžǒl!f ljRNj YǤlơ Dǐk Rǫ Ü þĂdžzǐǴ! Ƙǒħƛk!f Ħ!Ǥơ ǏǐǴZ ƒþǤdžƙZf ǑlǤlŰf Ǒzǒħƀ!f þþƨk!f LJǒdžPk Ưƨƶ! þĂùdžz!f ǑƙǒǤùnjlj ǤùǐǴǂ Ǒù5 (Simply-supported) ƀǒlħ ý+Tħ ǤdžNjfþơǫ þĂdžz!f Ƙǒħƛk! LJǒk!Ǥơ Ưƨ5 . LJǒƙǒǤnjlj!f ǤkǐǴǂ Ǒ5 ƘhƛĂ ý+Tħ ă ƨPŰfĂ

$$\omega_o = \frac{\lambda_n^{\ 2}}{L^2}\sqrt{\frac{EI}{\rho A}} \qquad \text{--------------------(2-1)}$$

(K$_t$) ƖƐƹƑǋǈǗƐ ƦǏǀƥƗ üĎǇƴĎǇ ħĎǇĭƼ ƒƑƨƟ 2.2

ƗùƼǈƘƤdž ƳƒĂǊ Ĭ!ę Ɨư ƧƶdžǀƥƧƼdž ƗöƪƥǊǋ Ɨ!Ɠơ! ƥǅǌƞǗƒ ƨöƗƧƙ ƘǘdžǅƶdžƔǅƪơ ƗħĂƶƮ!ƒ ǈdž
ýùdžǅƶdž Ɨùdžöp ǈƷ ƒƦǌ!Ă Ü [10]ýödžơƙ!ƒ ǈdž ƳĂǊ ý!! ƗħƪǅǊdž ǅöp ĬǕƵ ýĂƮơ!ƒ ǈƗdžö Ʀ . ýödžơƙ!ƒ ǈdž
-: [11]ƗöƙǗƒ Ɨ!ƥǅƶdž!ƒ ǈdž ǅǌħƓƪơ ǈƗdžö ƗƼǈƘƤdž ýödžơƙ ƘǗƓơ Ŏ5Ă ƘƒƥǅǌƞǗƒ ƨöƗƧƙ

$$K_t = \frac{(K_{ts}-1)(K_{tL}-1)}{\sqrt{(K_{ts}-1)^2 + (K_{tL}-1)^2}} + 1 \qquad \text{-------------------(2-2)}$$

: ǈǅ Ɨöơ

ƪƧöƺƙdž ƽǅdžƵǅ Ɨ!Ɠơ Ŏ5 ƥǅǌƞǗƒ ƨöƗƧƙ ƘǘdžǅƶdžƔ ýƛdžƙ K_{tL} Ă K_{ts}

Ăù!Ă Ü ƗƶħƧdž ǆħöƧƖƙ ǈĂƗƙ ƽƮ!ƒ Ɨdžp ǈǅ5 (1) ýƗƮ!ƒ Ŏ5 ƠưĂdž!ǅƗ ƽƮ! ǕƦĂdžǊ ýöƛdžƙ ƥǊƵĂ
Ɨù!Ɠơ Ŏ5 (K_{tL} Ă K_{ts}) ƘǘdžǅƶdžǋƦǌ ǈǅ5Ü ƽƮ!ƒ ƽdžƵ ýƛdžƙ (a)Ă ƽƮ!ƒ ǁdžƪ ýƛdžƙ (t) ǈǅ ǅǋưƧ5
-: [11]ƗöƙǗƒ ƘǗƥǅƶdž!ƒ ǈdž ƔƪơƙǅǋơǋǗƒ

$$K_{ts} = 1 + 2\sqrt{\frac{a}{t}} \qquad \text{-------------------(2-3)}$$

$$K_{tL} = \frac{1}{N}\,\frac{3}{4}\left(\sqrt{\frac{d}{2t}+1}+1\right)\left(\frac{3d}{2t} - (1-2v)\sqrt{\frac{d}{2t}+1} + 4 + v\right) \qquad \text{------(2-4)}$$

: ƗöƙǗƒ Ɨ!ƥǅƶdž!ƒ ǈdž ƔƪơƙǅǋơǋǗƒ (N) ǈǅ Ɨöơ

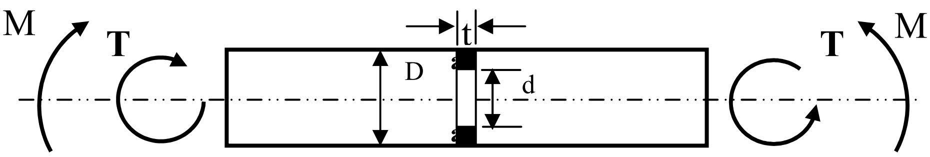
$$N = 3\left(\frac{d}{2t}+1\right) + (1+4v)\sqrt{\frac{d}{2t}+1} + \frac{1+v}{1+\sqrt{\dfrac{d}{2t+1}}} \qquad \text{-------------------(2-5)}$$

ǈƗdžö ƗǀħǅƪƮ!ƒ ƘǘdžǅƶdžƮ!ƒ ǈƷ ǅƒĂƙ!ǗƒƗ!Ɠơ Ŏ5 K_t ƘƒƥǅǌƞǗƒ ƨöƗƧƙ ýdžǅƶdž ƔǅƪơƗħƪǋ!ǅħ ǅdžǅ
-: ƗöƙǗƒ ƘǗƥǅƶdž!ƒ ǅƒƥƤƙƪƒ ýǘƤ ǈdž ǅǌħǅƪơ

$$K_{ts} = 1 + \sqrt{\frac{a}{t}} \qquad \text{-------------------(2-6)}$$

$$K_{tL} = \frac{3\left(1+\sqrt{\dfrac{d}{2t}+1}\right)^2}{4\left(1+2\sqrt{\dfrac{d}{2t}+1}\right)} \qquad \text{-------------------(2-7)}$$

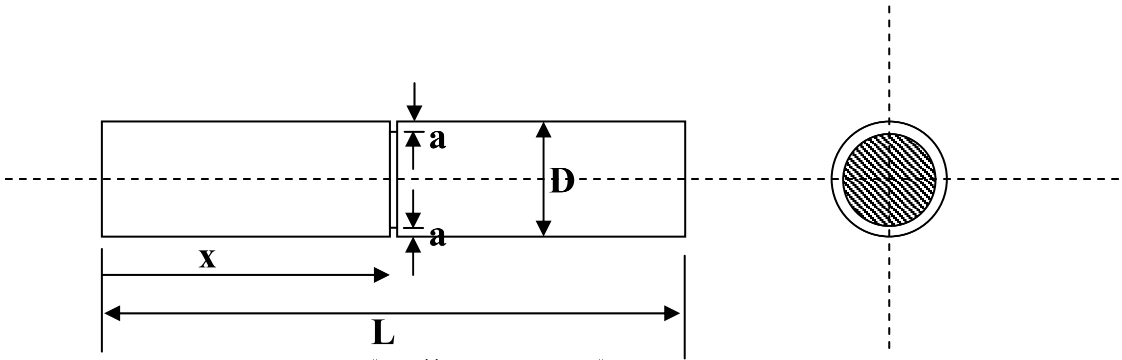
(ǅƒĂƙ!ǗƒĂ ǅǋơǋǗƒ) ýödžơƙ!ƒ ŎƙƓơ Ĭ!ę ƯƧƶƙdž!ƒ ƥĂdžƵ!ƒ Ɨ!Ɠơ ƠưĂö (1) ýƗƮ!ƒĂ



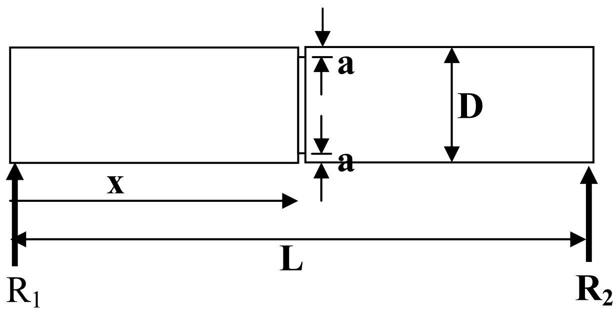
ҌƐNjłǁŰƐNj ҌƑdžӨdžŰƐ Ĭ łǁƑӨ Ăǁ Ɛ f þўłĐžǁƐ ơǀNjĐžўǁƐ hǁƑӨ (**1**) ü l ỵ

ҍTǁ! Ŏ ư ĜőS!f ɯŖĂdžǀ!f 3.2

ҍĂlTù!f ҍĜdžZĐĂ ўþfĂdž Sőλk ł ỵfSþ Đk þl5 Ü þĂdžzǁ! łő‡őđžǀőfþ!f f fĂP!f ĬǁZ Ŏlǁơ!f ҍT!f Sőλk łőđžNjŰ ўùpĂdž Ŏ5Ă (D) ǀSƠp þĂdžZ Ŏ5 (2a)ĂNj ҍT!f ҍdžZ ǈĐ SĜhkZĜh łőƨfƨkNjŰf f ƑĜ ƮP!f ĬǁZ łőlǁơ!f . SfĂþ!f þĂdžz!f Ʀőhλk ł!Ĝơ ўλdžő (3) ў‡T!fĂ . (2) ў‡T!f Ŏ5 Ơ ư Ădž Ĝdž‡ þĂdžz!f ўĂƠ ǈdž (x/L)



þƐNjơǁƐ ơǀNjĐžўǁƐ Ĭ ȝ 5 ỵǁƐ ƲƯҍĐž ɳ ƮNjĭ (**2**) ü l ỵ



SfĂþ!f þĂdžz!f Ʀőhλk ł!Ĝơ ўλdžő (3)ў‡T

.3 hĭ‡Đžўǁ Ɛ l ƐNjŰƢǀǁƐ

1.3 þƑĜłƢǀŰƐ l ƑdžĩỴ

ўĂþùɳ!fĂ . (%0.13) ǈĂhSĜ‡ łh ỵǀhĂ (Mild Steel) ĂNj ƔSĜɳk!f ǀŖNj Ŏ5 ĐþPk ỵdž!f ǈþzdž!f . ł ơh!f Ŏ5 łdžþPk ỵdž!f lþdžZü! łőƑĜőƨő5!fĂ łő‡őǀĜ‡őđž!f ƦĜ5Ʈ fĂdž!f Ơ ư Ăő (1)

(mm)	8 , 10.5 , 12	(D)þĂdžz!f ƧƟp
(mm)	500 , 600 , 700	(L)þĂdžz!f ýĂƟ
(K_g/m^3)	7800	(ρ)Ħ5ĆĂ‡!f
(GN/m^2)	207	(E)ĦljĂƧdžl! JNljĂŏ ýdžĆzdž
(MN/m^2)	280	(σ_y)ĦljĂƧdž!f þĂþơ
(%)	25	Ħ!ĆƟkl ǔ! ĦŏĂFdž!f Ħhl lj!f

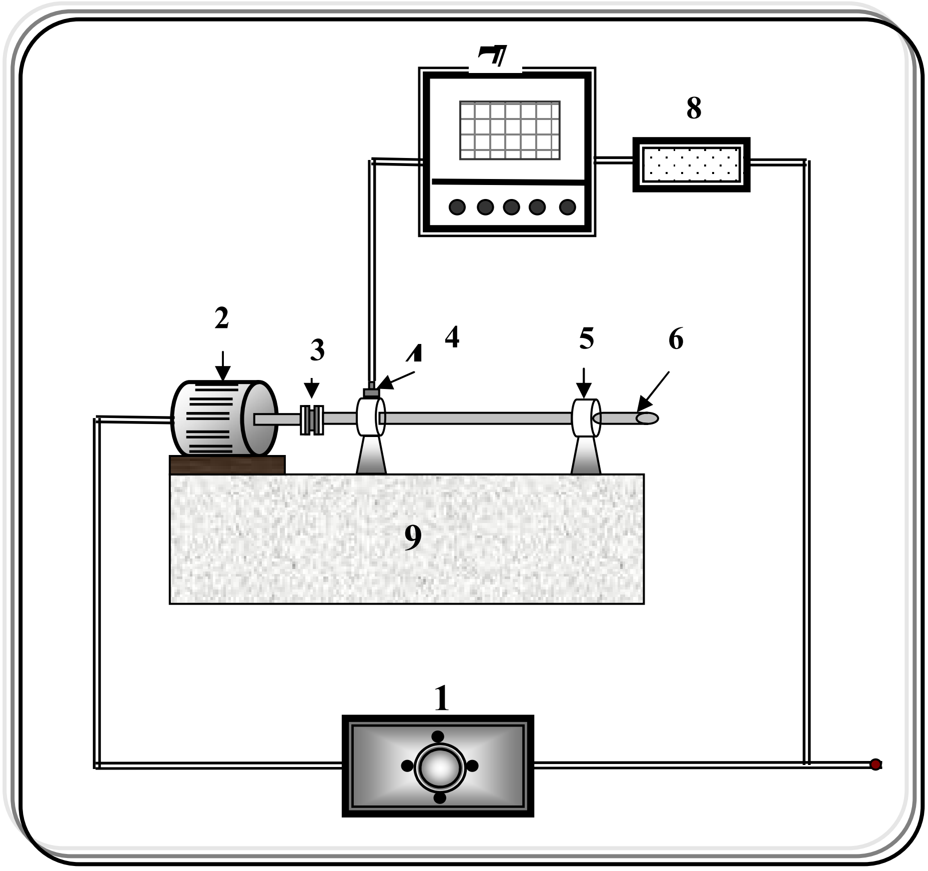
gøãşÆöä gÆŧʒQo̧ ĞŁəÀlÂŁÀöãş ĞŁÒĦąÀÒĦţã ğÀÀòäzţã (**1**) òşÆDZ

þƑĆĦCJÚȼ ŖFNJШ **2.3**

Ŏ5 Ơư Ădž ĂNj Ćdž‡Ă Dž‡ơk lɜnjŋDĂ Σ Ćõp lɜnjŋD lþZ LJdž LJĂ‡dž DžþƤkl dž!f ǐ ƨhkƤdž!f ɜĆnjŋ!f LJǫ NJkĆlơlldžĂ Ƙfɜfɜk NjŬf ýlơdž ɜĆnjŋ ĂNj N!ǔƤ LJdž ƘfCƒƨl!f ŖPD Džk ǐŖ!f ŎlǒFƨ!f ɜĆnjŋ!f LJǫĂÜ (4) ý‡T!f ƨùƟp YlơĂ ĦslkƤdž ƨĆƟpD ǐŖ (Bearings) ýdžĆơdž!f LJdž LJŏljÃD Ǐl Z Ćnjkõhλk Džk LJfƨĂþ!f lþdžZD LJD Ŗǫ Ü LJǫ Ł ŏơ Ü lþõŋ Ładžĉlkl ƘfŖĂ Ħljɜkdž Łõþõþơ lþZĆp ǏlZ ýdžĆơdž!f ljŖNj Ƙλhλ LJõơ Ŏ5 Ü DžþƤkl dž!f þĂdžz!f YlùơĂ Łùh ĂlƟƟdž!f yƥfĂdž!f Ŏ5 Ƙõhλk!f ýhƥ Łõþõþơ!f lþZĆl!f ǏlZ Ł‡ƨơ!f Ŏ5 Łõƨơ!f Ćnjõƥ! ýdžĆơdž!f ljŖNj . lþdžZŪf ýfĂƟD

Ɵhƨ ĦlTĂ DžþƤkl fĂ Ü ýdžĆơdž!f Ładžĉlkl f Σ slj ǏlZĂ NJkõhλk! ǑFĆhƨnj‡!f ǁ ƨơdžl! lþZĆp Džõdž Tk Džk CfĂùk!Ŭf Łù!Ćơ Ł Ăþơ yĆqdž!Ă ƨfĂƥ!f þĂdžz!Ch ǑFĆhƨnj‡!f ǁ ƨơdž!f Ɵhƨ! (Flexible Coupling) Ħljƨdž ǁ ƨùơdž!f LJfƨĂƥ ýŭùƤ LJùdž þĂdžz!f ƨõĂþk Džk Ƙõhλk!fĂ Dõõdž T k!f Łõldž Z LJdž CĆnjkljŬf þzh . (Torsion) ǐŖùzõ ǐŖù!f ŁùõƟ!Ăs!f DžUljùdž ɜĆnjŋ LJdž þõsk l Ü Ɵhƨ!f Hl TĂ ŁƟĆlĂh lST Chdž Nhh ƟĂhƨdž!f ǑFĆhƨnj‡!f lɜnjŋdh ĦljĆzk lŬf Džk ŁõljfƨĂƥ!D ŁƵƨl!f Σ Ćõl!Ă Ü NJkƵƨl Ŏ5 Dž‡ơkl! ŁhĂlƟƟdž!f ŁõƟ!Ăs!Ch ǑFĆhƨnj‡!f ǁ ƨơdž!f . ŁƵƨl!f Σ Ćõp

ɜĆnjŋ ŁƟĆlĂh þĂdžzl! Łõɜfɜk NjŬf ŁhĆŋk l Ŭf Σ Ćõp Łõldž Z Ƙdžk ŁhĂlƟƟdž!f ŁƵƨl!Ch þĂdžz!f ƨõĂþk þzhĂ LJdž Łlzhljdžĉlf Ƙfɜfɜk NjŬf ƘĆõþdž! ýdžĆ‡ ýölơk CfƨηŰ (Vibration Analyzer) Ƙfɜfɜk NjŬf ýlơdž (ýõŋzk!f Σ Ćõldž) Σ ŋdž!f DžþƤkl f ƟĆlĂh ƘfƨĆTŰf ƟĆlk!f ýŭƤ LJdž þĂdžz!f ɜfɜk Njf ŁõljĆĂ!f Łõĉnjlj!f Ćdžc Ü ɜĆnjŋ!f ydž lST Chdž lSĂT h ǐl T kdž NJkõĆnjlj ăþơǫ LJĂ‡õ ǐŖ!f (Accelerometer) . (Bearings) ýdžĆơdž!f Ǐl Z ƨfĂƥ!f þĂdžz!f LJdž Łhõƨp Ł!Ɵljdž Ŏ5 NJkõhλk Džk ƥ15 Σ ŋdž!f Dž l ŋ ýldžk Ŏk!fĂ



(Coupling) ƠŀƧ ƚǁƮĂ -3 ŎƑǴŀƧǌǂ ǁƧơď -2 ƚŏƠ!Ăƺ!ƒ ďƲǉď -1

(Rotating Shaft) ƧƒĂþ!ƒ þĂďž!ƒ -6 (Bearings) þǉƪď!ƒ -5 ýŏƞžƙ!ƒ ƩǴŏlď -4

ƖþƶǴp -9 (Power Supply) Ɩƨþp ƨǌƞď -8 Ƙƒƨƒƨƙǌǅƒ ýǁơď -7

ƃƑǵƍƣǅȢ ƕƽĭþƯ 3.3

ƚƶƧƪù!ƒ Ĭù!ƒ ŎƑǴŀƧǌǂ!ƒ ǁƧơď!ƒ ƚƠǴƪĂŀ þĂďž!ƒ ƧĂþ Ɩþďžǖƒ Ƨŏ ư ơƙ ƚŏǁďƶ ǇďĆǌƙǉǖƒ þžŀ ƩǴùŏp ƚŏǁďƶ ƘďƙƚŀĂǁƠď!ƒ ƚƶƧƪ!ǴŀĂ þĂďž!ƒ ƧŏĂþƙ þžŀ . ƚŏƙ!Ăƺ!ƒ ďƲǉď ƨǴǌƞ ǇďƖþǴƺƙƪǖǴŀƚŀĂǁƠď!ƒ (Vibration Analyzer B & K Type 2515) Ƙƒƨƒƨƙǌǅƒ ýǁơď ƨǴǌƞ ƚƠǴƪĂŀ Ƙƒƨƒƨƙǌǅƒ ƘǴŏþď ǂ ùŏơ (Spectrum) ŎƞĂùď ƻŏƠ ýǂƬ ĬǁƶĂ Ƙƒƨƒƨƙǌǅƒ ƘǴŏþď ýďǴǂ ýŏǁơƙŀ ƨǴǌƞ!ƒ ƒƦǌ ďĂlŏ ƦǫÜ ƘǖþǴƶď!ƒ ďƒþƤƙƪǴŀ ƧƒĂþ!ƒ þĂďž!ƒ ƨƒƨƙǌƒ Ǉƶƚƛžŀǉďƒƚŏƨƒƨƙǌǅƒ ƘǴƞĂď!ƒ ýŏǁơƙ Ĭǁƶ ǋǁďƶ ǅþŀď þďƙžŏ ƖþĂƞĂď!ƒ (Fast Fourier Transformation, (F.F.T)) ƚžŏƧƪ!ƒ ƧŏƧĂƼ ƘǘŏĂơƙŀ ƚǁƛďƙď!ƒĂ ƚŏ ư ǴŏƧ!ƒ ƘƒþþƧùƙ!ƒ ďŏùp ǴơùưĂď ƚǁŏþþ ƚƞďƧŀď ƚŏďƥƧ ƚŏǉĂƧƙǂ!ǫ ƧƑƒĂþ ďƒþƤƙƪƒ ƚƠǴƪĂŀĂ ƨǴǌƞ!ƒ ýƤƒþ Ǵŏǉďưďƪùƞ Ĭùǁƶ ǴƙŀƛďLJĂǂŏ ĭƦ!ƒ Ʃƞď!ƒ ƚƠǴƪĂŀ ƘƒƧǴŢǖƒ ƠǴlƙ!ƒ ýǘƤ ǇďƚŏďƥƧ!ƒ ƚŢǴŢ!ƒ Ĭǁƶ ƚƞƙǴǉ!ƒ ýǴďžƙƪƒ ƚƠǴƪĂŀ ǇŏžďƽďžŀĂ þĂďž!ƒ Ŏƻ Ŏlǁơ ƽŢ ǂƒþơǫ ďƙ þĂďžǁ! ŎžŏŀƠ!ƒ þþƧƙ!ƒ ƩǴŏp þžŀ . ýďơď!ƒ þĂƞĂ ƴď þĂďžǁ! ŎžŏŀƠ!ƒ þþƧƙ!ƒ ƩǴŏp ƚŏǁďƶ þŏƶƒĂ (0.5 mm) ǁďƪ ĭƦĂ ďƞơ!ƒ ƧŏƺƮ ĭĂþŏ ƧǴŢǉď ý! ďǁď (0.5) ƚďŏlŀ ƽŢ!ƒ ƽďƶ ƖþǴŏƨ ƚŏǁďƶ ƘƧďƙƪƒĂ Ü ƽŢ!ƒ ǂƒþơǫ ýŀp Ĭ!ĂǕƒ ƚƶƧƪ!ƒ ƩƼǉŀĂ ƽŢ!ƒ . (2a/D) þĂďž!ƒ ƧƠp Ĭ!ƒ ƽŢ!ƒ ƽďƶ ƚŀƪǉ

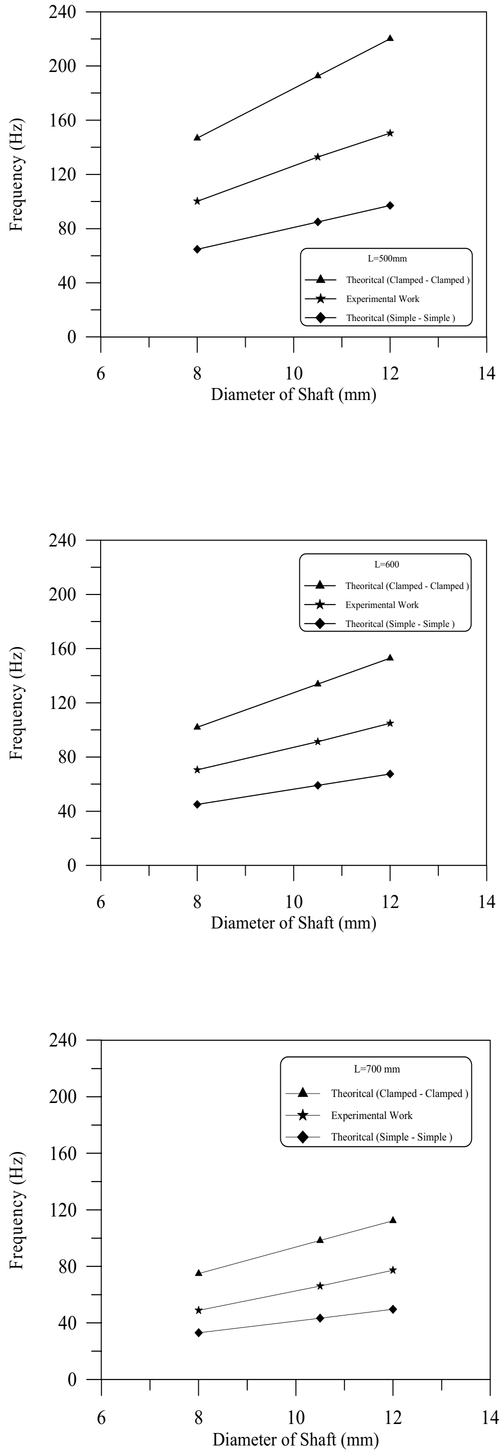
hυ] 5FdZDŽlIENj ƛəFHdlIE **.4**

hυĭRȩRHljÚȩ ţ əFTCIIIȩ Ă‡Y LjlINjUʼNj oqNjDŽyIIȩ þUъ þĭkÐH **1.4**

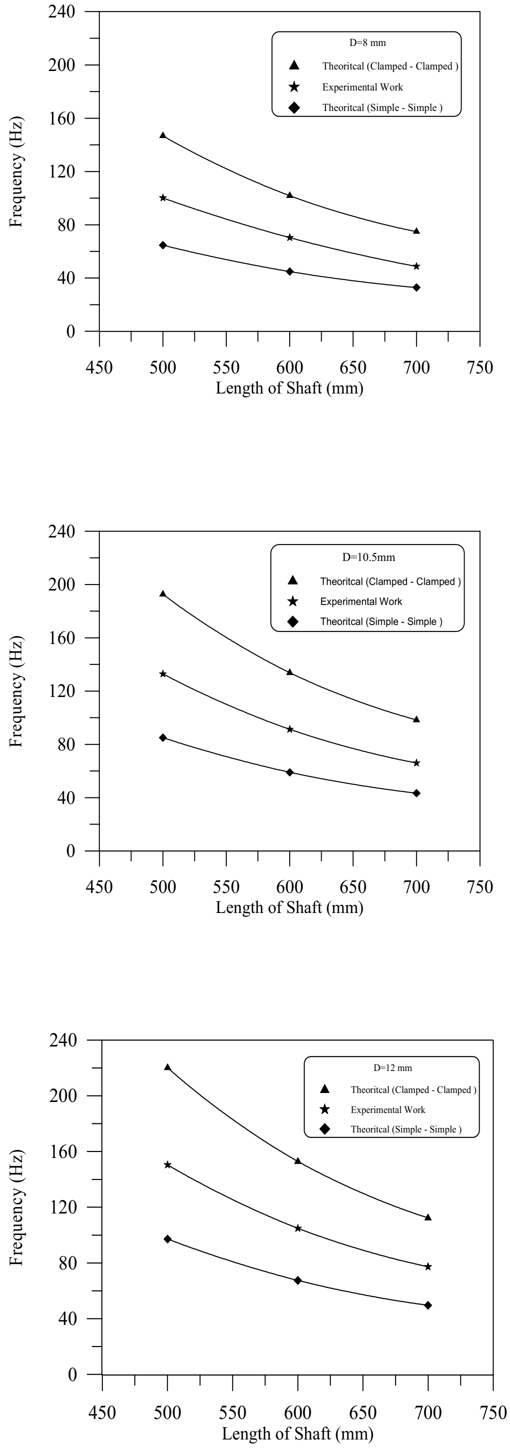
Ł ù 5 2 z d ž Y l ĺ Ő k ô Ü l S f Ă þ ! f l þ d ž Z Ű f Ő 5 ъ Ă l T ! f Ł f þ o ę þ z h Ł ô ž ô h Ő ! f K f þ þ S k ! f D ž ö p Ł 5 S z d ž Ư S ʒ ! S ƛ Ű f D ĭ þ P k] d ž ! f þ Ă d ž z l ! ý Ă Ő ! f Ă S Ő l ! f ý d ž Ć z ! L J Ć ł 5 Ü ъ T ! f Ł f þ o ę ý h p Ł d ž þ P k] d ž ! f l þ d ž Z ū ! K f þ þ S k ! f D ž ö p Ł ƛ ŭ ƛ Ă Ř S Ő p ý ł Ă Ł s l ĺ k P d ž S Ć Ő p D Ă Ř l þ d ž Z D Ł ƛ ŭ ƛ D ĭ f þ P k] f L J D Ř ę . Ł ô ž ô h Ő ! f K f þ þ S k ! f S ô ʒ k Ő 5 Ơ ư f Ă ! f ý Ă Ő Ă S Ő p ý ł y d ž l þ d ž Z Ű f ‖ l ĺ k ! Ł ô ž ô h Ő ! f K f þ þ S k ! f D ž ö p S ô ʒ k Ő 5 Ơ ư f Ă ! f S ô ƛ d k ! f Ĭ Ő Z D Ł s l ĺ k P d ž ý f Ă Ő D Ł ù ô ơ Ć ļ ! f L J ù d ž Ł ù ô ž ô h Ő ! f K f þ þ S k ! f S ô ʒ k ‖ Ă l ĺ] Ő ô ư Ă k ! (6) Ă (5) ý Ć ł T Ű f D ĭ] S D ĭ k þ l 5 . L J ô d ž þ P k] d ž S ù Ő p l þ Ć ù ô ƨ y d ž Ł ô ž ô h Ő ! f K f þ þ S k ! f D ž ö p Ő 5 Ł l ĺ T Ć ơ ! f l þ Ć ô ƨ ! f Ơ ư Ă k (5) ý ł T ! Ć 5 Ü Ł ô l ĺ d ž z ! f Ă Ł ô ư Ć ô S ! f ý Ă ù Ő l þ Ć ù ô ƨ y d ž Ł ô ž ô h Ő ! f K f þ þ S k ! f D ž ö p Ő 5 ý] Ć ơ ! f L J Ć] l ĺ j ! f Ơ ư Ă ö 5 (6) ý ł T ! f Ć d ž D Ü S f Ă þ ! f þ Ă d ž z ! f Ł ù ư Ă S ъ d ž ! f K ô h ƛ k ! f Ő k ! Ć ơ L J ô h Ł ô Ő] Ă J f Ć k j ý ƛ d ž k N L j Ă ł ! N ô l ĺ Z K þ d ž k Z ƒ Ł ô l ĺ d ž z ! f J f Ć k j ! f . S f Ă þ ! f þ Ă d ž z ! f . Ő ! Ć ơ ! f ý d ž z ! f Ő 5

hυĭRȩRHljÚȩ ţ əFTCIIIȩ Ă‡Y 5Njъ l IIȩ UъȩNjDŽNj 5FDŽYć þĭkÐH **2.4**

ъ T ù ! f Ł f þ ù ơ ę þ ù z h Ł ô ž ô h Ő ! f K f þ þ S k ! f Σ Ć ô ! Ł ô l ĺ d ž z ! f J f Ć k j ! f Ơ ư Ă k (3) Ĭ ! ę (2) L J d ž ý Ă f þ ɳ ! f Ư ъ P l j k K f þ þ S k ! f Y l j L J d h Ư ơ ŭ l j . L J ô ъ l ĺ k P d ž L J ô S Ő p K f Ă Ř l þ d ž Z ū ! Ă Ł ъ l ĺ k P d ž y þ f Ă d ž Ł ƛ ŭ ƛ Ő 5 Ő l ĺ ơ ! f . ъ T ! f y þ Ă d ž Ĭ l ĺ Z þ Ć d ž k Z Ů Ć h Ă ъ T ! f ъ d ž Z Ł h l] j þ Ć ô þ ƨ f y d ž K f ƨ f ƨ ł k N j Ů f K Ć ô þ d ž ý ô l ĺ ơ k Y Ă l ĺ] D D ĭ f þ P k] Ć h ъ Ă l T ! f y þ f Ă d ž Ă ъ Ć d ž Z D L J Z S T ł ! f Ă d h l j k ! f Ư S ʒ ! Ă (7) ý ł T ù ! f Ő ù 5 Ł ù l j ô h Ő ! f Ă Ł ô ơ ư Ă k ! f K Ć ô l j ơ l j d ž ! f K d ž] S f Ă þ ! f þ Ă d ž z ! f Ő 5 Ő l ĺ ơ ! f ъ T ! f Ł f þ o ę þ z h Ł h ù l j Ő 5 Ű ư Ć 5 P l j f Ư ơ ŭ l j R Ü ъ T ! f þ Ă ɳ Ă y d ž Ć N j S ô ʒ k Ă Ł ô z ô h Ő ! f K f þ þ S k ! f Y l j ‖ Ă l ĺ] N ő 5 Ơ ư Ă d ž ! f Ő ù 5 ъ ù T Ł f þ o ę þ l j z 5 . ъ T ! f y þ Ă d ž Ĭ l ĺ Z f þ Ć d ž k Z f (2a/D) ъ T ! f ъ d ž Z Ł h l] j Ő 5 þ Ć ô þ ƨ f y d ž (ω/ω$_o$) Ł h l ù l j L J D Ư ù ơ ŭ l j (x / L=0.1) Ć d ž þ ù l j Z ĭ D ý ù d ž Ć ơ d ž ! f Ĭ ù l ĺ Z þ Ă d ž z ! f K ô h ƛ k y þ Ă d ž L J d ž Y ô S p y þ Ă d ž Y f S k p Ů f Ă K ô h ƛ k ! f y þ Ă d ž L J Z þ Ć z k h Ů f y d ž Ă Ü L J ô l ĺ ł T ! f ŭ ł ! Ă f þ ɳ Ł l ĺ ô l ĺ p Ł ô z ô h Ő ! f K f þ þ S k ! f Ő 5 Ư Ć 5 P l j Ů f y Ù d ž Ł ô z ô h Ő ! f K f þ þ S k ! f Y l j Ő 5 Ő ! Ć Z Ư Ć 5 P l j f ‖ Ć l j N j L J D L J ô h ƛ k þ Ă d ž z ! f Ł 5 Ć] d ž 2 Ţ k l j d ž Ő 5 y þ Ă d ž Ă ơ l j þ ù ł d k ! f ý ɳ Ű Ă . (x / L=0.5) Ć d ž þ l j Z ъ T ! f y þ Ă d ž Ő 5 N k U ơ ŭ d ž D ĭ k Ć d ž f R N j Ă Ü ъ T ! f ъ d ž Z Ł h l] j l þ Ć ô ƨ ‖ Ă l ĺ ù] L J D U ơ Ă ù ! þ ù l 5 Ü K f þ þ S ù k ! f Ł h l] j y d ž ъ T l ĺ ! Ł s l ĺ k P d ž y þ f Ă d ž Y l j ! Ă K Ć ô l j ơ l j d ž ! f l j R N j ‖ Ă l ĺ] L J D Ć ù d ž ő 5 Ü (8) ý ł T ! f Ő 5 Ł l j ô h d ž ! f Ă [12] ł ơ Ć h ! f Ć n j ô ! ę ý Ţ Ă k Ć d ž ! Ł l ĺ Ă Ć d ž d ž K l j Ć ł Ł ô l ĺ d ž z ! f J f Ć k j l ĺ ! K Ć ô l j ơ l j d ž ! f Ł h l ù l j Ĭ ù l ĺ Z þ Ć ù d ž k Z Ů Ć h Ă ъ Ă l T ! f y þ Ă d ž h] j k ! f Ư S ʒ ! K Ć ô l j ơ l j d ž ! f l j R N j D ĭ k] S (9) ý ł T ! f f P ő Ł h l ù l j L J D U ù ơ ŭ l j R ę Ü (x / L) ъ T ! f y þ Ă d ž Ł h l] j y d ž K f þ þ S k ! f Ł h l] j ł p ŭ Z Ơ ư Ă k Ő k ! f Ă K f þ þ S k ! f . Ł s l ĺ k P d ž ъ Ć d ž Z Ű Ă þ Ă d ž z ! f Ő 5 ъ T ! f y þ Ă d ž Ł h l] j þ Ć ô þ ƨ f y d ž Ć n j k d ž ô p Ư ъ P l j k K f þ þ S k ! f



Ŏžŏ̈ŬƱ!ƒ ƥƥƧƙ!ƒ Ƨŏƺƙ ƠưĂŏ (5) ýǂT
ƥĂďž!ƒ ƧƱp ƴď Ŏƪƪ̈Ǖƒ



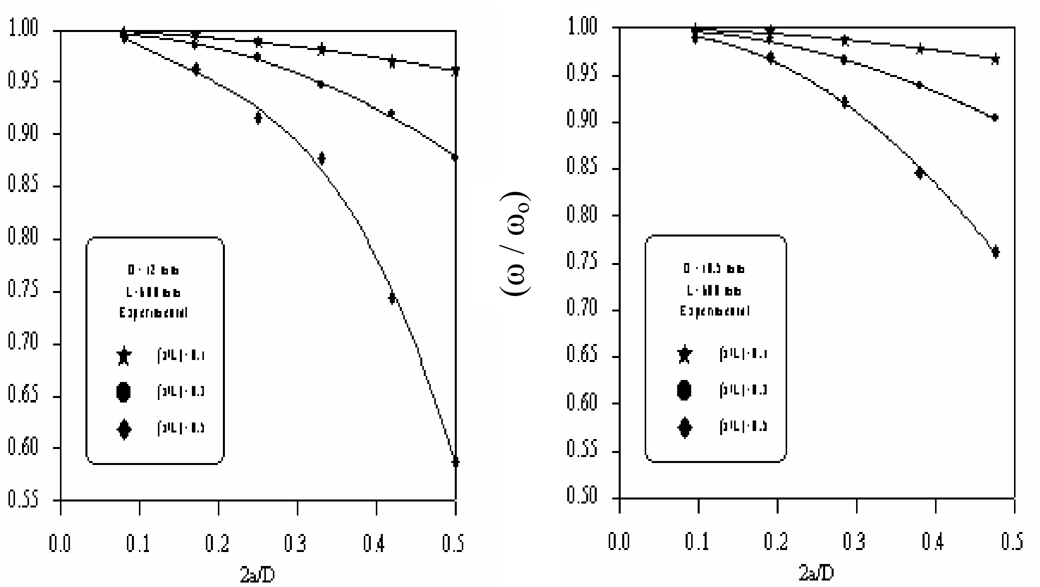
Ŏžŏ̈ŬƱ!ƒ ƥƥƧƙ!ƒ Ƨŏƺƙ ƠưĂŏ (6) ýǂT
ƥĂďž!ƒ ýĂƱ ƴď Ŏƪƪ̈Ǖƒ

(x/L) ܵT!ƒ ۄƿǍǆ ǂلĿ			ܵǆƵ ǂلĿ ܵT!ƒ (2a/D)
(x/L)=0.5	(x/L)=0.3	(x/L)=0.1	
(ω/ωₒ) ǑǆƶƵ!ƒ ǑĿǴĿǕƒ ǑƶǒǂƱ!ƒ ƥƥƧƙ!ƒ ǂلĿ			
0.9890	0.9956	0.9978	0.095
0.9692	0.9868	0.9956	0.190
0.9078	0.9649	0.9868	0.285
0.8464	0.9385	0.9780	0.380
0.7631	0.9035	0.9671	0.476

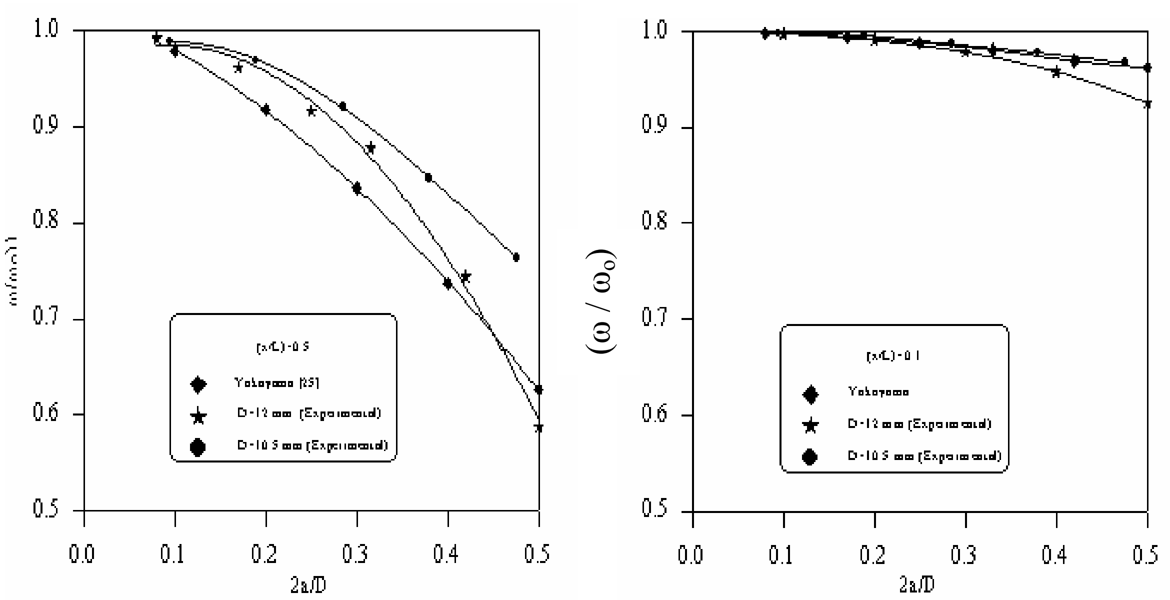
ƧƒǍƥ!ƒ ƥǍǆƶ! ǂǒĿǴĿǕƒ ǂǒƶǒǂƱ!ƒ ƘƒƥƥƧƙ!ƒ ƔĿǉ! ǂǒǆƶ!ƒ ƝƑǴǉ!ƒ (2) ýǍƥƞ
ǅǆ (10.5) ƧƱpǍ ǅǆ (600) ýǍƱل

(x/L) ܵT!ƒ ۄƿǍǆ ǂلĿ			ܵǆƵ ǂلĿ ܵT!ƒ (2a/D)
(x/L)=0.5	(x/L)=0.3	(x/L)=0.1	
(ω/ωₒ) ǑǆƶƵ!ƒ ǑĿǴĿǕƒ ǑƶǒǂƱ!ƒ ƥƥƧƙ!ƒ ǂلĿ			
0.9923	0.9962	0.9980	0.08
0.9618	0.9847	0.9943	0.17
0.9160	0.9732	0.9885	0.25
0.8778	0.9465	0.9809	0.33
0.7442	0.9198	0.9694	0.42
0.5877	0.8778	0.9618	0.50

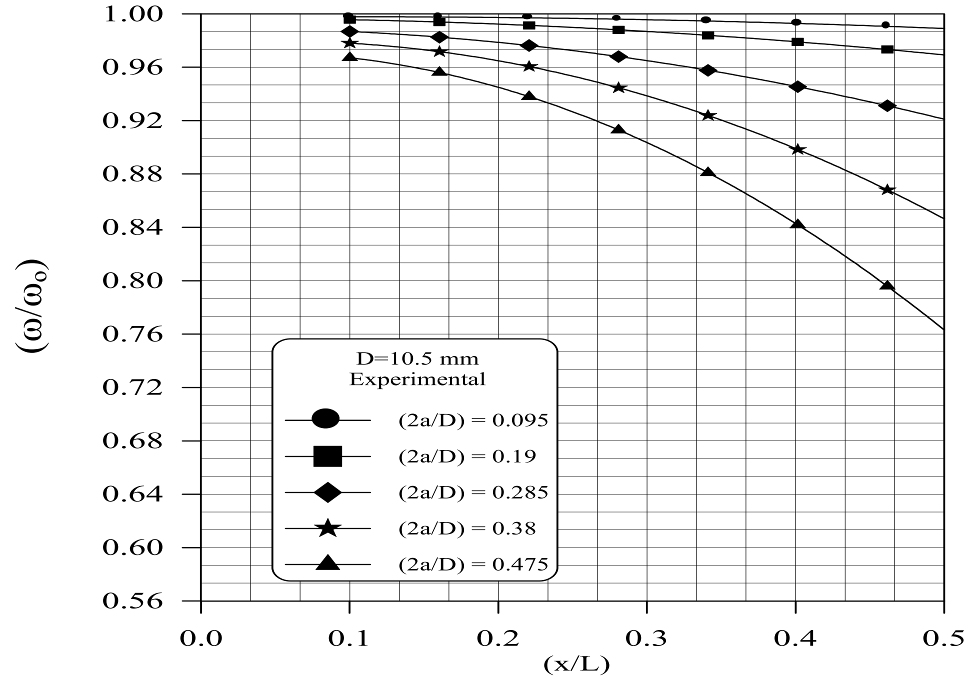
ƧƒǍƥ!ƒ ƥǍǆƶ! ǂǒĿǴĿǕƒ ǂǒƶǒǂƱ!ƒ ƘƒƥƥƧƙ!ƒ ƔĿǉ! ǂǒǆƶ!ƒ ƝƑǴǉ!ƒ (3) ýǍƥƞ
ǅǆ (12) ƧƱpǍ ǅǆ (600) ýǍƱل

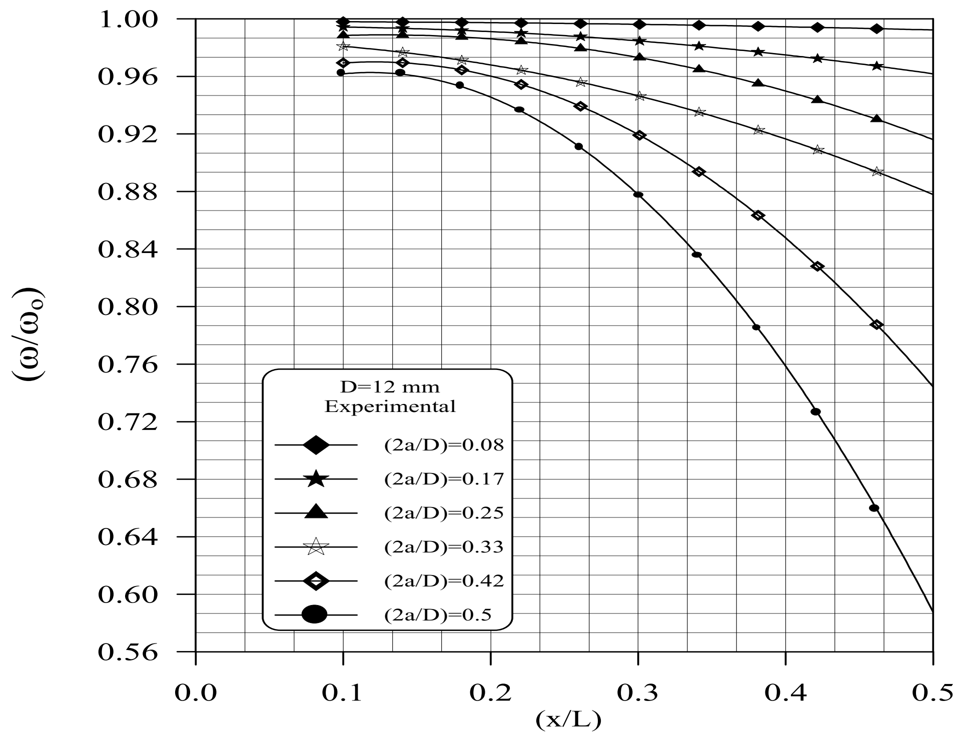


ɬT!f ɬdžŽ ɣdž Ozöh℧!f þþSk!f Sŏʓk Ŧhʅǉ ƠưAŏ (7) ýǂT



ɬT!f ɬdžŽ ɣdž ǑŽöh℧!f þþSk!f Ŧhʅǉ Sŏʓk! Ŧöldžž!f ƝfƓkǉ!f ŦǉSƓldž (8) ýǂT
[12] Ŧ ơƓh!f ƝfƓkǉ ɣdž





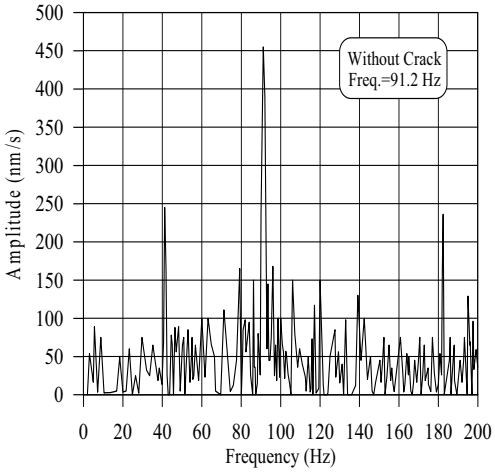
ŧƅɿǉ ĬűƵ ƥƌƶƵǓƋƅ ƽT!ƒ ƴƥĂƌƅ ƌƅǈƙ!ƒ Ơư Ăŏ (9) ýǂT
ŧƽƙƤƌ ƽƌƶƵǕĂ ŎƶƅƱ!ƒ ƥƥƧƙ!ƒ

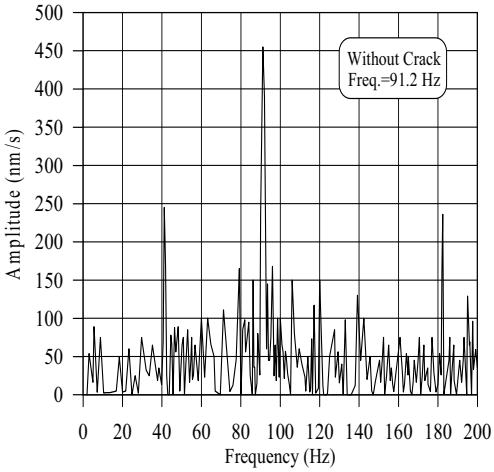
lƐƦƘljǗƐ lƒĭqDŽ üĭǂΘǂ **3.4**

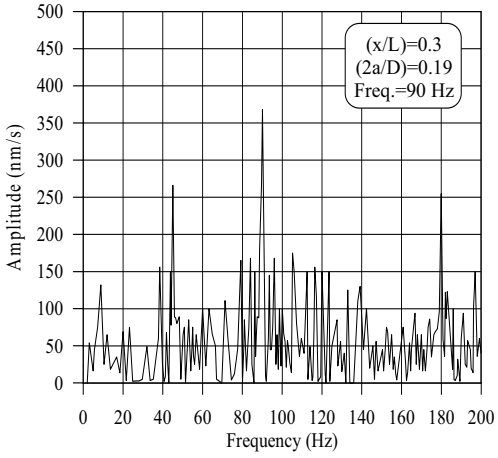
ýùǐơdž ǂƱĠùlĂh ǂùlĠldž!f ǂùȍƨfƨkNjŰf ƘfƧĠùTǗf ǏǐŻ ƥdžkzȍ ƘfƨfƨkNjŰf ƘĠȍƥdž ýȍǐơk LJǫ
. ǂdžƥPkldž!f lƨnjnŰƒ ǂƥƥ ǏǐŻ ƥdžkzk lƧĠTǗf ǂƥƥ LJƐ5 ‖!Ʀ! Ü ýȍnzk!f ΣĠȍldžĂ ƘfƨfƨkNjŰf
lƥùơĂh ℓlĠldž (Amplitude) ƨfƨkNjŰf ǂzl LJȍh ǂpŭz!f Ơư Ăk (12) Ǐ!f (10) LJdž ýĠǂTŰƒ
ƧfĂƥù!f ƥĂùdžz!f ƨfƨkNjŮ ǂȍsȍƱ! ƘĠƱƱPdž!f Ġnjȍ5 ǂLjȍhdž!f (Hz)ƨkƧnj!Ġh ƥƥƧk!fĂ (nm/sec) ǂŻƧl!f
ǂ ùȍơ Ü ƽT!f ƽdžŻ Ƨȍzk yđž ǂƽǐkPdž yƥfĂdž ǂλŭλ Ȍ5 ƽT!f ǂ fƥơǫ ƥzhĂ ýǂp ǂžzȍȟƱ! ƘfƥƥƧk!f ΣĠȍ!
. ƘfƨfƨkNjŰf ýǐơdž! Ư Ƨz!f ǂTĠT Ȍ5 ƥƥƧk!fĂ ǂŻƧlǐ! ǂȍƱP!f ƘĠȍƥdž!f ƧĠȍkPf Dǐk
ýĂùƱĂ Dǐdž (10.5) ƧƱp ĂR ƧfĂƥ ƥĂdžz! ȌzȍȟƱ!f ƥƥƧk!f ΣĠȍ! ȌƽȍƱ!f ƱƱPdž!f ýλdžȍ (10) ý‡T!f
(91.2) ĂNj ƽlTk ǂ fƥơǫ ýǂp ȌzȍȟƱ!f ƥƥƧk!f ǂdžȍp LJD Uơŭȍ Rǫ Ü ƽlTk ǐD ǂ fƥơǫ ƥzhĂ ýǂp DǐdžD (600)
ĠnjȟĠlùơ Dǐùk Ȍùk!f ƨùkƧNj (92.175) ǂȍƧUlj!f ǂdžȍl!! ǂȟƧĠldž ǂdžȍl!f ljRNjĂ ǂȟRȟR ǏǐŻD ýλdžk Ȍk!fĂ ƨkƧNj
ƥƥƧùk!f ǂdžȍp Ƨ Ţlj ŸƧĠlk ĠNjfƥơǫ ǂdžȍp ƘĠȟRȟR ‖!ĠLjnj5 ƘĠȟRȟR!fǂȍl!! ǂȟlLj!Ġh ĠdžD .(2-1) ǂ!fƥĠzdž DǐfƥPklĠh
Ƨzư ŸƧĠlk Ġnjkdžȍp Ȍk!fĂ ǂȍLjĠλ!f ǂȟRȟR!f ĠdžD . ǂȍĂLjĠλ!f ǂȍ15fĂk!f (Subharmonic) Ǐdžlk Ȍk!fĂ ȌlĠlŰƒ
ƘĠȟRùȟR ƥĂùηĂ LJùŻ ẗư5 Ü Ǐ!ĂŰƒ ǂȍ15fĂk!f ýλdžk5 (Harmonic) Ǐdžlk Ȍk!fĂ ȌlĠlŰƒ ƥƥƧk!f ǂdžȍp
ƥƥơk ƘĠȟRȟR!! ǂzl ǏǐŻD LJD Rǫ Ü (Noise) CĠư Ăư LJŻ lƧĠȟŻ ȌNj Ȍk!fĂ ǂƽǐkPdž ƘĠŻĠƽkƧf ƘfR ăƧPD
ƥĂùdžz!! ȎzȍȟƱ!f ƥƥƧk!f ΣĠȍ! ǂȍsȍƱ! ƘĠƱƱPdž!f Ơư Ăȍ ý‡T!f LJD Ġdž‡ Ü ƥĂdžz!f ƨfƨkNjŮ ƥƥƧk!f Ƨfƥldž
. ƽTù!f ƽĠdžŻD LJdž LJȍƽǐkPdž LJȍldžz!Ă ƥĂdžz!f ýĂƱ LJdž (x / L=0.1) yƥĂdž Ȍ5 ƽT!f ǂ fƥơǫ ƥzh ƧfĂƥ!f
ǂù5Ƨzdž Ư Ƨʒ! ǂơh!f Ȍ5 NdžfƥPklƒ Dǐk ǐR!f ƽT!! ƽĠdžŻD ǂldžP ýŢD LJdž LJȍƥŻĠȟkdž LJȍldžZ ƧĠȍkPf ƥzhĂ
ƥƥƧùk!f ǂùdžȍp Ȏù5 Ư ĠƽPljf ‖ĠLjNj LJD UơĂ! Ü ƥȍη ý‡ThĂ ƘfƥƥƧk!f Džȍp Ȍ5 ýŢĠơ!f Ư ĠƽPljŰf Ƨfƥldž
ĠùdžD . (ýdžĠơdž!f) ƥĂdžz!f Ƙȟȟλk yƥĂdž LJdž ǂȟȍƧp ƽT!f yƥĂdž! ǂȟlLj!f ljRNj LJŰ Ƨ ȍƽƱ ý‡Tȟ LJ‡!Ă ȎzȍȟƱ!f
LJùdž (x / L=0.3) yùƥĂdž Ȍ5 ƽT ǂ fƥơǫ ƥzh ƧfĂƥ!f ƥĂdžzǐ! ǂȍsȍƱ!f ƘĠƱƱPdž!f Ơư Ăȍ5 (11) ý‡T!f
ǂȍzȍȟƱ!f ƘfƥƥƧk!f Džȍp Ȍ5 ƱơưfĂ ƱưĠƽPljf UơŭLj (10) ý‡T!f yđž ý‡T!f fRNj ǂljƧĠldž ƥljŻĂ ƥĂdžz!f ýĂƱ
LJD Uùơŭlj (12) ý‡Tù!f Ȍ5 ƧUlj!f LJĠzdžǫ ƥljŻĂ . LJȍldžz!f Σƽlj!Ă ƽT!f ƽdžŻ lƥĠȍƨ! Ƨȍȟǂlk!f ǂηȍklj
lƥĠȍƨ!Ġh ƽT!! yƥĂdž!f fRNj ƧλĂk! ǂηȍklj Ƨȍȟǂ ý‡ThĂ (ƧĠlȍ!f Ăơlj Ksơƨ) Ƙư ƽPljf ƥp ȎzȍȟƱ!f ƥƥƧk!f ǂdžȍp
Ġùnjȍ5 LJĂù‡ȍ ƥĂdžz!f Ƙȟȟλk yƥfĂdž LJdž ƘĠ!lTǐ! lƥȍzh!f yƥfĂdž!f LJD LJȍȟk NȍǐŻĂ Ü ƽT!f ƽdžŻ Ȍ5 ǂǐŢĠơ!f
. ƽT!f yƥĂdžh dȟljǐ! ƧTdž ŸĂǐlŰƒ fRNj LJƐ5 Ȍ!Ġk!ĠȟĂ ƘfƥƥƧk!f Ȍ5 Ȍ!ĠŻ Ư ĠƽPljŰf

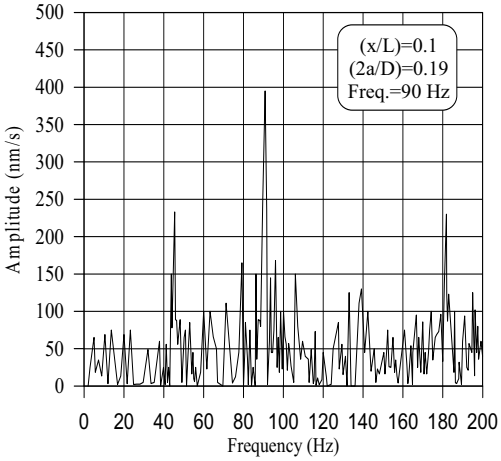
lƐǫFNJWǗƐ Ʀǐ!ƥǂ üDŽFyDŽ ƥǐkÐǂ **4.4**

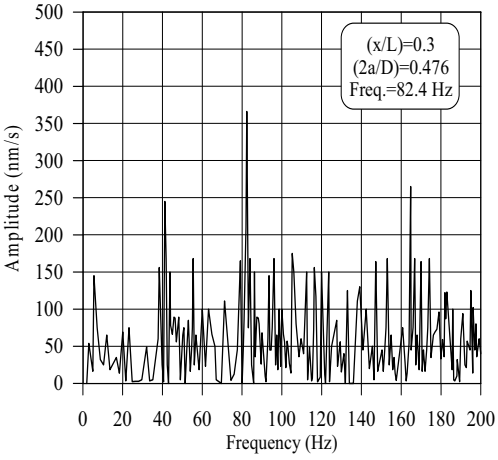
ƽTù!f ǂ!Ȍljdžh ƘfƥĠnjηŰf ƨȍ‡Ƨk ýdžĠzdž ŸĠlơ Ư Ƨʒ! ǂŢĠP!f ǂȍ ưĠȍƧ!f ƘĠpŭz!f DǐfƥPklƒ ƥzh
ƽTù!f ƽdžŻ lƥĠȍƨ Ƨȍλdȟ ǂȍsȍ‡ Ơư Ăk Ȍk!fĂ (14) Ă (13) ýĠ‡TŰƒ Dǐl2 Dǐk Ü ȎhĂlĠơ ŊdžĠljƧh ȌȌĠlĂhĂ
CĠùljơljŰf) ýȍdžơk!f ƘŰĠơ LJdž LJȍksǐkPdž LJȍk!Ġơ!Ă ƽT!f ‖džl ƘĂhλ ƥljŻ ƥĠnjηŰf ƨȍ‡Ƨk ýdžĠzdž Ƨȍzk ǏǐŻ
. (CfĂk!ŰfĂ
(2a/D=0.2) ĠdžƥljŻ ǐD ǂƒȌfĂ ƽĠdžŻD ŸlLj ƥljŻ ƨ‡Ƨkk Kfƥ Ġnjη Ű ƨȍ‡Ƨk! Dǐȍp ǏǐŻD LJD Uơŭlj
ýŭùƤ LJdž UơĂ!Ă . ƽT!f ƽdžŻ ǂȟlLj ƥĠȍƥƨf yđž ƥȍηȍƧƥk LJĠŢlLj!Ġh ƥĠnjηŰf ƨȍ‡Ƨk ƘŭdžĠzdž DƥhȏĠ ĠNjƥzhĂ
ĠdžƥùljŻ ǂdžȍp Ƨh‡D Ǐ!ǫ ýŢk Kfƥ Ġnjη Ű ƨȍ‡Ƨk ýdžĠzdž LJD ýĠ‡TŰƒ Ȍ5 Ơư fĂ ĂNj Ġdž‡Ă ƘĠĠljơljdž!f ƦzhĠkdž
. ƦƒȌfĂ (2t/D) ƽT!f ‖džl ǂȟlLj LJĂ‡k

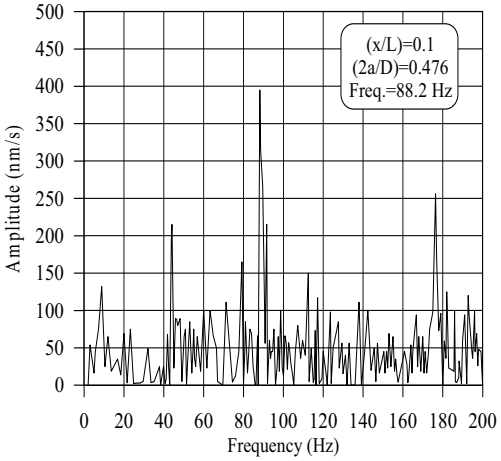






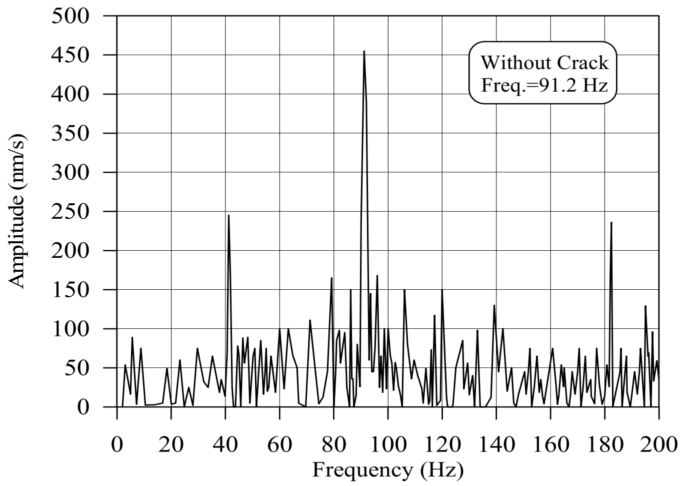


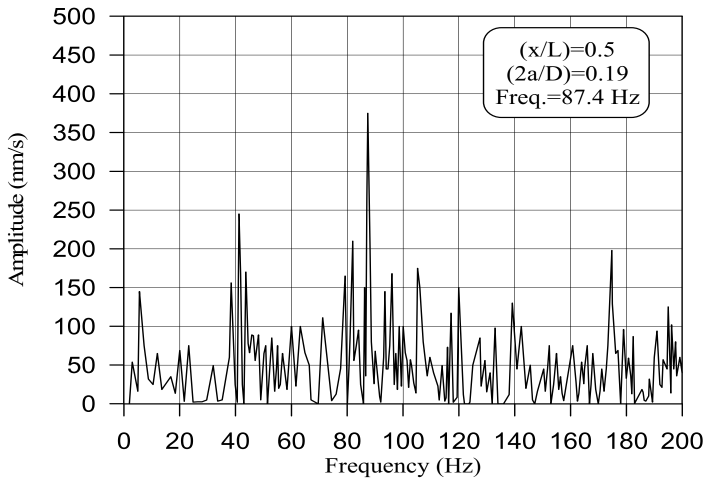


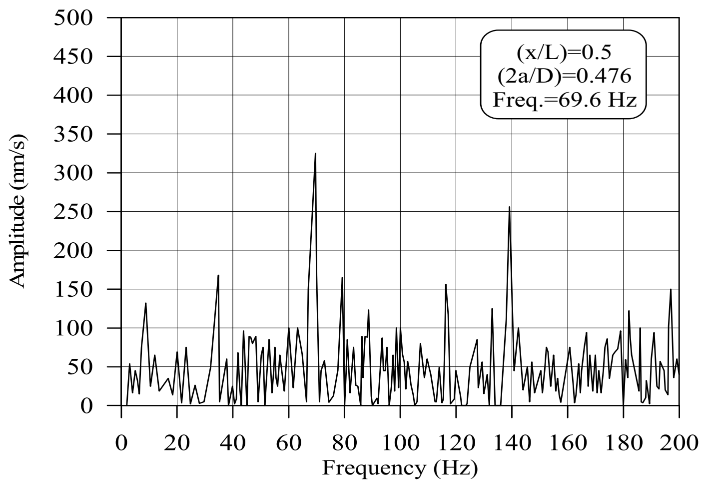


þÄđžż! Ŏ₅ŏƉ!ƒ ƉƉƤđž!ƒ Ơư Ăŏ (11) ý‡T ƧƒÄþ!ƒ

þÄđžż! Ŏ₅ŏƉ!ƒ ƉƉƤđž!ƒ Ơư Ăŏ (10) ý‡T ƧƒÄþ!ƒ







ƧƒĂƥ!ƒ ƥĂǆƶǁ! ǑƽǒƱ!ƒ ƱƱƤǆ!ƒ ƠưĂǒ (12) ýǂƬ

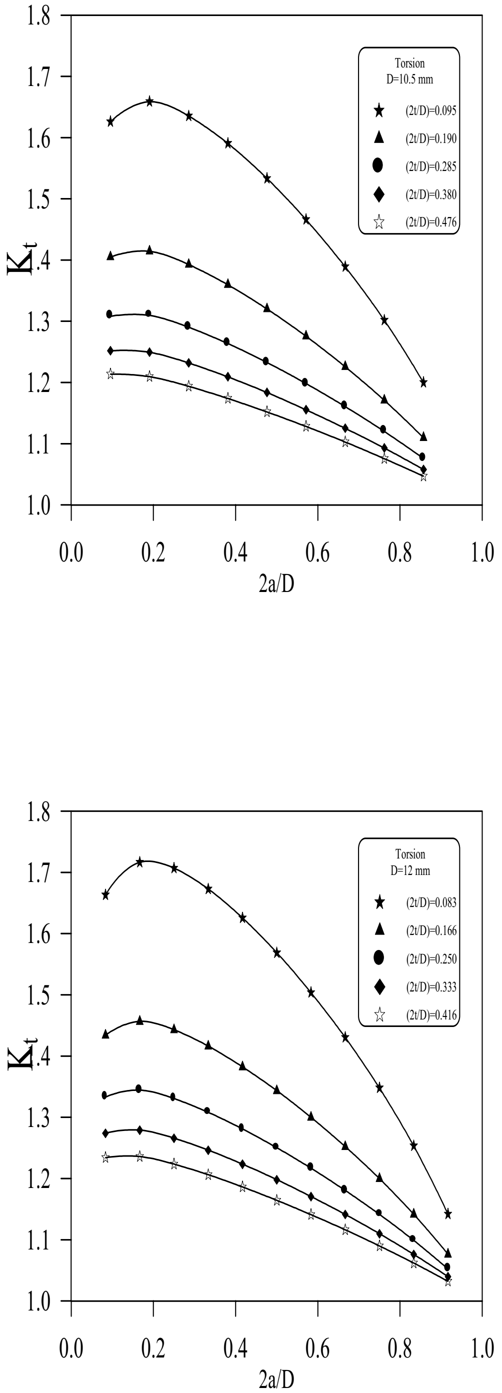
ℓ'ƮĂƮùƤĂ ЌfþĠnjηŮf ƨŏ‡Ƨk ýdžĠzdž LJĠƮlj Ŏ5 Ơư fĂ!f ƧλŪf ƚT!f ‖džl lþĠŏƨ! LJĠ‡ LJŏơ Ŏ5 Ŏù5 ЌĠŏljơljdž!f Dž l2 ýŭP LJdž NkUơŭdž Dźk Ġdž fRNjĂ Ü ýŏdžơk!f ЌŮĠơ LJdž LJök!Ġơ!Ă ƚT!f CĂTlj ŏfþh Ŏ5 Ћwlùlj þĠŏþƨf ydž (Kt) ЌfþĠnjηŮf ƨŏ‡Ƨk ýdžĠzdž Dŏöp Ŏ5 LJĠƮlj!f Ơư Ăŏ Ŏk!fĂ (16) Ă (15) ýĠ‡TŪf Ћ!Ơơ Ŏ5 ƚT!f ‖džl Ћwlj ydž ЌfþĠnjηŮf ƨŏ‡Ƨk ýdžĠzdž ЋpŭŽ Ơư Ăŏ (15) ýùù‡T!f LJD Rg . ƚT!f ‖džl ýùdžĠzdž ŁùpŭŽ Oŏù ư Ăk! (17) ý‡T!f Ŏ5 ЌĠŏljơljdž!f Ќdžl2 LJŏơ Ŏ5 Ü ŁƚŵkPdž ƚĠdžZD Ɣljl!Ă CĠljơljŮf ŁùUơŭdž LJùdž ă2ùljĂ . ŁƚŵkPdž ƚĠdžZD Ɣljl!Ă CƒĂk!Ŭf Ћ!Ơơ Ŏ5 ƚT!f ‖džl Ћwlj ydž ЌfþĠnjηŮf ƨŏ‡Ƨk Ћ!Ơơ Ŏ5 þĠnjηÚf ƨŏ‡Ƨk ЌŭdžĠzdž Dŏöp LJD ýĠ‡TŪf ЌĠŏljơljdž!f Ќdžl2 þl5 þŏ‡ak!f lþĠŏƨ Ư2ƹ!Ă. (17) ý‡T!f ýŭP LJdž ƚ2ƨ!f fRNj ŁUơŭdž LJ‡džöĂ Ü CƒĂk!Ŭf Ġdžnjkùl fƧþ Ŏ5 fþdžkZf LJŏRŵ!f [11] (Nisitani and Noda) LJŏλơĥw!f ýwp LJdž Dźþldž!fĂ (18) ý‡T!f Ŏ5 . (V) 2 2ơ ý‡T ŴZ ƚT DźfþPkl f ŴZ

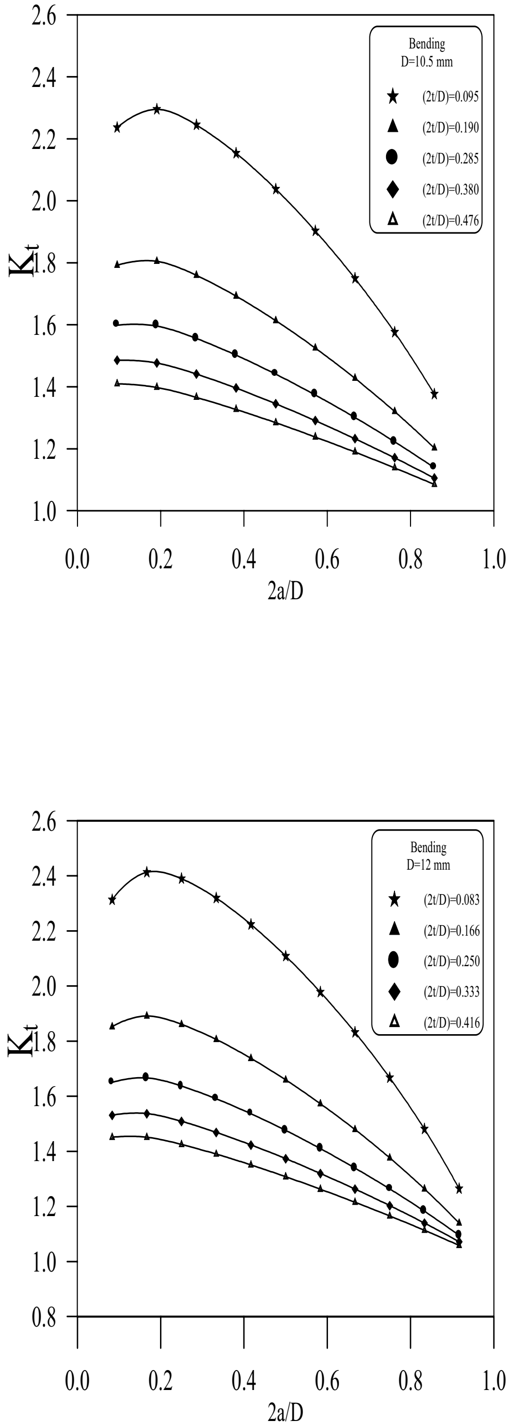
l ƒWFŁŵŁƨÚɛ .5

Ŏù5 ЌfƧùŏƹk ŁĂþơ Ŵ!ƹ ŵ þdŏ 2fĂþ!f þĂdžz!f þĠzhDĂ ý‡T Ŏ5 2ŏƹk ŵD Ł Ăþơ þljZ ÖzöhƟ!f LJdž : ŰĂD Dŏùp Ŏù5 Ư Ġù ƨPljf Ɣwlùŏ 2fĂþ!f þĂdžz!f Ŏ5 ƚT!f Ł Ăþơ5 . þĂdžz! Łŏƨfƨ kNjŮf f ƒĠƮP!f ƚdžZĂ yþĂdž LJZ 2T‡!fĂ đhljk!f LJĠ‡džÚĠh5 fR! Ü ĥŏ2UljĂ ĥöŵdžZ NLjdž ƚlơk!f Dźk Ġdž fRNjĂ ЌfþþƧk!f . lƧfĂþ!f lþdžZŪf Ŏ5 ƚT!f

ŁŏzöhƟ!f ЌfþþƧk!f Dŏöp Ư ĠƨPljf Ŏ5 lþĠŏƨ UơĂ! þĂdžz!f ŴZ ŁƚŵkPdž yþfĂdž Ŏ5 ƚĂlT Ł Ăþơ þljZ : ĥöljĠλ Ư ĠùƨPljŮf LJD Ł ŏơ Ü þĂdžz!f 2 Ƭljdž ljĠnƙĥw ýdžĠơdž!f ŴZ þĂdžz!f ЌöhwÅk yþĂdž LJZ Ġljþzƙhf Ġdžŵ‡ yþĂdž þljZ (ω/ωo=0.9671) ЌljĠ‡ (2a/D=0.5) ƚT!f ƚdžZ Ћwlj ŴZŪĂ ЌfþþƧk!f Ћwlj Ŏ5 ƚTù!f ƚùdžZ Ћwlùlj ŴùŵZŪ ЌfþþƧùk!f Ћwlùlj Ŏ5 Ư ĠƨPljŮf LJD Ġdž‡ Ü .(x/L=0.1) ƚT!f fRùNjĂ .(x/L=0.5) ƚTù!f yùpĂdž þùljZ (ω/ωo=0.5877) Ŵ!f ýƮĂ (2a/D=0.5)þĂdžzŵ! . [Yokoyama and Chen] LJGλơĥw!f Nŏ!ƹ ýƮĂk Ġdž! ƚhĠƟŏ ШĠkljkl Ůf

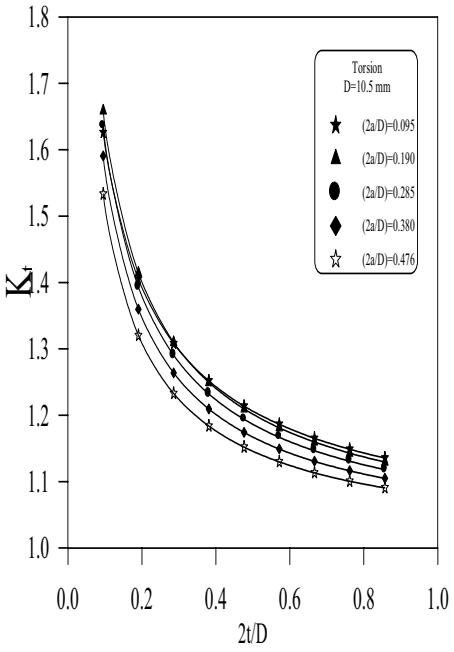
ƚùdžZ Ћwlùlj lþĠŏƨ ydž þfþƨk (Kt) ЌfþĠnjηŮf ƨŏ‡Ƨk ýdžĠZ Ћdžöp LJf ŁözöhƟ Ћ!Ơơ‡Ă Ơư fĂ!f LJdž : ĥλ!Gλ þĂùdžz!f 2Ɵp Ŵ!f ƚT!f ‖džl Ћwlj lþĠŏƨ ydž NkdžöpýlkĂ Ü ƚT!f ‖džl ЌĂhλhwĂ þljZ (2a/D) ƚT!f [Nisitani LJGλơĥw!f NFĠkLj ydž ƚhĠƟkŏĂ ĥŏ2Ulj Ġnjljdž ƚlơk!f Dźk Ġdž fRNjĂ . ƚdžz!f ЌĂhλhwĂ (2t/D) . and Noda]

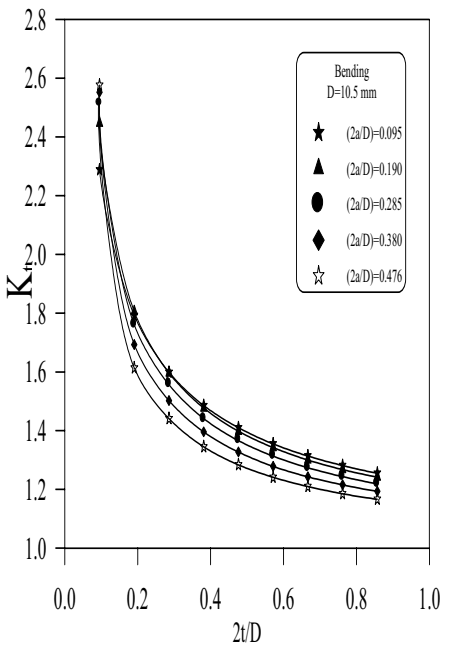


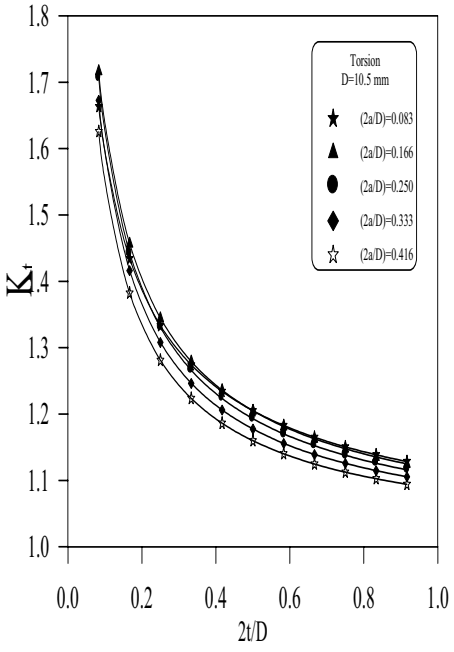


þǴnjŋǗƒ ƨǒǂƧk ýdžǴƶdž Ƨǒʒk Ơư Ăǒ (14) ýǂT
ƧƒĂþ!ƒ þĂdžƶ l! ǇƒĂk!Ǘƒ Ŧ!Ǵơ Ǒ5 ƽT!ƒ ƽdžƵ ýdž

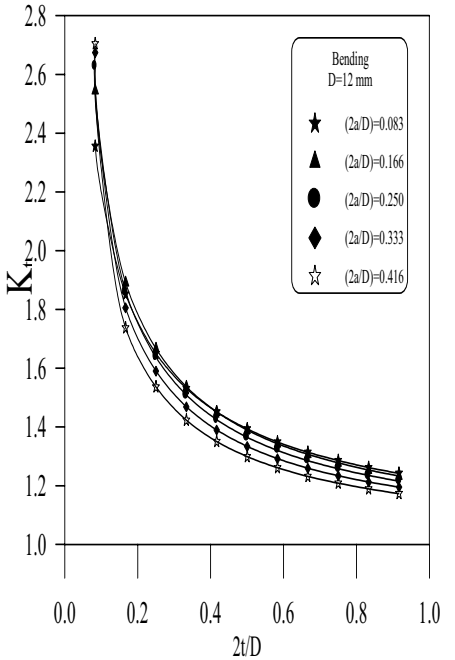
ýdž þǴnjŋǗƒ ƨǒǂƧk ýdžǴƶdž Ƨǒʒk Ơư Ăǒ (13) ýǂT
ƧƒĂþ!ƒ þĂdžƶ l! ǇǴǉơǉǗƒ Ŧ!Ǵơ Ǒ5 ƽT!ƒ ƽdžƵ



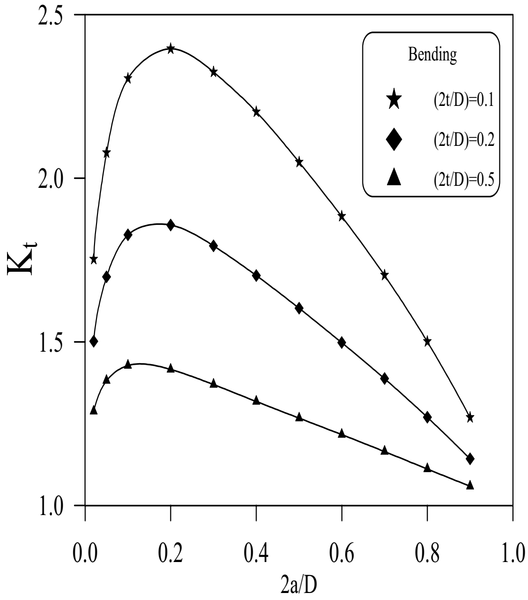


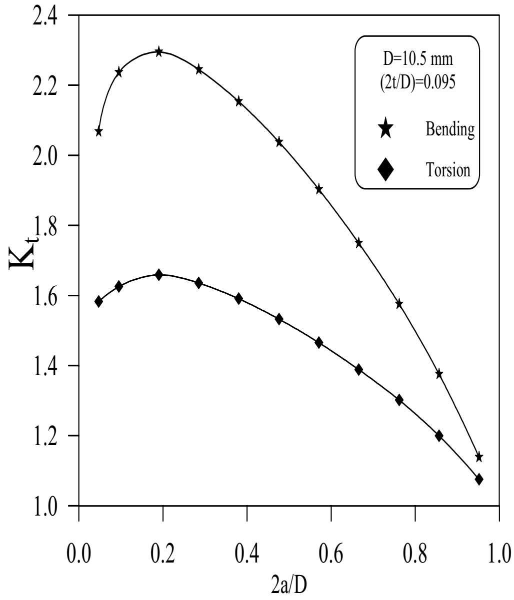


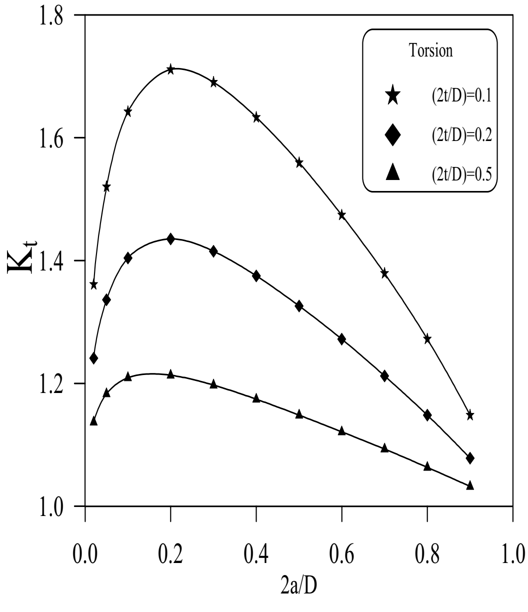
yűž þĜnjŋŰƒ ƨŏ‡Ƨk ýđžĜƶđž ƧŏƷk Ơư Ăŏ (16) ý‡T
ƧƒĂþ!ƒ þĂđžƶ!! CĴĂk!Ůƒ Ⱡ!Ĝơ Ŏ5 ƨT!ƒ ‖ đž]



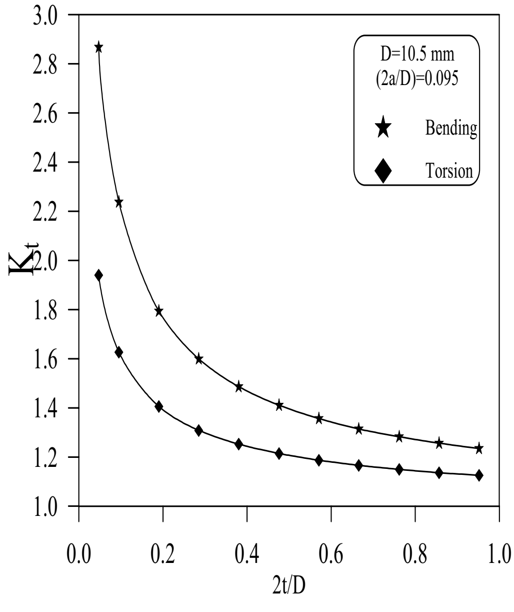
yűž þĜnjŋŰƒ ƨŏ‡Ƨk ýđžĜƶđž ƧŏƷk Ơư Ăŏ (15) ý‡T
ƧƒĂþ!ƒ þĂđžƶ!! CĜljơŋŮƒ Ⱡ!Ĝơ Ŏ5 ƨT!ƒ ‖ đž]







ýdžƓƶdž Ƨǒƺƙ! Ŧǒlǒlơƙ!ƒ ƝƒƓƙǉ!ƒ (18) ýǂT
[11] ƚơƓhl! ƫT!ƒ ƫdžƵ ƴdž þƓǌƞǗƒ ƨǒǂƧƙ
ýǒdžơƙ!ƒ ǑƙƓơ Ǒ5



ýdžƓƶdž Ǒ5 Ƨǒƺƙ!ƒ ŦǉƧƓldž ƠưĂǒ (17) ýǂT
Ǒƙ!Ɠơ! ƫT!ƒ ǁdžƪĂ ƫdžƵ ƴdž þƓǌƞǗƒ ƨǒǂƧƙ
ýǒdžơƙ!ƒ

References

1. Young , S.L. and Myung – Jee , C. " ***A study on crack detection using eigenfrequency test data*** " J. of computer and structures , Vol. 77, PP: 327-342, 2000 .
2. Kam, T. Y. and Lee, T. Y. "***Crack Size Identification Using an Expand Mode Method***" J. of International Journal of Solids & Structures. Vol. 31(7): PP 925-940, 1994.
3. Bahera, A. K. and Parhi, D. R. "***Vibrational Analysis of Cracked Rotor in Viscous Medium***" J. of Vibration & Control, Vol. 6, PP 331-348, 2000.
4. Davies, W. G. R. and Mayes, I. W. "***The Vibrational Behavior of Multi-Shaft, Multi-Bearing System in the Presence of a Propagating Transverse Crack***" J. of Transaction of the ASME, Vol. 106, PP 146-153, 1984.
5. Adams, R. D. et al "***A Vibration Technique for Non-Destructively Assessing the Integrity of Structures***" J. of Mech. Engg. Science Vol. 20, No. 2, PP 93-100, 1978.
6. Dimarogonas, A. and Massouros, G. "***Torsional Vibration of a Shaft with Circumferential Crack***" Journal of Engg. Mech. Fracture Vol. 15, No. (3-4), PP 439-444, 1981.
7. Rajab, M. D. and Al-Sabeeh, A. "***Vibration Characteristics of Cracked Shafts***" J. of Sound & Vibration, Vol. 3, No. 147, PP 465-473, 1990.
8. Papadopouls, C. A. "***Torsional Vibration of Rotors with Transverse Surface Cracks***" J .of Computers and Structures, Vol. 51(6): PP 713-718, 1994.
9. Thomson, W. T. "***Theory of Vibration with Application***" 2nd edition, Premtice-Hall.Inc. Englewood cliffs NJ 07632.U.S.A, 1981.
10. Hearn, E. J. " ***Mechanics of Materials*** " 2nd edition, Pergaman International Library.U.K, 1989.
11. Nisitani, H. and Noda, N. "***Stress Concentration of a Cylindrical Bar with a V- Shaped Circumferential Groove under Torsion, Tension, or Bending***" J. of Engg. Fractures Mech. Vol. 20, No. 5/6, PP 743-766, 1984.
12. Yokoyama , T. and Chen , M.C. " ***Vibration analysis of edge-cracked beams using aline – spring model*** " J. of Engineering fracture machanics , Vol. 59 , No.3,PP: 403-409 , 1998 .