Research article **Available online www.ijsrr.org** **ISSN: 2279–0543**

International Journal of Scientific Research and Reviews

A Novel Method of Flaw Detection in a Structure Triggered by Pendulum Impact using Acoustic Resonance Frequency Measurement

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ABSTRACT

It is well-known fact that, the mass-production process is adapted for producing identical components on large scale. Non-destructive testing (NDT) method based on acoustic resonance facilitates to test these components in-line. It follows the principle of acoustic resonance. The component under test (CUT) is triggered by an impact or a shock wave is induced in it, and the acoustic response is acquired and analysed. The components having identical physical properties possess unique signature of the acoustic response. These CUTs can be sorted on the basis of their acoustic resonant frequency (ARF). The tested CUTs are generally classified in three classes namely PASS, FAIL and REWORK. In case of CUTs like small metal-castings, only PASS and FAIL classification is adapted which is also known as Go (pass) and NoGo (fail) gauging. The consistency in acoustic excitation of CUT plays an important role. In this paper we have proposed, developed and tested acoustic excitation of CUT using pendulum mechanism. The consistency of the pendulum-impact is tested by using loud-speaker. The acoustic resonant frequencies of a set of components are tested by using power spectrum, and the frequency shift is detected by introducing a fault in a test-component. The results are useful for detecting faulty component which helps to decide whether, the CUT is to be processed further. The decision saves labour-cost and time.

KEY WARDS: Acoustic Resonant Frequency (ARF), Non-destructive testing (NDT), Go-NoGo gauging, pendulum impact device, Flaw detection

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INTRODUCTION

Since last few decades the production rate of manufacturing industries raised considerably because of demand. The open policies of different countries have increased import and export business of different products. This has generated extreme need for industries which work in metals such as automotive, pump, pipe, valve manufacturing industries and foundries. The products of the above said industries involve sub-assemblies and ancillaries to make the final product.

The manufacturers are required to follow some process standards for grading their product. Very commonly used technique is to sample some "n" number of components randomly from a produced batch. The data of measured values of these samples are processed according to the recommended procedure stated in the standard and then the batch is declared with that resultant value. This technique can have probability of passing a faulty component. The standards like DIN ISO 9000 require both demonstrated and documented product quality to satisfy the subjective and destructive testing of the sampled specimen/component. This leads the manufacturer to follow cumbersome and costly technologies and lengthy procedures[1]

Sometimes this forces the manufacturer to out-source some of the components and sub-assemblies from vendors. The vendors are supposed to process the component right from start to semi-finish/finish. e.g. a small casting is to be tested for its homogeneity, porosity, hardness before further process. Then non-destructive technique (NDT) can be employed for quality assurance without affecting the chemical and physical properties. For NDT methods like magnetic particle test, Ultrasonic test, eddy current test, dye penetration test and Visual test, trained operator is required to evaluate/judge and subjectively interpret the results. The acoustic resonance testing (ART) is best suited method. Upon excitation of the component under test (CUT), the vibrational characteristics of CUT are investigated to detect the defects. It is considered as a whole-part test. Even though defect is anywhere in the component, it changes the captured signal's signature as opposed to scanning methodologies. This technique is mainly used for PASS(Go)/FAIL (NoGo) gauging type applications. The acoustic signal means sound related signal in the range of about 20Hz to 16kHz. ART is basically comparison process where the oscillatory signature of a target (CUT) is compared with the reference or master component. The signature of the reference component is derived by learning-base which is nothing but signature of the component. ART basically requires an excitation source. The source is nothing but a device or a mechanism which releases potential energy to the CUT in form of a mechanical shock wave. In response to this energy the CUT produces decaying acoustic vibrations. The vibrations are nothing but a bunch of frequencies which are dependent on the physical and structural properties of the component. This source of information can be used for detecting dimensional defects and material-homogeneity of the CUT. The NDT consists of several methods which can be used for quality checks. ART is an NDT which overcomes many drawbacks of other NDTs. It is basically a whole part test[2]

In view of above said different NDT methods and their limitations, we have proposed, analysed and tested a pendulum mechanism based exciter and it is used for ART for a set of CUTs. Brief outline of the paper is as follows: Section 2 covers a brief literature review of different NDT applications. Section 3 focuses on the basics of induced acoustic emission and analysis of pendulum test set-up. Section 4 deals with experimentation and result analysis which also highlights the applicability. The paper concludes with section 5.

LITERATURE REWIEW

The Pencil lead break (PLB) method, first proposed by Nelson N. Hsu, is also known as the Hsu-Nielsen (PLB) method. It is used for checking sensitivity of the AE sensors and not used for excitation of structure for investigation.

PLB is a well-adapted excitation source for generating an acoustic emission (AE). It is based on a very simple principle that, a carefully broken pencil lead against a rigid block or a body, which then releases an impulsive stress and consequently, an elastic wave. It is reliable and reproducible wideband signal source which is useful for analysing wave propagation in a structure under investigation. It is also used for detecting the frequency response of the AE sensors. The sensors generally used are microphones, shielded piezoelectric elements mounted in a metal housing. It is mainly used for non-destructive testing NDT applications[3]

Visual inspection is one of the way to check CUT. It requires sufficiently illuminated and clean surface of the CUT. The resolution and sensitivity of the inspection can be enhanced by adapting techniques like magnetic particle, liquid penetrants. Magnetic particle test can be used for ferrous components. The inspection method can be adapted to detect flaws which lie near the surface[4].

Optical methods can be used to detect surface flaws like material changes and phase formations. Use of fibre braggs grating (FBG) sensors helps in health monitoring of structures. High cost of the FBGs limits the deployment of the technique.[5] Eddy current testing method is one of the widely used methods for inspecting surface and near surface cracks, corrosion and other structural defects.[6]

A transceiver module can be excited with 1MHz to 50MHz frequency source to generate high energy acoustic waves to identify and detect flaw existence and flaw dimensions. It uses time of flight technique. It is a well-established technique but needs special arrangement of water bath for holding CUT. The CUT needs to be scanned in multiple dimensions hence it is time consuming procedure[7].

Coin-tap test is a well-known test which induces vibrations in the CUT and the change in sound between defected and defect-free region indicates the presence of damage. The method cannot pin-point the defect in the structure but helps to take decision like Go-NoGo. The sensitivity of measurement decreases with depth of the defect[8].

Mohanty KK et al. showed that pressure based microphones can be used for sensing acoustic signals. Their analysis showed that acoustic signals provide better information than vibration signals. They have concluded that, the vibro-acoustic signals have significant potential in detecting faults in the bearing at various shaft speeds[9].

The acoustic emissions are transient elastic waves generated from rapid release of strain energy because of deformation of the surface of the material under test. AE is the same phenomenon as of stress wave generation resulting from a local displacement of the material[10].

The AE technology has been successfully used for monitoring the defects in the Reinforced cement concrete structures like bridges and tanks. The practical applications of AE have become difficult in factory because of ambient noise[11]. The impact creates stronger AE signals than friction but fracture creates more AE signals than impact but the amplitude is weak. The results are guidelines for determining the fault location and machine fault diagnosis[12]. Chassaing JC et al. have adapted an approach where the combined time and frequency domain considered for acoustic resonance prediction. They documented two cases namely 1-degree of freedom (1-DOF) mechanical system and acoustic resonance in a closed-end tube. The systems are excited with range of frequencies (50Hz to 900Hz). The frequency is swept up to 3 kHz by using a speaker as an excitation element. They have found that it is possible to predict the correct resonance frequencies and corresponding pressure mode shapes[13].

Loutas TH et al. has followed a novel approach for monitoring rotating machinery with the help of acoustic emission technique. It is necessary to know the background of the system before start of the test-run. They have recorded the acoustic emission generated by rotating the gear without meshing which is treated as noise. The fast Fourier transform (FFT) of the recorded sample was analysed. Frequencies of 20Hz to 200 kHz seem to dominate with some high frequency components in the region of 300kHz to 550kHz. The results give valuable information about the condition of the machine[14].

Deng X et al. worked on a bottleneck problem of sorting eggs on the basis of Go-NoGo basis. Detection of eggshell cracks is a challenging process when the large quantities of eggs are to be sorted. Their work is focused on eggshell crack detection using vibration based response analysis. It has been shown that vibration based methods have batter accuracies than machine vision methods, especially for hairline and invisible cracks in eggs[15].

Induced Acoustic Emission Testing

Basic principle

It can be seen from above discussion that, the acoustic emission testing (AET) has wide area of application. The AET needs an excitation source to induce vibrations. It is a mechanism which rapidly releases mechanical energy to Component Under Test (CUT). When the CUT is exited with an impact source, it vibrates at resonant frequencies related to modes of CUT. The vibrations are picked up by an acoustic pick-up device and stored in computer which is a time domain data. This data is then transformed into the frequency domain data as a spectrum of the signal. Spectrum represents the resonant modes of the CUT related to the acoustic resonance frequency. The spectrum is analysed and stored as a signature of standard master component. The same process is followed for detecting the spectrum of CUT. The clarity in distinction between the spectrum-signatures of CUT and the standard is identified to detect the defective CUT. Figure 1 shows the block diagram of the proposed system.

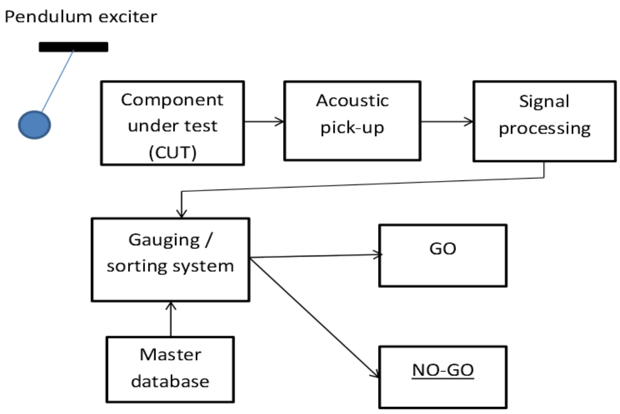

Figure 1: Block diagram of the system.

This methodology is used for segregating the CUT on the basis of Go-NoGo decision. The comparison on the basis of peak-amplitude and the position of it in the signature-spectrum of both standard component and CUT helps to detect the defective CUT. This method is sensitive to impact variation and needs a highly standardised impact device mechanism. The force of excitation needs to be measured by using an on-board force sensor or an accelerometer which is expensive and needs an extra channel for data acquisition[24].

Experimental test set-up

In this paper we have proposed and developed pendulum mechanism as an impacting device. The mechanism is fabricated in such a way that the bob hits CUT only once and multiple hits are inhibited. The consistency of impacting force is tested practically. Figure 2 shows the force resolution diagram of pendulum.

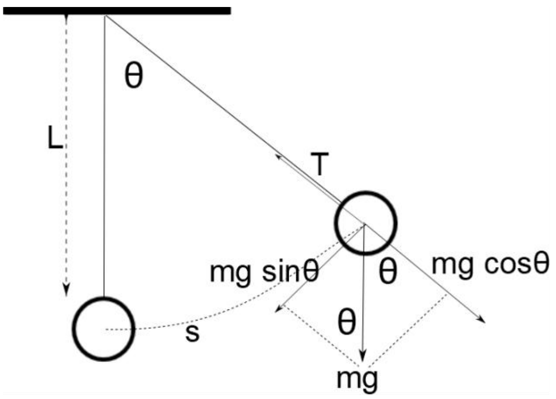

Figure 2. Force resolution diagram.

$F = -kx$ (1)

$F \alpha \theta$

According to the free body diagram the restoring force F can be calculated as

$$F = mg.sin\theta \quad (2)$$

If θ is smaller then 5^0 then θ(radian) = $sin\theta$

ex. 5^0 (radian) =0.087 = 0.087 θ

We know that the angular displacement s can be calculated as $\theta = s/l$

therefore $sin\theta = s/l$ (3)

$$F = mg.\frac{s}{l}$$

With approximation θ(radian) = $sin\theta$

Therefore $F = -\left(\frac{mg}{l}\right)s$ (4)

$$F = -ks$$

where $\left(\frac{mg}{l}\right) = k$

Hence it can be seen the Hook's law is obeyed

When the pendulum is at height 'h', then it has potential energy (P.E.)

P.E. = mgh (5)

When it is released then the potential energy is converted in to kinetic energy (K.E.)

$$\text{K.E.} = \frac{1}{2}mv^2 \qquad (6)$$

The maximum velocity attended by pendulum can be calculated by equating equations (5)and (6)

$$\frac{1}{2}mv^2 = mgh$$

$$v^2 = 2gh$$

$$v = \sqrt{2gh} \qquad (7)$$

Figure 3 shows the resolved height component at the initial position of pendulum.

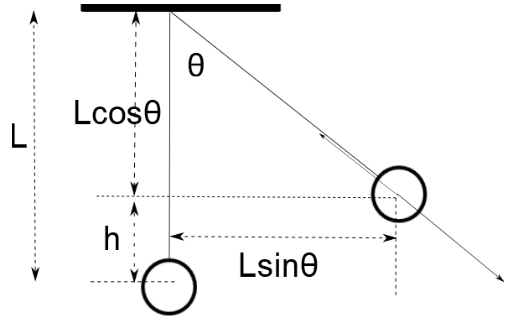

Figure 3. Height components

$$\text{h} = L - Lcos\theta$$

$$\text{h} = L(1 - cos\theta) \qquad (8)$$

Substituting equ. (7) in to equ.(8) we get

$$v = \sqrt{2gL(1 - cos\theta)} \qquad (9)$$

The total mechanical energy (M.E.) is calculated as

$$\text{M.E.} = \text{K.E.} + \text{P.E.} \qquad (10)$$

At lower position the P.E.=0 hence plugging equ. (9)in to (10) we get

$$\text{M.E.} = \frac{1}{2}\, m\, v^2 + 0$$

$$= \frac{1}{2}m2gL(1 - cos\theta)$$

$$\text{M.E.} = mgL(1 - cos\theta) \text{ joules} \qquad (11)$$

It can be seen that, if the movement of pendulum is stopped after hitting pendulum-bob to the CUT then the M.E. applied to CUT is according to equ.(11). But this case will be existent if the physical properties of the CUT (elasticity, stiffness etc.) absorb the whole M.E. of the pendulum. This is impossible in real case.

It is the fact that the pendulum-bob ($m1$) and the CUT ($m2$) are two masses and impacting on each other. The interaction between these two masses can be understood by referring to conservation of momentum

$$m1u1 + m2u2 = m1v1 + m2v2 \qquad (12)$$

Where $u1$ = initial velocity of object with $m1$ before impact

$u2$ = initial velocity of object with $m1$ after impact

$v1$ = initial velocity of object with $m2$ before impact

$v2$ = initial velocity of object with $m2$ after impact

According to the dynamics of proposed system CUT($m2$) ≫ bob ($m1$)

Hence there will not be any movement of CUT($m2$). It can be considered as a stationary mass. It shows that it will have ($u2 = v2 = 0$) hence the equ.(12) Will be

$$m1u1 + m2(0) = m1v1 + m2(0) \qquad (13)$$

In real case the whole energy will not be absorbed by CUT because of 'coefficient of restitution (e)'. It is equated as

$$\frac{v2-v1}{u2-u1} = -e \qquad (14)$$

This shows that $\quad v1 = -e(u1) \qquad (15)$

The first impact of the bob against the stationary CUT can be modelled as follows.

$$I = m(\Delta v) \qquad (16)$$

Where $\quad \Delta v = \sqrt{2gL} - (-e(\sqrt{2gL}))$

$$I = m(\sqrt{2gL} - (-e(\sqrt{2gL}))$$

The change in momentum can be calculated as

$$I = m\sqrt{2gL}(1 + e) \qquad (17)$$

We know that the change in momentum is impulse and it is a product of force and time. The amount of time as extremely small hence it can be denoted as Δt. The equ. (17) can be rewritten as

$$F\Delta t = m\sqrt{2gL}(1 + e) \qquad (18)$$

The Δt and Δv can be measured and the force F can be calculated.

$$F = \frac{m\sqrt{2gL}(1+e)}{\Delta t} \qquad (19)$$

Equ.(1) and equ.(19) can be combined to get

$$F = -kx = \frac{m(\Delta v)}{\Delta t} \qquad (20)$$

The consistency in the impact force is tested by using a set-up as shown in Figure 4. The bob of the pendulum is allowed to hit on centre of a loud speaker's diaphragm. The loud speaker is constructionally same as moving coil microphone. It is single degree of freedom mass-spring-damper system. It is a self generating transducer which follows Faraday's first law of electromagnetic induction.

The displacement of the voice-coil fitted on diaphragm generates an electro motive force (emf). As the mass and geometry of the coil, magnet, number of turns on voice-coil and the flux density are constant, the induced emf is proportional to the rate of change of displacement of the voice-coil. The electrical output from the pendulum exciter is tested repeatedly. It is found that the pendulum impact exerts consistent force on the speaker-diaphragm. It generates 502 mV_p as shown in Figure 5. The acoustic resonance frequency of vibration is 250Hz as shown in Figure 6.

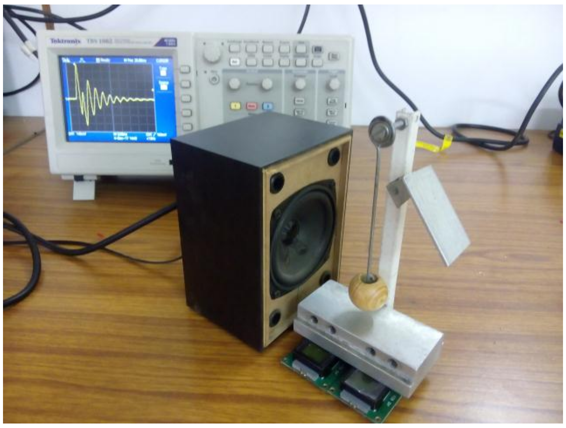

Figure 4. Photograph of set-up for testing force consistency

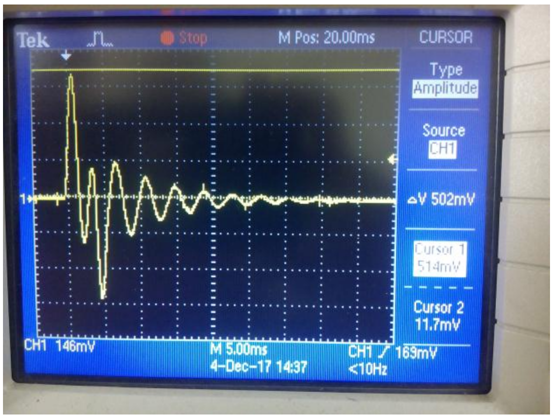

Figure 5. Electrical response of the set-up

EXPERIMENTATION AND ANALYSIS

Significance of Acoustic Response

Every object has its own resonance modes. Upon impact, the CUT tends to resonate in its natural modes. In a simple case, CUT with Single degree of freedom will resonate at a fundamental frequency given by,

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{21}$$

The mass and elastic constant of CUT decides the natural resonant frequency (NRF). If any change in any of the two parameters exists then there will be corresponding change in the resonant frequency. This frequency can be observed in the acoustic response of the CUT. In practice the CUT is a multi-degree of freedom system hence it will have multiple resonant modes. Thus blow-hole and porosity decreases the mass of CUT and a crack decrease the elastic constant of the CUT. This affects overall spectrum of the CUT and shows shift in it. However, this will not affect all the modes of CUT. Only those modes will be affected whose deformation falls in the region of defect.

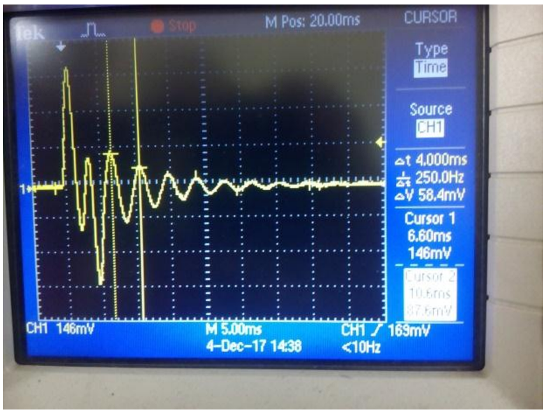

Figure 6. Acoustic resonance frequency of speaker

Figure 7. Seamless pipe-pieces (Length: 305 mm, Diameter: 30 mm) as CUT

Analytical evaluation of Acoustic Resonant frequency of CUT

The testing was carried out on the CUT shown in figure 7. The CUT is modelled in solid-works by using dimensional and physical data of the same CUT and the vibrational pattern is analysed for detection of dominant modes of vibration. It is found that the natural modal frequency of the CUT is 1.864kHz. This analysis also helped to select the point of excitation on the CUT and the support at which the vibration pattern is not disturbed.

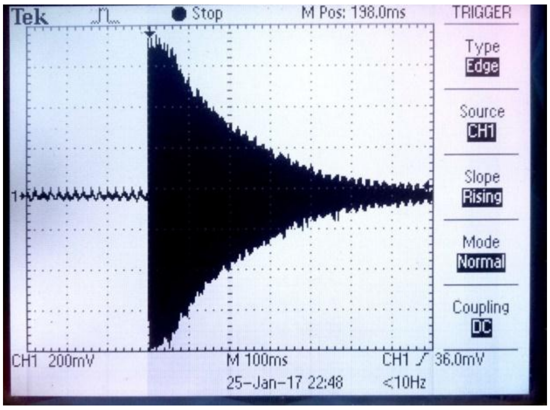

Figure 8. Decaying response of CUT

Detection of Acoustic Resonant frequency of CUT

The CUTs shown in Figure 7 are used for experimental detection of acoustic resonance frequency. These are off-the-shelf available seamless pipes of mild steel taken for investigation. The CUT is placed on a soft sponge base in order to vibrate freely. An audio pick-up is installed aiming towards the CUT. The CUT is then excited by the pendulum impactor shown in Figure 4. Upon excitation the CUT is vibrated in audible sound signal. It responded with damped free vibrations. The acquired signal was in time domain and captured on a Digital Storage Oscilloscope (DSO). It showed typical decaying signal as in Figure 8. The signal was held on DSO and magnified in time-scale. The frequency of the same was measured by using DSO menu. The frequency was 2.04kHz. It shows that the signal was well within the audio range.

The same signal is captured in a computer using Data Acquisition (DAQ) card NI-6009. According to Nyquist criteria the required sampling frequency should be at least twice the highest frequency in audio spectrum. The DAQ card is set to a sampling frequency of 40kHz. The peak frequency observed in power spectrum of captured signal is 2065Hz. The same is seen in photograph in Figure 9. The same procedure is followed for all six CUTs and the result is documented in Table.1

The average acoustic resonance frequency $\bar{X}$ is defined as,

$$\bar{X} = E(x) = \frac{x_1 + x_2 + \cdots + x_n}{n} \qquad (22)$$

where, x is the frequency of CUT and n is the time that frequency occurs. The average of frequencies is 2062.5Hz.

δ_x is standard deviation defined as

$$\delta_x = \sqrt{\frac{\sum_{i=0}^{n}(\delta_x - \bar{X})^2}{n-1}} \qquad (23)$$

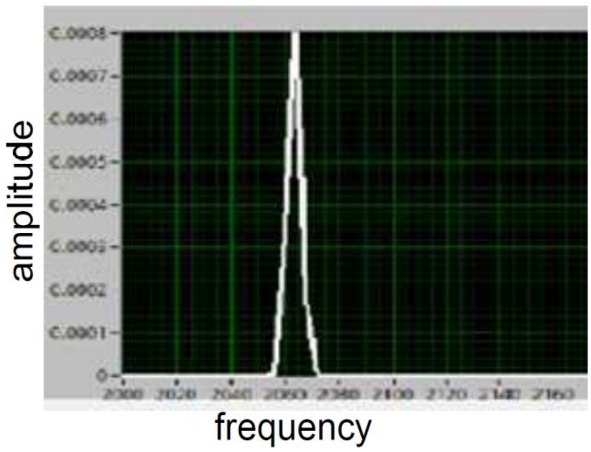

Figure 9. Peak frequency at 2065 Hz

The parameters such as frequency, amplitude, rise time, number of zero crossings, etc. may be calculated in a similar way.

Table 1: Measured Frequencies of CUT

Sr. No.	CUT No.	Acoustic resonant frequency
1	CUT-1	2065 Hz
2	CUT-2	2060 Hz
3	CUT-3	2058 Hz
4	CUT-4	2056 Hz
5	CUT-5	2069 Hz
6	CUT-6	2067 Hz

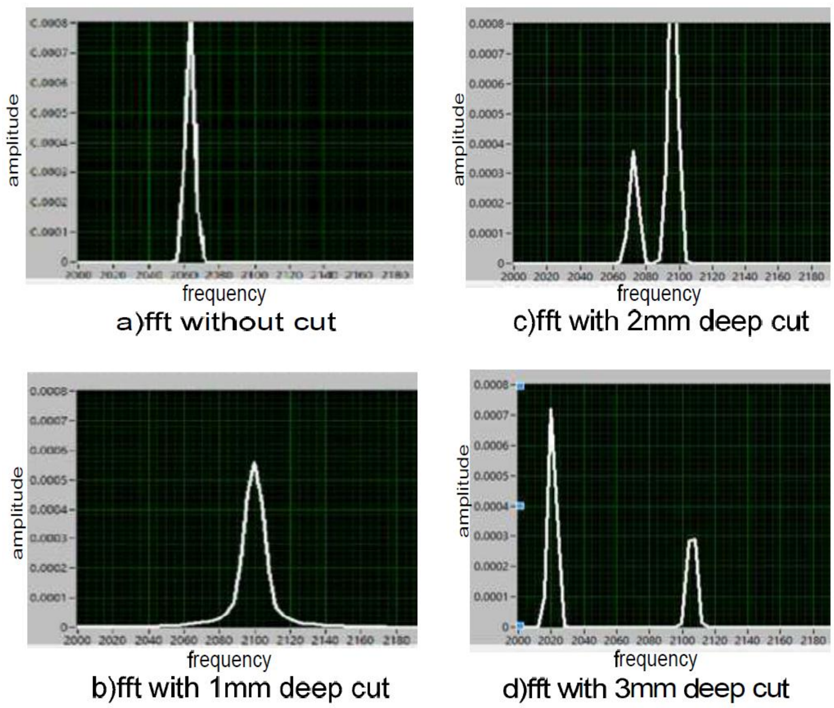

Figure 10. Peak frequency and depth of cut

Table 2: Depth of cut and peak frequency

Sr. No.	Depth of cut	$F1$	$F2$
1	No cut	2065 Hz	0
2	1 mm	2100 Hz	0
3	2 mm	2072 Hz	2096 Hz
4	3 mm	2020 Hz	2106 Hz

Dependency of acoustic resonance frequency on Structural integrity

The acoustic resonance frequency detection (NDT) is a vibrational characteristic of a CUT and can be used to detect structural flaw. The measurement taken can detect flaw anywhere in the CUT. The physical and geometrical structure of CUT causes to have unique set of characteristic frequencies. It means that the CUT with same physical properties will have same vibrational properties[2].

Any flaw in the CUT changes the structural integrity. After exciting the CUT with pendulum impact, the natural frequencies will be excited by resonating the CUT. This acoustic resonance testing (ART) can be used to detect faulty CUT.

Spectral response of CUT for depth of cut

The experimentation was carried on one of the CUT as shown in Figure 7. The wall thickness of the same is 3mm. It is kept on a sponge base and excited with the pendulum mechanism as shown in Figure 4. The acoustic signal captured by an audio pick-up is taken in computer by interfacing Data Acquisition (DAQ) card NI-6009. The power spectrum of the acquired acoustic signal in Figure 9 shows that the peak frequency, at which the CUT resonates, is 2065Hz. Now for testing dependency of acoustic resonance frequency of CUT on its structural integrity, a random place is selected on outer surface of CUT for making a small cut. The cut is made skew to the central axis of component. The peak frequencies in power spectrum are observed in Figure 10. The depth of cut and the peak frequency are documented in Table.2 The deeper cuts in CUT exhibited multiple peak frequencies denoted by $F1$ and $F2$.

CONCLUSION

The acoustic resonant frequency detection is possible practically, only when the CUT is set to vibrate freely. It is seen that the CUT resonates at the acoustic resonant frequency. This frequency is dependent not only on the geometry of the CUT but also on the spring constant of the material. If the identical CUTs are excited with consistent impact force, they show identical vibrational response.

The results are tabulated in Table.1. From the results it is observed that, the dimensionally identical CUTs show different acoustic resonant frequencies. But it may be because of variation in elastic constant, mass variation, material phase formation, non-uniform wall thickness and geometrical errors. It is observed that the cut in the component totally changes the vibrational response. The surface finish and superficial flaws on CUT cannot considerably change the vibrational signature.

The ART technique can be adapted for in-line inspection of CUT. It can detect major flaws like deep cracks. However it cannot detect the position of the flaw in CUT. This technique can be used for automatic segregation of components with large geometrical variations, such as bare castings before further processing. This will save labour cost, time and rejection.

If the acoustic resonance frequency of the CUT is low, then a low speed DAQ card or an inbuilt audio system of computer can be utilized which will cut-down cost of the system. The technique cannot be used for complex shaped CUT. It is suitable for large CUT with low elastic constant.

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