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Determination of materials damping properties through the phase difference between strains

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**ABSTRACT:** The original method and experimental procedure for measuring materials damping capacity through the phase difference between axial and transverse strains is presented. The results of the determination damping capacity of carbon steels and Mn-Cu alloy specimens are presented. A direct experimental estimation of the static tension and stress gradient effect on the materials damping properties at flexural vibrations is carried out. The data are correlated with damping characteristics of the metals obtained by free damped oscillations method.

**INTRODUCTION**

In parallel with indirect methods of measuring damping (inelasticity characteristics) in metals the so-called direct methods are widely used at present. The stress-strain hysteresis loop method is among them. In this method inelastic strain per cycle $\Delta e_1$ which is equal to the hysteresis loop width on $\sigma - e'$ coordinates is taken as an inelasticity characteristic, see Fig.1. The strain-strain hysteresis loop method is based on the measurements of the hysteresis loop width on $e - e'$ coordinates ($e$ and $e'$ are the axial and transverse strains, respectively). Also damping capacity is obtained by using the phase difference $\alpha$ between stress and strain. However the first and third methods require a load gage and the second one has low resolution. Because of this, it was suggested new method to obtain specific damping capacity (SDC) under time-harmonic strain conditions of tension-compression or flexure (the so-called strain phase shift method).

**I THEORY**

Suppose that phase shift $\alpha$ between stress and strain is due to the time lag of the inelastic component $e_i$ from elastic component $e_e$ of the strain. Then if $\alpha = \alpha_0 \sin \omega t$, so

$$ e(t) = e_0 \sin \omega t + e_i \sin(\omega t - \gamma) = e_0 \sin(\omega t - \alpha), \quad (1) $$

where $\gamma$ is the phase shift between elastic and inelastic components of the strain. Angle $\alpha$ is connected with $\gamma$ in the following manner

$$ \alpha = \alpha_0 \sin \gamma, \quad \text{and} \quad e_0 \sin \gamma = \Delta e_1 / 2. $$

The time dependence of transverse strain can be presented as

$$ e'(t) = -\nu e_0 \sin \omega t - \nu e_0 \sin(\omega t - \gamma) = \nu e_0 \sin(\omega t - \alpha + \pi - \phi), \quad (2) $$

\[561\]
where \( \varepsilon_0 \) is amplitude value of the strain \( \varepsilon \), \( \nu \) is Poisson's ratio, \( \nu_e \) and \( \nu_i \) are Poisson's ratios for elastic and inelastic components of the strain, respectively, \((\pi - \varphi)\) is the phase shift between axial and transverse strains.

From Eqs. (1) and (2)

\[
\varphi = \nu \varepsilon_0 \sin y/\nu_e \varepsilon_0 - \alpha = (\nu/\nu_e - 1) \alpha
\]

(3)

Eq. (3) allows to obtain the inelasticity characteristic of materials

\[
\Delta \varepsilon_e(\varepsilon_0) = 2\nu_0 \rho \varphi(\varepsilon_0)/(\nu - \nu_e)
\]

(4)

or SDC

\[
\psi(\varepsilon_0) = \pi \Delta \varepsilon_e/\varepsilon_0 = 2\pi \rho \varphi(\varepsilon_0)/(\nu - \nu_e)
\]

(5)

In practice it can be accepted that \( \nu_e = \nu \) when strains are very small and \( \nu_i = 0.5 \).

The main problem of the study connected with measuring the phase difference between two time-harmonic signals is that practically all elements of the measuring system, including strain gauges, are sources of the phase shift. Furthermore it was found that some types of instrumentation amplifiers produce a phase shift of the input signal.

2 EXPERIMENTAL PROCEDURE

2.1 Description of the Apparatus

Experiments have been carried out on the test setup KD-1M schematic of which is shown in Fig.2.

Vibratory system consisted of a specimen with a mass on the end. The specimen was rigidly fixed in the massive frame. The system of specimen static loading comprised the upper grip, the load cell and a thin strip (250x40x0.5 mm, titanium alloy VT-8) having negligibly small flexural stiffness and SDC and attached to the specimen in the node of the second flexural mode. The frame was suspended on thin steel wires.

The resonance method was used for excitation of vibrations by means of an electromagnetic system involving the waveform generator, power amplifier and electromagnets. The electromagnetic system made it possible to excite flexural (first and second mode) and axial vibrations of a specimen.

Measuring system (MS) consisted of strain gages the signals from which passed through the instrumentation amplifier UT-8 and came to the digital phase meter FK2-35, digital voltmeters V7-39, double-channel oscilloscope SI-83 and frequency meter F551A. MS control, data acquisition and processing were executed by PC-AT-486 computer.

The SDC was used as an inelasticity characteristic of materials. It was obtained by free damped oscillations method and the strain phase shift method.

2.2 Specimens and strain gages

Steels 20, 45 and Mn-Cu alloy specimens were investigated. For special investigations PT-3V (titanium alloy) and EP-898 (steel) specimens were used.

There were used the foil metal strain gages KF5-R1-3-400V (400Ω, two grids in axial and transverse directions, gage length 3 mm, 2.2 GF) and KF5-P1-3-400 (400Ω, 3 mm, 2.2 GF) produced by VEDA Inc. under license from the Hottinger Baldwin Messtechnik.

The surfaces of some specimens were preliminary electropolished to a depth of 150 \( \mu \)m to remove the surface layer damaged by machining. The distribution of strains along the specimen gage length was obtained by strain gages KF5-P1-3-400, cemented directly at the mass, at the attachment and in the center of the specimen gage length.
2.3 Error connected with strain-gages inelasticity

Let strain gage inelasticity causes a time lag of the measured signal from true strain and the lag angle be $\phi_e(\varepsilon)$. Then it is not difficult to obtain the following relationships

$$\alpha = \alpha_m + \alpha_r - \Delta \phi_{m},$$

$$\varphi = \varphi_m + \Delta \phi_{r},$$

where $\alpha_m$ and $\varphi_m$ are the experimentally measured phase differences between $\sigma$ and $\varepsilon$ and between $\varepsilon$ and $\varepsilon'$, respectively; $\alpha_r$ is the phase difference between $\sigma$ and strain $\varepsilon_0$ of the load cell due to its inelasticity; $\Delta \phi_{m} = \phi_{m}(\varepsilon_0) - \phi_{m}(\varepsilon_0)$; $\Delta \phi_{r} = \phi_{r}(\varepsilon_0) - \phi_{r}(\varepsilon)$.

Special testing was carried out using titanium alloy PT-3V specimen and ten KF5-R1-3-400V gages. The gages were cemented one after another in the same area of the specimen. The phase shift was measured at frequency $f = 109.9$ Hz (second mode of vibration) and its random error was found to be $\Delta \phi = \pm 2.8 \times 10^{-4}$ rad.

2.4 Phase meter

Digital phase meter FK2-35 makes it possible to measure phase shift in the range from 0 to 360 deg (or from -180 to 180 deg) with an accuracy of 0.01 deg and a resolution of 0.001 deg. This is assured under equality of the input signals, their voltage being within 10 mV...5 V and frequency within 0.1 Hz...10 MHz. All those conditions were carefully met.

2.5 Effect of the instrument input impedance

MS included the instruments connected in parallel with the phase meter and had the input capacity 35...75 pF. As special investigation shown the phase shift induced by the instrument input impedance was obtained to be 0.020 deg at the frequency $f = 112.8$ Hz and 0.035 deg at $f = 1015.1$ Hz.

In order to eliminate this error two absolutely identical measuring channels were created, see Fig.2. During the phase shift measurements the frequency meter was disconnected. In this case the effect of the input impedance appeared to be within the phase meter resolving ability.

2.6 Effect of connecting cables

Coaxial cables no more than 1.5 m in length were used in the MS. As the test revealed, cables up to 5.0 m in length in the frequency interval from 0 to 1000 Hz had no pronounced effect on the phase shift.

2.7 Phase shift, induced by the instrumentation amplifier and strain gages

Signals from the strain gage KFS-R1-3-400V come to two channels of the eight channel instrumentation amplifier UT-8. Each channel powers a full (or half) Wheatstone bridge by an alternating current (5 V, 5 kHz). As known, similar amplifiers have a property to shift the phase of amplifying signal because of its reactive components. In such MS it is impossible to separate the phase shift occurring due to the amplifier and the inelasticity of strain gages and materials. For this reason preliminary tests were conducted with a so-called reference specimen (titanium alloy PT-3V), which differed from all other ones only by very low damping capacity.

Strain gages were cemented on the active and passive specimens. Axial grids of the gages, as well as the transverse ones, were connected in a half Wheatstone bridge. Then the vibrations of the active specimen with stress amplitude $a_0 = 60$ MPa and different frequencies were excited. The frequency was varied by the excitation of vibrations of axial and various flexural modes and by using some masses on the end of the specimen. Gain factors of the channels were selected so that the amplitudes of the output signals from axial and transverse strain gages were equal. Under these conditions total phase shift $\varphi_{m+r}$ can be presented as algebraic sum

$$\varphi_{m+r} = \Delta \phi_i + \Delta \phi_{r} + \varphi_r,$$

where $\Delta \phi_i$ is the difference between phase shifts due to the channels; $\varphi_r$ is the phase shift due to inelastic properties of the reference specimen material.

The frequency dependencies of $\varphi_{m+r}$ for different values of Poisson's ratio were obtained prior to 1000 Hz. Poisson's ratio was varied by different location of strain gages relative to the attachment of the specimen inasmuch as a plane stressed state arises in the immediate vicinity of the attachment and influences the ratio value.
The total phase shift at frequency \( f \) and Poisson’s ratio \( \nu \) will be defined by the equation

\[
\varphi_p = \Delta\varphi + \Delta\varphi_m + \varphi,
\]

and with consideration of Eq. (8)

\[
\varphi = \varphi_p - \varphi_{mr} + \varphi_r.
\]  

(9)

Using the free damped oscillations method SDC for the reference specimen was obtained to be \( \psi = 3.3 \times 10^{-4} (\sigma_0 = 60 \text{ MPa}) \). Basing on Eq. (5) it was calculated that inelasticity characteristic of materials can be measured with a sufficient accuracy under conditions \( \psi \geq 0.03 \) (\( \varphi \) is neglected).

Time stability of the \( \varphi_{mr}(f) \) relationships for instrumentation amplifier UT-8 is very high. But this circumstance does not preclude the necessity of their periodic verification, which is a drawback of the proposed experimental procedure.

3 RESULTS AND DISCUSSION

3.1 The stress state effect

When measuring the damping capacity of materials it is a general practice to cement strain gages on the most stressed areas of the specimen gage length. At the same time at deformation of relatively wide specimens the passage of transverse strains immediately in the areas mentioned above are hampered, resulting in a plane stressed state. This circumstance may have an essential effect on the phase shift \( \varphi \).

Consequently, it is necessary to make the measurements of angles \( \varphi \) in the areas of the specimen gage length, where uniaxial stress state is taking place.

The specimens tested in this part of the study was steel EP-898. There was no connection between the vibrational system and the static loading system through the strip.

Eight strain gages KF5-R1-3-400V were cemented along the specimen gage length. Then distributions of the axial and transverse strains along the specimen corresponding to the different vibration modes were measured and the values of Poisson’s ratio were obtained.

The numerical analysis of the prismatic cantilever beam stress-strain state at free flexural and axial vibrations was made with the use of the finite element method. Sixteen-node rectangular parallelepiped applied for analysis of thick plates was used as a finite element.

From the results obtained by both the analysis and the experiment it follows that the influence of the attachment extends to the length which is less than twice the width of the specimen. For this reason the phase difference between axial and transverse strains was obtained at a distance \( l \geq 2xb \) from the attachment or the mass.

3.2 Static tension effect

Steel 20 without heat treatment and Mn-Cu alloy after annealing (820 deg, 2 hour, cooling in furnace) were investigated. The dimensions of the specimen gage length were 150x20x5 mm.

Testing of the specimens was performed at the second flexural mode of vibrations.

A specific feature of the vibrating system is that at static tensile loading of the specimen through the strip a considerable change in its stored energy takes place first of all through the redistribution of the bending moment along the specimen gage length and due to the axial displacement of the point where the strip was attached to the specimen.

To determine SDC \( \psi_p \) of a specimen via SDC of the vibrating system obtained in the experiment it was used the method of recalculation which also allows to finde SDC under conditions of homogeneous stress \( \psi_h \) and pure bending \( \psi_{ph} \).

The stress amplitude dependencies of SDC obtained using the strain phase shift method are denoted by \( \psi_r \) and shown in Figs. 3 and 4 by open circles.

![Fig. 3-Damping versus stress amplitude for steel 20 specimen under tensile stress \( \sigma_p = 0 \).](image-url)
As can be seen, qualitatively the behaviors of dependencies, obtained by the methods of strain phase shift and free damped oscillations are identical. At the same time quantitatively characteristic \( \psi_p \) is closer to \( \psi_{eb} \) for steel 20 specimen or is in intermediate position between \( \psi_{eb} \) and \( \psi_b \) for Mn-Cu alloy specimen. It must be taken into account that the strain phase shift method makes it possible to determine inelasticity characteristic of a limited volume of a specimen directly under strain gages. Consequently, the effect of special damping properties of the surface layer on \( \psi_p \) must manifest itself more than on \( \psi_{eb} \).

![Fig. 4: Damping versus stress amplitude for Mn-Cu alloy specimen under tensile stress \( \sigma_0 = 0 \)](image)

The attempt was undertaken to estimate the effect of the surface layer for steel 20 specimen. The investigation revealed that \( \psi_{eb} \) on the electro-polished area of the specimen was 18...32% greater than in the case of unelectropolished area. Thus, energy dissipation in the unelectropolished surface layer is largely suppressed as a result of magnetoelastic hysteresis blocking by residual compression stresses, which effect in a similar way to static tensile stresses. But it does not impede microplastic deformations which appear to be the other mechanism of energy dissipation in steel 20.

This mechanism causes a rise in \( \psi_p \) with increasing static stresses, see Fig.5. By this means the strain phase shift method is more sensitive to the state of a surface layer, than the free damped oscillation method.

The characteristic \( \psi_{eb} \) is independent of changes in the vibration system stored energy, as is indirectly supported by qualitative agreement between dependencies \( \psi_p \) and \( \psi_b \) for both metals, see Figs. 5 and 6. Their quantitative distinctions, insignificant for Mn-Cu alloy and more essential for steel 20, in all likelihood are the consequence of various extent of the surface layer effect on the damping capacity of the specimen and on the damping capacity of the limited volume of the specimen.

![Fig. 5: Relative change of damping versus tensile stress for steel 20 specimen (stress amplitude \( \sigma_0 = 130 \text{ MPa} \)](image)

3.3 Stress gradient effect

Carbon steels 20 and 45 after annealing (930 deg, 2 hour, cooling in furnace) were investigated. The dimensions of the specimen gage length were 240x25x20 mm.

The experiments were carried out at first flexural mode of vibration. As before SDC was obtained by free damped oscillation method (\( \psi_b \))
and the strain phase shift method (ψs); in so doing ψs was obtained on the electropolished and unelectropolished areas of the specimens. Then the thickness of the specimens was decreased by removing the metal from the strain gage free side and the test was repeated with the same strain gages (the experiments was carried out at h = 25, 10, 5 and 2 mm).

The annealing of the specimens was executed with the aim of reducing to a minimum manufacturing residual stresses. The residual stresses control was provided and shown that they were less than 15 MPa.

![Graph](image)

**Fig.7** - Damping versus stress amplitude for steel 20 specimen

As may be seen in Fig.7 ψs is somewhat greater than ψs. However, qualitatively the stress gradient effect on mentioned characteristics is practically identical, see Fig.8 (there are shown ψs dependencies for unelectropolished surfaces only).

![Graph](image)

**Fig.8** - Relative change of damping versus stress gradient (α0 = 40 MPa)

The stress gradient has a qualitatively different effect on ψs in the case of unelectropolished surfaces for steel 20 and 45 specimens. At the same time on the electropolished areas the ψs variations are not more than 20%.

A comparison of the inelasticity characteristics on the electropolished and unelectropolished areas as shown that the degree of distinction between the inelasticity of the surface layer and the rest volume of the specimens is of first impotence. For steel 20 specimen ψs on the electropolished area was 1.5 times higher than on the unelectropolished one, but for steel 45 specimen, on the contrary, more than 2 times lower. It has been just this reason which explains the distinction between dependencies for the steels investigated, shown in Fig.8. The absence of damaged by machining surface layer on the electropolished areas causes the independence of ψs from the stress gradient.

By this means the stress gradient effect on inelasticity characteristics of a specimen takes place only in the cases of essential distinction between the surface layer and the rest of material inelasticity characteristics.

### CONCLUSION

The method and experimental procedure for measuring damping capacity of materials through the phase difference between axial and transverse strains has been developed.

The strain phase shift method makes it possible to obtain damping characteristics of a limited volume of specimens or structural elements which are close to damping characteristics of specimens under conditions of homogeneous stress.

Damping characteristics determined by the strain phase shift method are independent on changes in a specimen or vibration system stored energy and of the extent of vibration system isolation.

The results of a direct experimental estimation the stress gradient and static tension effect on damping properties of materials were obtained. It was established that stress gradient influence depends on the relation between a surface layer and a base material inelasticity characteristics and may manifest itself in a qualitatively different manner.
REFERENCE


