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N. I. Dreiman
Tecumseh Products Company

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Nelik Dreiman, Ph.D, Sr. Project Engineer. Tel.: 517/ 423 – 8582; FAX: 517/ 423 – 8426; E-mail: ndreiman@tecumseh.com. Tecumseh Products Company, 100 E. Patterson St., Tecumseh, MI 46286, USA;

ABSTRACT

The sound radiation efficiency of the tested cast iron and nodular (ductile) iron, forged iron and cast-iron samples have been characterized by the attenuation rate of the sound. It has been shown analytically that the attenuation rate of the sound affected by combination of such mechanical and physical parameters of a metal as internal friction Θ^{-1}, *yield stress* σ_0, *modulus of elasticity* **E**, *metal density* ρ, *Poisson's ratio* **μ**. *The correspondence between measured attenuation rate and those analytically predicted from tabulated metal properties is reasonable good, indicating that some sound radiation parameters can be tailored and predicted to a certain degree through proper selection of metals and metallurgical processing. Performed spectral analysis of the sound radiation of the medium alloy steel cylinder at elevated temperatures (100°C – 250°C) shows that the resonance frequency peaks have been shifted up to 300 Hz with increase of the temperature.*

NOMENCLATURE

a	: Sphere contact diameter	r_S	: Radius of sphere
B	: Sound transmission losses constant	**T**	: Absolute temperature
C_0	: Speed of sound in air	t_{60}	: Reverberation time
C_L	: Dilatational wave velocity	V_0	: Impact velocity
D	: Bending stiffness	α	: Metals compression during collision
E	: Modulus of elasticity	β	: Constant
F	: Applied point force	α_1, β_1	: Linear dimensions of the plate
f_n	: Natural frequency	γ	: Dimensionless frequency
h	: Thickness of the plate	ΔL	: Sound level change
H	: Sphere drop height	ΔQ	: Activating energy
I_d	: Acoustical efficiency coefficient	η	: Loss factor
L	: Cylinder length	μ	: Poisson's ratio
m, **n**	: Mode number	ρ_0	: Density of a material
m_P	: Mass of plate	ρ_S	: Density of sphere metal
P_D	: Sound radiation power	ρ	: Density of plate metal
Q^{-1}	: Metal internal friction	σ_0	: Yield stress
R	: Bolzman constant	Ψ	: Lowe radial dispersion factor
r_C	: Cylinder radius	ω	: Circular frequency

INTRODUCTION

Despite of wide use of plastic and composite materials for a machine structural components, metal still makes up a large portion of the average machine, especially in such parts as cylinder blocks, crankshafts, etc., and where combination of high strength at both normal and elevated temperatures are required. Analysis of sound radiation from solid bodies appears in works of Morse and Ingard [7], Skudrzyk [8], Cremer and Heckl [2]. Further studies of this were conducted by Koss and Alfredson [6], Dreiman [3], Endo [4]. The literature survey shows that the sound radiation parameters of a metal in relation to chemical composition, heat treatment and method of manufacturing have not been investigated, even though such study would make it possible to determine physical and mechanical properties of the construction metal satisfying the prescribed sound parameters of a mechanical system.

ANALYTICAL DEVELOPMENT

The sound power P_D radiated by thin metal plate excited by a point force of amplitude **F** is given by

$$P_D = [F^2/16\,(m_P D)^{0.5}]\; I_D\,, \qquad (1)$$

$$I_D = 4\beta\pi^{-1}\int t^2\,dt\,/\,\{[\beta/\gamma + \eta\,\gamma^2 t\,(1-t^2)]^2 + t^2\,[\gamma^2\,t\,(1-t^2)^2 - 1]^2\}$$

where $D = Eh^3 / 12(1-\mu^2)$; $\beta = \rho_0 c_0/\omega$ - constant; $\omega_C = c_0^2/(m_P D)^{0.5}$. $\gamma = \omega/\omega_C$.
The very important source of loss factor is damping properties of the structure. Principally, the sources of damping are the internal friction Q^{-1} of the metal, external (Coulomb) friction due to interfacial slip at joints, hydrodynamic (viscous) damping. When a solid vibrates in a gaseous medium and mechanical interfaces are eliminated, the predominating component causing the loss at audio frequencies is internal friction Q^{-1}. The sound radiation of the metal plate (considering internal friction losses only) at frequencies below critical P_{DL} after series expansion and integration of I_D function is

$$P_{DL} = P_0 / (1 - \gamma^3\;Q^{-1}/4\;\;\beta\pi) \text{ when } (\beta/\gamma)^2 \Box 1 \qquad (2)$$

We use δ - function transformation

$$\delta[\varphi(t)] = \pi^{-1}\lim_{\beta/\gamma\to 0}(\beta/\gamma)/[(\beta/\gamma)^2 + \varphi^2(t)]\,, \qquad (3)$$

to find sound power radiated by the plate with internal losses at the frequencies above the critical **($\gamma > 1$).**

$$P_{DH} = P_0\,\{\beta/[\;\beta + Q^{-1}\pi^{-1}\;(\sqrt{\gamma}\,(\gamma-1)]\}\,, \qquad (4)$$

where $P_0 = F^2/16\,(m_P D)^{0.5}$ represents sound power radiated by a metal plate with zero losses. Equations (2) and (3) indicate that value of the internal friction does not affect very much radiated sound in the low frequency range, but in high frequency range increase of the internal friction will reduce sound power peaks.
The sound radiation efficiency of a solid may also be characterized by attenuation rate **d** of the sound when the excitation of the system is removed, so that energy is no longer supplied to the system. In this case the rate of change in the sound pressure level per unit of time will be $d = \Delta L/t + B$, dB/s , where ΔL is change in sound level in dB, **t** is time in seconds, and **B** is a constant accounting for losses due to the environmental scattering, transmission to neighboring elements, and absorption at interfaces.
The dynamic response of the system components to impact-type forces can be considered as forced (acceleration noise) and free vibration (ringing noise). The sudden motion of the end surfaces during contact produces a sound pulse followed by the ringing noise. Duration of the sound pulse is equal to the impact force duration τ. Sound radiation due to free vibration following impact is very often dominant and a duration of the sound radiation (ringing) can be characterized by the reverberation time $t_{60} = 2.199 / f_n\;Q^{-1}$. The total duration of sound radiation from a vibrating component is equal to the sum of forced and free vibration time. In many analytical and experimental works the dynamic analysis of collision and its associated acoustic radiation was based on a scheme suggested by Hertz. However, strict application of the Hertz law to the causes of metallic bodies contact is very often limited. The simplest and most successful static relation known as the Mayer law which is applicable in such case may be described by the relation [5]:

$$F = \pi\sigma_0\,a^2 = 2\pi\sigma_0\,r_S\,\alpha = m_S\,(d^2\alpha/dt^2)$$

or

$$(d^2\alpha/dt^2) + (2\pi r_S\,\alpha\,\sigma_0)/m_S = 0 \qquad (5)$$

The maximum compression occurs at the time $\tau = (\pi/2)\,(m/2\pi r_S\,\sigma_0)^{1/2}$ which represents the entire duration of the contact. For plates thin relative to their lateral dimension and deformed to only small curvatures under impact load, an approximate theory has been developed corresponding to the simple one-dimensional behavior of the beam.
The natural frequency of the plate with free edges boundary conditions can be expressed as

$$f_{m1n} = C_0^2 / 2\pi \, [\, Eh^3 / 12m_p \,(1 - \mu^2)\,]^{1/2} \, [\,(m/\alpha_1)^2 + (n/\beta_1)^2\,] \qquad (6)$$

Taking into account sound radiation time ($t_{60} - \tau$), and natural frequency of the plate, we can estimate the attenuation rate of sound radiation for rectangular metal plate from the following equation:

$$d = \frac{60\,[\,(m/\alpha_1)^2 + (n/\beta_1)^2\,]\, Q^{-1} (\sigma_0 \, Eh^3 \, r_S)^{1/2}}{4.85\,[\sigma_0 \,(1 - \mu^2) m_P \,\rho\, r_s]^{1/2} - 0.35\,[\,(m/\alpha_1)^2 + (n_1/\beta_1)^2\,]\, Q^{-1} (\pi\, Eh^3 \, m_S)^{1/2}} + B \quad (7)$$

The attenuation rate of a plate sound radiation has been shown to be affected by the geometrical parameters of the plate, physical and mechanical properties of the metal. Alloying elements are incorporated in metal to improve physical and mechanical properties, to increase resistance to chemical attack, to influence other special properties such as magnetic permeability, neutron absorption, resistant to the continuous heat, etc. It is important for the noise control and nondestructive diagnostics purposes to study the effect of the microstructural changes as well as physical and mechanical properties of the metal on its sound radiation parameters.

In the case of longitudinal impact of a sphere on a finite elastic cylinder, the longitudinal natural frequency f_n of the cylinder in **n**-th vibrational mode is

$$f_n = n\, C_L \,/\, 2L , \qquad (8)$$

where $C_L = (E_1 / \rho_C)^{1/2} / (1 + n^2 \Psi^2)$ denotes dilatational wave velocity corrected for dispersion due to radial inertia, $\Psi = \pi \mu r_C / 2L$ is the Love radial dispersion correction factor, $n_1 = 1,2,3,...$ is the mode number for longitudinal vibrations. Taking into account total sound radiation time and natural frequency of the cylinder we can estimate the attenuation rate d_C of the cylinder's sound radiation from the equation below:

$$d_C = \frac{60\; n\; \eta\; (\sigma_0 \; E_1)^{1/2}}{2.199\sigma_0\rho_0 \,(4L^2 + \pi^2 n^2 \mu^2 r_C)^{1/2} - \mu\,\eta\,(2\pi\, r_S \rho_C E_1)^{1/2}} + B \qquad (9)$$

EXPERIMENTATION AND RESULTS.

A rectangular plate 50x50x4 mm in size have been made from two groups of cast irons and tested in the anechoic chamber. . Sound radiation was induced by the impact of the steel sphere. on the center part of the suspended sample. The position of the specimens and drop height **h** of the steel sphere were kept identical throughout the tests. Hence, the impact velocity ($V_O = 2gh$) and amplitude were assumed to have remained constant through the tests. The Hewlett-Packard Structural Dynamic analyzer 5423A has been used for the data collection and analysis. The first group the rectangular plates had different amount of carbon and constant concentration of silicon (1.95-2.1%), manganese (0.18-0.2%), and phosphorus (0.11-0.12%). The second group of rectangular samples had different amount of silicon with constant amount of carbon (2.7-2.9%), manganese(0.19-0.21%), and phosphorus(0.1-0.12%). The attenuation rate of sound is shown in Fig.1 for the first group and Fig.2 for the second group of cast irons . The investigated alloys demonstrated high level of the attenuation rate. This can be explained by the graphite inclusions and microplastic deformations in local volumes of the metallic matrix which affect mechanical and physical properties of cast iron. With increasing carbon and silicon concentrations the number and size of graphite inclusions grow, which increases also the damping factor . The sound attenuation rate of first group falls within limits of 40 to 98 dB/s. For the second group of cast irons the attenuation rate is within the limits 67-106dB/s.

Tested in the anechoic chamber cylindrical samples have the following dimensions: diameter D = 4 in. (0.102 m) and length L = 9 in. (0.229 m) .The chemical composition of the specimens is shown in the table below. Figure 3 shows the attenuation rate of sound for medium alloy steel, forged- iron and cast iron samples.

Material	**Chemical composition, %**								
	C	***Mn***	***P***	***S***	***Si***	***Ni***	***Cr***	***Mo***	***V***

Medium Alloy Steel	0.20	0.45	0.015	0.007	0.33	3.20	2.02	1.20	0.40
Forged Iron	3.50	0.80	-	-	2.10	3.00	-	0.05	-
Cast Iron	3.50	0.30	-	-	2.30	3.00	-	0.05	-

As you can see the choice of material can produce significant differences in the sound attenuation rate. The correspondence between measured rate and those predicted from tabulated properties of the metals is reasonable good, indicating that attenuation rate can be tailored and predicted to a certain degree through proper selection of metal and its metallurgical processing.

It is clear that the mechanical properties of the metals will be affected by variation of the temperature caused by change of the compressor operating conditions. The medium alloy steel cylinder (Sample 1) have been heated in the Thermolyne F-6025 furnace for study of the temperature effect on the radiated sound. A temperature stabilization time of approximately 16h have been allowed for the specimen between each temperature setting and following sound radiation test. All measurements were carried out at various temperatures ranging from room temperature to 250° C (480° F).

The spectral analysis of the sound radiation of the specimen at elevated temperature indicates highly dominant components at frequencies in the range of 7.6 kHz to 7.9 kHz. The typical distribution of the peaks in the frequency range 6 kHz to 8.5 kHz for the specimen heated to 115 ° C (239 F), 121.1°C (250° F), 164.4°C (328°F), 185°C(365° F), 235.6°C (456° F) , and , in comparison, the spectrum at room temperature 18° C (64.4° F) is shown in Fig.4. The shift of the resonance frequency for the investigated range of temperatures is shown in Fig.5. The peak of resonance frequency was shifted on 287 Hz (from 7887Hz to 7600Hz) when the temperature increased from 18° C (64.4° F) to 235.6°C (456° F).

The process responsible for the properties and structural changes are initiated by the activating energy ΔQ by which thermal agitation excites at an efficient rate when temperature of metal rise, a phenomena formally simulated by the Arrhenius law:

$$\textbf{rate} \;\infty\; \textbf{exp} (- \Delta Q / RT) \qquad (10)$$

where R is Bolzman constant, and T - absolute temperature. The shift of the resonance frequency with the temperature change could be calculated using a similar expression:

$$f(T) = \gamma f_n^{- \Delta Q / RT} \qquad (11)$$

The temperature dependence of the attenuation rate are shown in Fig 6 . Compared to its room temperature value (14.51 dB /s) , attenuation rate increases to a maximum - 27.16 dB /s at 115° C (239° F), decreases suddenly to minimum (10.33 dB /s) at 161° C (323° F). At higher temperatures of the specimen the sound attenuation rate are increased to 23.81 dB /s.

CONCLUSIONS

1. The attenuation of the sound radiated by the metal has been shown to be affected by the geometric dimensions of the sound radiation system, physical and mechanical properties of the metal. Controlling the chemical composition, heat treatment and mechanical working of the metal we can modify the physical and mechanical properties.
2. The experimental data show that elevated temperature caused resonance frequencies shift and also affected the value of the attenuation rate.
3. Recorded high attenuation of the sound in the temperature range 100° C - 130 °C is a result of internal friction peak which associated with the presence of interstitial carbon or nitrogen impurity atoms in cast iron (Snoek effect) [9].

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Fig.1 Sound Attenuation Rate. First cast iron group

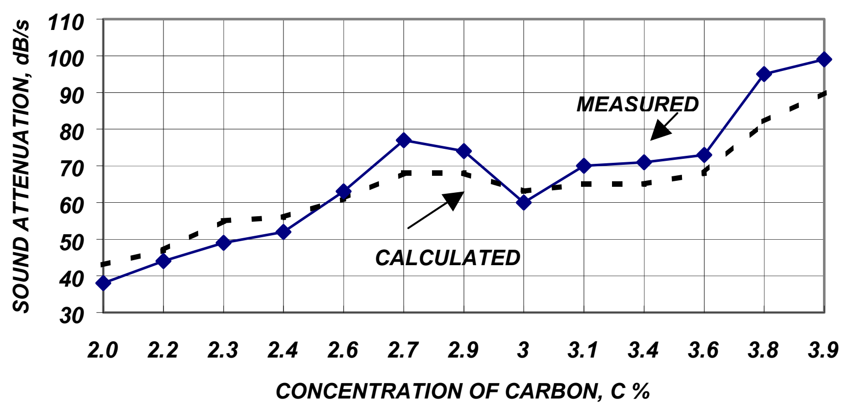

Fig.2. Sound Attenuation Rate. Second cast iron group.

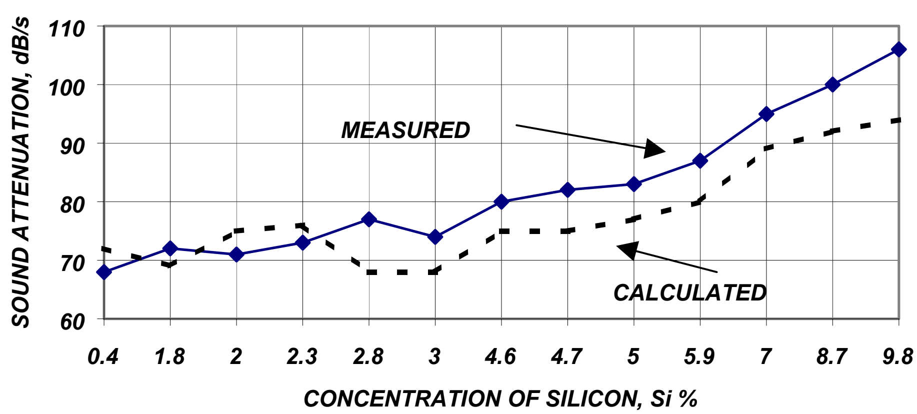

Fig.3 .SOUND ATTENUATION RATE OF MEDIUM ALLOY STEEL, FORGED IRON, AND CAST IRON

Fig.4. SHIFT OF THE FREQUENCY WITH THE TEMPERATURE

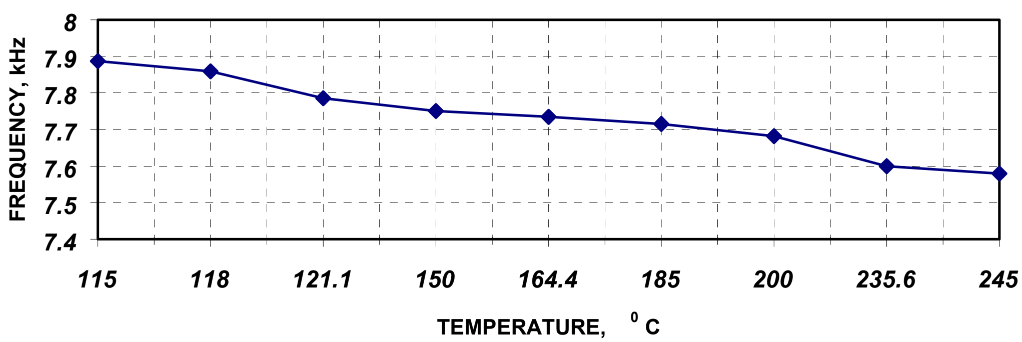

Fig.5. TEMPERATURE DEPENDENCE OF THE ATTENUATION RATE