A New AMB Configuration for Measurement of Material Damping in Metals

H. BLEULER, M. BLÖCHLIGER, J. DUAL AND C. GÄHLER

ABSTRACT

Material damping can be determined by measuring the damping of eigenmodes of vibrations in probe rods. Conventionally, these probes are supported mechanically and the supports must be moved to the nodes of the vibrational mode considered. Nevertheless, for materials with low damping, considerable amounts of energy may still be dissipated in the supports, thereby affecting the measurement of intrinsic damping of the material. Support losses may be considerably reduced, however, if the rod is suspended magnetically. Furthermore, no support adjustment is required even if this measurement for several eigenmodes is desired. In this paper, the damping of longitudinal vibrations in magnetically levitated steel rods is described. The results show values of intrinsic damping which are in some cases four times lower than those measured using conventional set-ups. The magnetic support uses a homogeneous magnetic field in order to avoid eddy currents. A description of the set-up as well as experimental results are included.

1. INTRODUCTION

When a structure vibrates with one of its eigenfrequencies under a harmonic load, the damping of that particular mode determines up to what stress levels the vibrational amplitude will increase. Therefore, it is important for design of a structure to know its damping properties, if vibrations are expected to cause problems.

One of the sources of damping is the intrinsic or material damping, other sources include friction in joints, acoustic radiation and viscous damping. If the motion is harmonic, the material damping may be described using a complex modulus. The ratio of the real part of this modulus to the imaginary part is called the loss tangent. For materials with low damping, the loss tangent is equal to $1/Q$, where Q is the quality factor of the vibrational mode considered.

Recently, the design of high Q resonators has received considerable attention in efforts to detect gravitational waves. [3]. Furthermore, material damping is a very sensitive measure of the state of a material. Damping measurement has therefore often been used as a microstructural research tool by metallurgists [1].

Hannes Bleuler, Institute of Industrial Science, University of Tokyo, 7221 Roppongi, T 106, Minato ku, Tokyo, Japan
Mike Blöchliger, Jürg Dual, Institute of Mechanics, Swiss Federal Institute of Technology (ETH), 8092 Zürich, Switzerland
Conrad Gähler, Mechatronics Lab, Swiss Federal Institute of Technology (ETH), 8092 Zürich, Switzerland

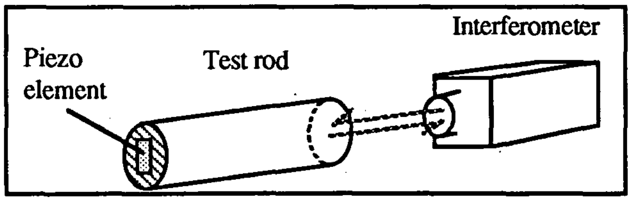

Fig. 1: Configuration of excitation and measurement of the vibrations in the test rod

Measurement of material damping is particularly difficult for materials which have low intrinsic damping. For such materials a crucial consideration is the manner by which the specimen is supported. In particular, poor support conditions result in energy losses and consequently in overestimation of the damping.

2. DAMPING MEASUREMENT

Material damping may be assessed by determining the damping of eigenmodes of vibrations in a test specimen. The set-up for longitudinal modes of vibration is illustrated in Figs. 1 and 2: A small piezo element is attached to the front face of the test rod. It is driven by a sinewave generator and thus exerts a sinusoidal force $F(s)$ on the test rod. (s is the Laplace transform variable.) The axial displacement $x(s)$ of the opposite front face of the test rod is measured using a heterodyne laser interferometer.

A standard technique to determine the damping uses the frequency response

$$x(s) = G(s)\,F(s) \tag{1}$$

in the range of an eigenfrequency of the test rod. The eigenfrequencies in the free-free longitudinal mode which is considered here are given by

$$\omega_i = i\,c_0 / (2L) \tag{2}$$

where c_0 is the wave speed of longitudinal waves in the rod and L is the length of the rod. Typically, the frequencies are in the lower kHz range.

The frequency response may be written in modal decomposition as

$$G(s) = \sum_i G_i(s) \tag{3}$$

where

$$G_i(s) = \frac{k_i}{s^2 + 2\,\delta_i\omega_i s + \omega_i^{\,2}} \; ; \quad 2\,\delta_i = \frac{1}{Q_i} \tag{4}$$

If the quality factors Q_i are sufficiently high (e.g. $Q_i > 1000$), the transfer function around the i-th eigenfrequency ω_i is approximately

$$G(s) \approx G_i(s), \tag{5}$$

along with a superimposed phase shift of $(i-1)\,\pi$.

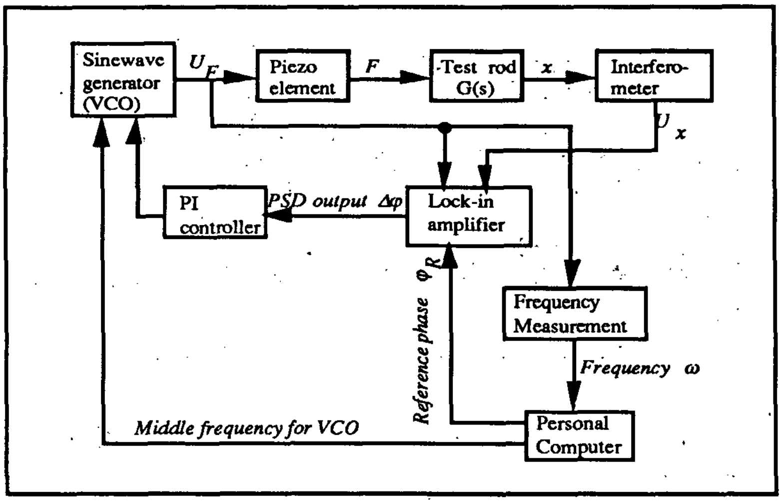

Fig. 2: Signal flow chart of the measurement set-up
PSD = Phase Sensitive Detector

To measure the transfer function G(s), the output of the interferometer measurement system and the output of the sinewave generator are fed into a lock-in amplifier (Figure 2) which is used to determine the phase φ between the two signals. The sinewave generator signal is used as a reference signal. By feeding back $\Delta\varphi$, the difference between φ and the reference phase φ_R to the VCO input through a PI controller, the VCO frequency can be kept stable within $\Delta\omega/\omega \leq 10^{-6}$ while keeping φ equal to φ_R. [2]. The quality factor Q of the resonator is determined by measuring two frequencies at phase values of $\pm\ \pi/4$ with respect to the phase at resonance.

3. AMB SUSPENSION

3.1. ADVANTAGES OF AMB SUSPENSION

In conventional set-ups, the test rod is suspended by threads or laid on a weak piece of styrofoam. The support usually adds a considerable amount of damping. It is possible to minimize this effect by positioning the supports at the nodes of the eigenmode considered. However, this procedure needs to be repeated for every frequency and test specimen of interest. For accurate measurements, this is a very cumbersome procedure, in particular when several frequencies should be considered.

In contrast, suspension by means of magnetic bearings avoids mechanical contact and thus reduces the (undesired) external damping. Moreover, this configuration is a multi- frequency configuration in the sense that the damping may be measured at different frequencies without adjusting the suspension or anything else.

The AMB suspension set-up described in the following section is the result of a student's project [4].

3.2. EXPERIMENTAL SET-UP

ARRANGEMENT OF THE BEARINGS

The influence of the magnetic bearings on the longitudinal vibrations of the test specimen should be as insignificant as possible - *i.e.*, the damping in axial direction should be as small as

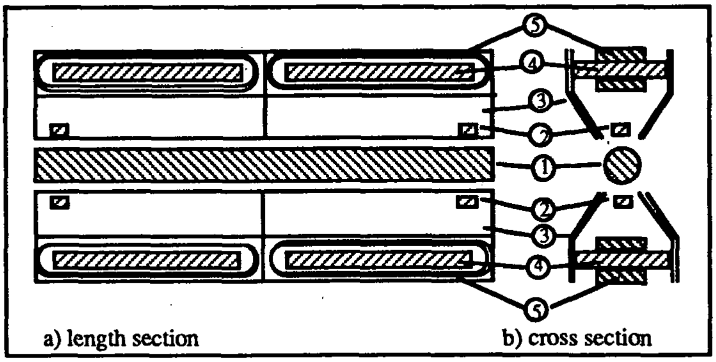

Fig. 3: Test stand
1: Test rod; 2: position sensors;3: magnetic poles; 4: coil core; 5:windings.
The main goal of the design was to provide a magnetic field that is homogeneous in the axial direction.

possible while simultaneously preserving stability. This is the only restriction on the dynamics of the AMB suspension system. For the lateral degrees of freedom, the only requirement is to preserve the stability. A set-up with two vertically oriented bearings was found to be sufficient for stable flotation; additional bearings for lateral stabilization are unnecessary. The two bearings are used to control the vertical position of both ends of the test rod. Single sided bearing control is sufficient. The two coils below serve for test purposes, cf. section 3.3.

The test stand is shown in Figure 3.

SHAPE OF THE BEARINGS, POSITION SENSORS

In AMB systems without axial control, eddy currents and hysteresis effects are the major sources of axial damping. They both occur when

a) the magnetic field in the test rod is changing with time, or

b) the test rod is moving in a magnetic field that is not homogeneous in the direction of the motion.

The former case will disturb damping measurements only if the change with time has strong frequency components at the resonance frequency of the rod considered. In the latter case, the energy for both eddy currents and hysteresis comes from the mechanical movement. This produces damping of the vibrational mode in all cases. Therefore, it is crucial that the magnetic field be homogeneous along the whole length of the test rod in the axial direction.

This has consequences for the design of the bearings as well as for the selection of position sensors. For bearings, the familiar AMB set-up with spatially concentrated magnetic coils is not suitable. Instead, the two coils must cover the whole length of the test specimen. As to the sensors, both eddy current and inductive position sensors produce magnetic fields. Therefore, reflective type optical sensors are used.

In order to cancel effects of lateral motions of the test rod on the control signal, two sensors are used for each bearing, above and below the specimen. The position signal is then obtained by a differential measurement.

FLEXIBILITY

The test stand is designed to operate with test rods of a diameter between 0.006 and 0.020 m and a length of 0.5 m. The nominal air gap varies between 1.5 and 0.5 mm. The magnetic poles are made of metal sheet and don't carry windings If necessary, they may be exchanged easily.

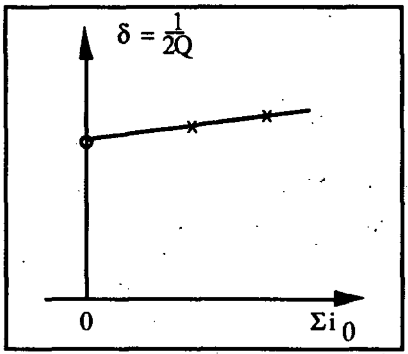

Fig 4: Estimating the damping caused by AMB suspension. 'x' denotes measured values of damping, 'o' the estimated "true" value. The independent variable Σi_0 of the plot above is the sum of the bias current of the upper, and the constant current in the lower coil. The lowest possible value is achieved when the lower magnets are turned off. The force exerted by the lower coils will cause the position controller to increase the mean current in the upper coils correspondingly.

3.3. DETERMINING THE IMPACT OF THE AMB SUSPENSION ON THE EXPERIMENTAL RESULT

It is of interest to know how much the AMB suspension influences the experiment and the quantity to be measured. As mentioned earlier, eddy current damping occurs where the magnetic field is not homogeneous in the direction of the vibrational motion. This phenomenon cannot be avoided at the end of the rod. In order to estimate the magnitude of this effect, the static load of the AMB can be increased artificially through two magnets placed below the rod. They are designed in the same way as the two carrying magnets, and their coils are connected to two constant current sources with equal currents. In this way, the flux density at the operational point can be increased, and the damping measurement can be carried out for different flux densities. As shown in Figure 4, it is then possible to separate material damping from eddy current damping by extrapolation.

We assume that the damping caused by the AMB suspension coils is proportional to their bias magnetic field and thereby to their bias current. This can be seen by assuming that a change in magnetic field strength preserves the shape of the flux lines. We further assume that if the fields from upper and lower coils are superimposed, the effects of inhomogeneities and thus the damping effects will be added, too. So we assume that the damping caused by AMB suspension will be proportional to the sum of bias currents in the upper and the lower coils.

3.4. CONTROL

The AMB suspension system is controlled by decentralized digital PD controllers. These were realized with a DSP board. The interface software running on the host PC enables the user to comfortably change control parameters on line and to easily reproduce all previous experimental conditions.

If the currents in the two upper bearing coils are different, there will be an inhomogeneity in the field at the transition from one bearing to the other. Therefore, it is important to keep variations of the coil currents small in the presence of disturbances. This is the criterion for the controller tuning, the selection of the sampling time and the design of the sensor filters.

The coil currents were used as control signals ("current control"). Better noise rejection could probably be obtained if the coil voltages were used as control signals ("voltage control", see [5]).

4. EXPERIMENTAL RESULTS

Measurements were made on a low carbon steel rod (Ck15, containing 0.15% C, 0.5% Mn, nominally, untreated) with length and diameter of 0.5 m and 0.01 m, respectively. The first 4 longitudinal modes of vibration were considered. The corresponding eigenfrequencies were 5.164, 10.324, 15.481 and 20.638 kHz. The maximum strain amplitude was *circa* 10^{-6}.

Three experimental conditions were examined. The rod was first supported in the middle on a styrofoam cube with a side length of 0.01 m. Then it was suspended magnetically with no additional current applied to the lower coils. In the final measurements, the current in the lower coils was set to 0.2 A, thereby increasing the magnetic field in the gap by about 50%. This was the maximum current that could be used. in this configuration.

The resulting quality factors are shown in Fig. 5. For mode 1, the quality factors coincide for all three experimental conditions at a value of about 25000. The magnetoelastic damping, one of the sources of intrinsic damping, therefore does not seem to be affected by the magnetic field of the suspension.

With the styrofoam support, the modes with even numbers are heavily damped, because the styrofoam piece is at an antinode of the vibration. This effect is completely eliminated when one uses the magnetic bearings (mode 2).

For higher mode numbers (n > 2) the quality factor seems to decrease by about 20% with frequency. This effect is probably due to increased stress in the attachment of the piezoelectric element and does not imply dependence of intrinsic damping on frequency.

5. CONCLUSIONS AND OUTLOOK

AMB suspension allows one to assess material damping of ferromagnetic materials. The influence of the supports on the measured value for the quality factor known from conventional experiments can then be eliminated. It was shown that the magnetic fields applied had only an unmeasurably small influence on the result of the damping measurement for the longitudinal vibrations. Further work will involve investigations on the behaviour of other types of modes (bending, torsion), hopefully making it possible to correlate values obtained in the various modes.

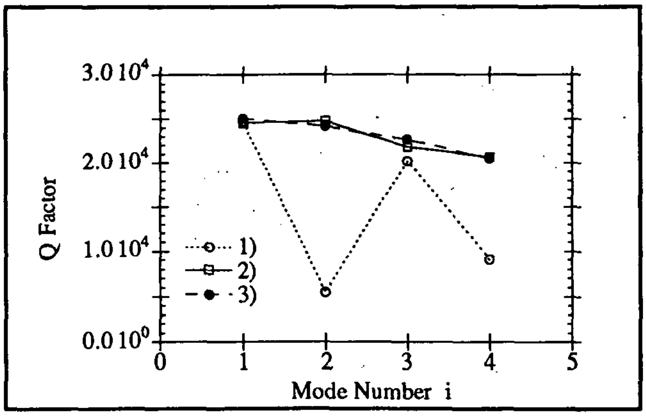

Fig. 5: Quality factors measured for 3 different test conditions:
1) Supported in the center using styrofoam

2) Supported with AMB and no current in the additional coils
3) Supported with AMB and a current of 0.2A in the additional coils

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