Acoustical Test Instrument of Mechanical Properties with Shaft Work pieces

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Abstract. Main discussed Mechanical Properties measurement with Shaft Work pieces, and used the method of acoustic resonance to measure Mechanical Properties such as intensity, hardness and toughness in this paper. Introduced design process of instrument for hardware and software. Development of this Instrument, it may instead of such as the universal testing machine, the hardometer and the impact-toughness tester as NDT. Derived some expressions about acoustic parameters and Mechanical Properties, then design the acoustic test instrument through the sensor and electronic technology. Build NDT system that is based single chip computer. This article showed some of parameter as tensile strength, extensibility, hardness and impact-toughness, shown relation expression these parameters and acoustic testing, through computer simulation calculation and regression analysis. For example tow kinds of the shaft work pieces, give testing data and some diagram and graphed to research in circuit system. Take some analysis of the system accuracy and give out conclusion.

1. Introduction
Metal such as steel and ductile iron axle sample's mechanical property testing, it general needs to sampling from the solid of components, then processing proof sample or proof stick. At last we can obtain the result by the testing of universal testing machine, impact ductility testing machine and hardness meter. The method's shortcoming is long cycle, high expenses, low precision and its damage inspection. Its cost can't underestimate especially as for the components whose precision requiring higher or ultra precision processing parts. This kind of testing method just is sample survey and its result can't represent completely workpiece itself mechanical property.

We can dependent on nondestructive testing to improve the method of processing parts mechanical property and metal's material. The study of ductile iron parts' mechanical property on-line and one by one testing using conic resonant method is introduced in this paper. And compare the result with ultrasonic inspections.

Acoustical resonant method is a better method about testing mechanical property and matrix structure especially it is applicable to that testing by on-line and one by one about ultra precision processing parts.

The paper studies a method according to the actual production's needs, on premise that non-damage tested object to development the acoustical test instrument. That is able to suit to be used in quick detecting ductile iron through the physical phenomenon of mechanical vibration to evaluate the intrinsic quality to satisfy the needs of modern production and testing.
2. Basic theory

2.1. The testing mechanism of the resonant frequency
The article's physical phenomenon involves instantaneous vibration according to the principle of d'Alembertion [1]. With a Shaft Work piece, if it meet some condition such as \( L/d > 5 \), that is its ratio between length(\( L \)) and diameter(\( d \)), then may be believed to be not affect as transverse vibration when the axle vibrates at longitudinal direction [2]. The equation of having damping random vibration as follows:

So that frequency of the shaft work piece it can be expressed

\[
f_0 = \frac{1}{2L} \sqrt{\frac{E}{\rho}}
\]

In the equation, \( f_0 \) is the resonant frequency, \( L \) is the length of the test sample, and \( E \) is the elastic modules of the dynamic state.

Therefore

\[
f_0 = \frac{\pi d^2 gE}{16WL}
\]

In the equation: \( \rho \) - the density of the test sample; \( W \) - the weighty of the test sample; \( d \) - the diameter of the test sample; \( g \)-the acceleration of gravity.

2.2. The testing mechanism of the logarithmic decrement
In order to keep the non-ideal elastic object's vibration; we must incessantly supply energy to the object. This phenomenon because of material internal reason causing the consumption of mechanical energy is named logarithmic decrement, which has the quite sensitive quality with metal matrix structure [2-3].

After the elastic object is stimulated, it will take place vibration because exist the logarithmic decrement makes the elastic object in the state of free attenuation, the vibration respond curve is the declination of index rule. The logarithmic decrement in the free declination vibration, it may be indicated using the Napierian logarithms two amplitude's vibration ratios in unit time that is logarithmic decrement as \( \delta \).

\[
\delta = \frac{1}{n} \ln \frac{A_1}{A_{n+1}}
\]

In the equation (3), \( n \) is the number of amplitude decrease from \( A_1 \) to \( A_{n+1} \) (the number of vibration). Parameter \( A_1 \) and \( A_{n+1} \) is arbitrarily at here respectively, so only when we test the number of vibration \( n \). We can calculate the logarithmic decrement \( \delta \). The logarithmic decrement has a relationship with the internal friction value \( Q^{-1} \) as follows:

\[
Q^{-1} = \frac{\delta}{\pi}
\]

2.3. The relationship with the ductile iron's constitution, the mechanical property and the acoustical resonant parameter
The material of ductile iron should be regarded as the two-phase mixtures about the ductile iron and the matrix structure [4]. Different organizational structure has corresponding characteristics each other with their different elasticity and analyticity. It presented the acoustical resonant limit is resonant frequency and logarithmic decrement having different count.

The ductile iron is low elastic substance, which can't be adept to the matrix's elastic deformation; the graphite hinders the deformation of matrix structure. So, resonant frequency is susceptible for the graphite's state, distribution, the spherical diameter the number the volume that is occupied and the other free compound while the damping capacity is susceptible for the Pearle or the ferrite's change in the matrix structure [6]. In the end, either the resonant frequency or the logarithmic decrement relates
to its elastic modules of the dynamic E that is, E is closed relate to the matrix structure, according to
the equation about the theory of intensity and the elastic modules mentioned by Hashin [5].

\[ E = \frac{9KG}{3K+G} \]  \hspace{1cm} (5)

Through multiple regression analysis and data process with computer fitting of numerical value,
built mathematics equations between elastic modulus E, internal friction value \( Q^I \) and mechanical
Properties, witch can be expressed

\[ HB = 152.7 + 0.05168 \frac{E}{(Q^I)^2} \] \hspace{1cm} (6)

\[ \sigma_b = 391.6 + 0.18794 \frac{E}{(Q^I)^3} \] \hspace{1cm} (7)

\[ \delta = 5.6 + 0.0018315 \frac{\alpha_k^2}{\sqrt{(Q^I)}} + 4.27729 \frac{\alpha_k^2}{E} \] \hspace{1cm} (8)

\[ \delta = 2.5 + 0.1541 \alpha_k \] \hspace{1cm} (9)

From the equation (1), we know the acoustical parameter, resonant frequency \( f_0 \), is only in close
relationship with the elastic modules of the dynamic state \( E \). Figure 1 is the curve of the relationship
among the ductile iron's camshaft's \( E \) and the intensity, the plasticity and the toughness.

![Figure 1](image_url)

**Figure 1.** The relationshop among the ductile iron's \( E \).

In the equation: \( K \) - the elastic modules of compressed; \( G \) - the coefficient of rigidity.

From this we know increasing the graphite volume will make the elastic modules declined. Relationship
between with Brinell hardness \( HB \) and yield strength \( \sigma_{0.2} \) is express

\[ HB = K \sigma_{0.2} \begin{cases} \sigma_{0.2} \leq 7, (N/mm^2), K = 11.2 \\ \sigma_{0.2} > 7, (N/mm^2), K = 0.4 \end{cases} \]

In the matrix structure, increasing the content of ferrite can increase vibrate logarithmic decrement
and decrease \( E \), at the same time the \( E \) is higher having carbon object in ductile iron.

From aforesaid analyzing, we know that the graphite and the matrix structure all closed relate to
resonant frequency and logarithmic decrement and their common action relates to the elastic modules
of the dynamic state. In acoustical resonant method, only when we test axle sample's resonant
frequency, we can calculate the elastic modules of the dynamic state \( E \).

So, testing the elastic modules \( E \) and the logarithmic decrement according to the Hooke's Law,
based in these we can indirect test the ductile iron axle sample's mechanical property, also we can
reach the aim of nondestructive testing about ultra precision axle sample's.
3. System design of the acoustical test instrument

3.1. The principle of acoustic resonant nondestructive testing

Work principle of acoustic resonant nondestructive testing system is illustrated in Figure 2.

![Figure 2. The Acoustical Testing Device.](image)

The testing sample was laid on frames and it is supported by one or two point. The electromagnetic exciter excites the end of the sample through impulse. The machinery vibration wave is transmitted in rigid body sample. The sensor receives signal. The signal is processed by acoustic resonance testing system. The result is sent to monitor and printer with time-sharing method.

3.2. The general designing and study of hardware of testing system

The structure of hardware of acoustic resonance nondestructive testing system is shown as Figure 3.

![Figure 3. Principle of the acoustic resonant testing system.](image)

The system consists of sensor of sound signal, amplifier, and band-pass filter of variable frequency center, wave-detector circuit, voltage compare circuit, signal chip computer, monitor and printer. The signal processing of acoustic resonance detecting system is divided into two path circuits. The signal through the first line is amplified and sent to shaping 1 circuit to reshape. The signal through the other line is sent to filter. The square wave from shaping 1 go through 74LS393 counting/frequency division 16 frequency division gate-control system to the input T1 of 8031 counter. Time is 0.1 second. The number of pulse is calculated. According to the value of the counter and scanning with P1.0 – P1.3, again, the center frequency of band-pass filter of variable center frequency is chosen. The signal of second path is across through band-pass filter. The disturbing of high and low frequency is filtered out. This output signal is divided into two lines again: the signal of the first line goes through shaping 1 circuit and 74LS393 twice frequency division. Next, this signal goes through gate-control circuit and is connected to counter T1. The number of pulse is worked out. The signal of another line passes through detection circuit. The enveloping line of instantaneous vibration wave is taken out; the output is sent to upper and lower limit comparator circuit. Then, the output of compare is connected to exclusive-or circuit: one output of the exclusive-or circuit is connected to INT0 to control the timing of T0 the other output meets with the impulse from shaping 2 to control the on-off impulse signal passing. Then, the number of impulse is calculated.

3.3. Design of microcomputer processing system

In Figure 3, the acoustic resonance detecting system selects 8031 single chip computer smallest system as core unit. 8031 has the function of timing and counting. Two 16-bit timers T0 and T1 are included in 8031. The range of testing frequency is in 0 – 65536Hz and it can satisfy the quest of design [4]. The single chip computer has a extend EPROM memory, and in order to transmit data and address by port P0 with time-sharing method. The external address latch is adopted.
3.4. The study and design of front and back channel circuit

The analog channel adopts three-level amplifier. Filter circuit adopts band-pass circuit variable center frequency with high gain multi-end feedback and electric power. The maintained amplitude of detected signal can be sent to back-end circuit without distortion. Therefore, the accuracy of controlling of timing and counting is ensured.

Center frequency of general filter is fixed. Only the signal in some of frequency segments can be passed through. In order to decrement some of noise signal effectively. The width of band B is limited to be thin. By actual verify, resonant frequency of mental material is in 8 – 15 kHz and width of band is 8 kHz. Obviously, the filter with fixed center frequency can not satisfy the request. On the condition that width of the band is fixed.

The only method to solve this problem is changing center frequency. Therefore, in this circuit we select a sixteen-way multi-way analog switch AD7506 to cooperate with P1.0 – P1.4 of microcomputer to intelligently control the switch of filter circuit. Then, we obtain the purpose to dynamic at any moment scan the property of frequency, and to automatic regulate the center frequency of every sub-segment.

The amplifier and exclusive-or gate compose the upper and lower limit voltage compare circuit. It is used to control upper and lower limit amplitude from detector. When the amplitude of signal more than x₁ or less than xₙ₊₁, the exclusive-or gate will output a low level. When the amplitude of signal is between x₁ and xₙ₊₁, the output of exclusive-or gate is high level. Therefore, we use exclusive-or gate’s output to control the initiation of timing and counting. When 8031 timer T0 is with gate control mode 1, it began to time. On the other hand, when the output of exclusive-or gate is low level, the timer don’t time if the output is high level, the timer is permitted to time. The value of timer t is the time that the amplitude of signal spends changing from x₁ to xₙ₊₁. The flow out value of T0 sent to 30H.

When the value of P1.7 is 0, the signal can pass by reshape device 1 and is sent to 74LS393 to time. It’s propose is to decay 0.1 second to calculate the number of pulse, and make sure the dynamic center frequency of band-pass filter. When the value of P1.7 is 1, furthermore when the output of exclusive-or gate is high level, the signal can pass by reshape device 2 and is sent to 74LS393 to time. Now the signal first path can’t pass. When the output of exclusive-or gate changes into negative, the signal of two paths will is cut off. The counting value n at this time is the number of impulse when amplitude of signal decrements from x₁ to xₙ₊₁.

4. Application effect of the acoustical test instrument instrument

![Figure 4. Relation between main mechanical properties.](image)

Relationship with the hardness, tensile strength and other mechanical properties are shown as Figure 4. Through detecting many test sticks and camshaft hereinbefore, may be gained this result: increase internal friction result in plasticity and toughness to be improve; increase resonant frequency can be improved dynamic elastic modulus that the tensile strength and the hardness intensify all, and the
integration of mechanical properties is improved evidently. The greatest error of system is 0.045%. Untouched detecting effectively distance is 5 – 20mm.

5. Conclusion
For the design and study of acoustic resonance NDT instrument, succeed to take combined with mechanical properties and acoustical parameters to realize NDT of the mechanical properties with mental material as test the shaft work piece. It is significance to advance the test precision and the automation level of NDT.

References
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