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ACOUSTIC RADIATION OF FERROUS METAL WITH ALLOYING ELEMENTS

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Abstract

In the analytical and experimental work reported in this paper, sound radiation of the rectangular plates made from iron-chrome (Fe - Cr) and iron - manganese (Fe-Mn) alloys have been studied in some detail. The analytical study shows that the sound radiation efficiency of a metal depends upon geometry, external static and dynamic loads, boundary conditions, surrounding medium, physical and mechanical properties of the metal. The analysis of the experimental data indicated that the change of the chemical composition and corresponding alloys structural changes affected the attenuation rate of the sound radiated by the metal plates.

INTRODUCTION

Despite of wide use of plastic and composite materials for a compressor 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 $\mathbf{P}_{D}$ radiated by thin metal plate excited by a point force of amplitude **F** is given by

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

$$I_D = 4\beta\pi^{-1}\int_0^1 t^2\,dt \,/\, \{[\beta/\gamma + \eta\gamma^2 t(1-t^2)]^2 + t^2[\gamma^2\, t(1-t^2)^2 - 1]^2\} \qquad (1)$$

where m_P is the plate mass; $D = Eh^3/12(1-\mu^2)$ is bending stiffness, $\beta = \rho_0 c_0/\omega$ - constant; ρ_0 and c_0 are density and speed of sound in medium; η is loss factor; μ is Poisson's ratio; h is thickness of the plate; $\gamma = \omega/\omega_C$ is dimensionless frequency; I_D is the acoustical – mechanical efficiency coefficient; $\omega_C = c_0^2/(m_P D)^{0.5}$ is critical frequency. 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 after series expansion and integration of I_D function is

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

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 radiation 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

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

where **F** is the applied load, **a** is the contact diameter, m_S is the mass of the sphere , r_S is the radius of the sphere, σ_0 is the yield stress, and α is a compression. 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

$$f_{mln} = C_0^2 / 2\pi [Eh^3 / 12m_p (1 - \mu^2)]^{1/2} [(m/\alpha_l)^2 + (n / \beta)^2] \qquad (6)$$

where **(m)** and **(n)** is the mode number, **h** is the thickness of the plate, (α_l) and (β) are linear dimensions of the plate. 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:

$$d = \frac{60 [(m/\alpha_l)^2 + (n / \beta)^2] Q^{-1} (\sigma_0 Eh^3 r_s)^{1/2}}{4.85 [\sigma_0 (1 - \mu^2) m_p \rho r_s]^{1/2} - 0.35 [(m/\alpha_l)^2 + (n / \beta)^2] Q^{-1} (\pi Eh^3 m_s)^{1/2}} \qquad (7)$$

where ρ is the metal density. The attenuation rate of 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.

EXPERIMENTATION AND RESULTS.

. A rectangular plate 50x50x4 mm in size made from Iron-Chrome(**Fe-Cr**) and Iron-Manganese (**Fe-Mn**) alloys have been tested in anechoic chamber. The chemical composition of the specimens are shown in Table 1. During the test, the samples were horizontally suspended by thin steel cables to reduce losses of the vibration energy at contact points. Sound radiation was induced by the impact of the steel sphere 10mm dia.(4.5 g) on the center of the plate. 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. The Hewlett-Packard HP35670A analyzer has been used for the data collection and analysis.

Table 1

Sample I.D.#	*Cr, %*	*Sample I.D.#*	*Cr, %*	*Sample I.D.#*	*Mn, %*	*Sample I.D.#*	*Mn, %*
1	0.32	*10*	14.96	*24*	*0.43*	*33*	*2.20*
2	0.80	*11*	18.99	*25*	*0.71*	*34*	*2.90*
3	0.85	*12*	21.66	*26*	*0.87*	*35*	*4.80*
4	1.57	*13*	25.25	*27*	*1.02*	*36*	*9.92*
5	1.96	*14*	29.69	*28*	*1.26*	*37*	*12.35*
6	3.17	*15*	34.67	*29*	*1.42*	*39*	*28.30*
7	4.25	*16*	43.55	*30*	*1.59*	*40*	*39.68*
8	5.38	*17*	59.92	*31*	*1.65*	*41*	*52.01*
9	9.88			*32*	*1.68*	*42*	*58.56*

IRON-CHROME ALLOYS

Sensitivity of the physical and mechanical properties of the metals to the metal structure changes [1] indicates that the phase composition will affect the radiated sound. The spectra of sound radiation computed for samples #6 (3.17% **Cr**), #10 (14.96% **Cr**) and #11 (18.99% **Cr**), are illustrated in Figure 1. Maximum peaks for samples #6 (**Q^{-1}** $= 2.12 * 10^{-4}$) and #10(**Q^{-1}** $= 10.6 * 10^{-4}$) are located in the high frequency range. The sample #11 with relatively high internal friction (**Q^{-1}** $= 23.2 * 10^{-4}$) has higher level components in low frequency range. Figure 2 shows the attenuation rate of sound (1), duration of the ringing sound (2) radiated by plate, change of the internal friction **Q^{-1}** (3) , and phase boundaries of the **Fe-Cr** alloys with increase of chrome content.

The sound attenuation rate changed in the limits 23 dB/s to 90 dB/s with increase of the chrome content in the alloys. The sound attenuation rate of the alloys with up to 0.85%**Cr** is not more than 21 dB/s. When the percentage of chromium rises up to 20% **Cr** the carbides in the alloys remain in the martensitic form, which means that the alloys are permanently hard and brittle. The sound attenuation rises and reaches the maximum (90 dB/s) for the alloy with 18.99% **Cr** located on the boundary of single (**α - Fe**) phase and two- phase (**α - Fe + σ**) region of the structural diagram. The sound attenuation rate changed in the range 30 dB/s to 45 dB/s for the alloys with more than 21% **Cr**.

Sensitivity of the physical and mechanical properties of the metals to the metal structure changes [1] indicate that the phase composition will affect the radiated sound.
Figure 3 shows the attenuation rate of sound (1), duration of the ringing sound (2) radiated by plate, change of the internal friction Q^{-1} (3), and phase boundaries of the **Fe-Mn** alloys with increase of manganese content.
The sound attenuation rate changed in the limits 15 dB/s to 55 dB/s with increase of the manganese content in the alloys. The alloys with manganese below 2% show a microscopic structure of perlite and alpha ferrite on slow cooling in the air. For these alloys the attenuation rate changed from 15.1dB/s for the sample #29 (1.42% Mn) to 40Db/s for the sample #30 with 1.59% Mn. When content of the manganese increased above 2%, a martensitic structure appears. The attenuation rate decreases to 18 dB/s in passing boundary of single α - **Fe** phase and α -**Fe** +γ phase (sample #34, 2.9%Mn). The attenuation rate is particularly high (up to 54dB/s) in the α -**Fe**+γ phase region apparently due to the fact that the structural transformation occurring in **Fe-Mn** alloys rich in iron have substantial influence on the physical properties. In alloys with 10%-14% Mn the transformation of single α - **Fe** phase into α -**Fe**+γ phase and metastable ξ-phase is accompanied by an increase in the strength of the alloy. In alloys with more than 14% Mn the γ -phase is partially transformed into $\alpha + \gamma$ phase, resulting in low elasticity limit and high plasticity that holds the attenuation rate in range 19 dB/s to 30 dB/s.
The change of the sound attenuation follows the change of the internal friction with increase of the manganese in the alloy.

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 sample, physical and mechanical properties of the metal. The physical and mechanical properties can be modified by controlling the chemical composition, heat treatment and mechanical working of the metal.

2. The maximum attenuation rate for Iron – Chrome alloys has been observed at two phase (α - **Fe** + σ) of the **Fe –Cr** structural diagram .

3. The maximum attenuation rate for Iron-Manganese alloys have been observed at two phase (α - **Fe** + γ) region of the **Fe – Mn** structural diagram .

4. The variety of alloying elements added to the iron or steel to modify its physical and mechanical properties as well as heat treatment, and mechanical working of the metal should be investigated for noise-reduction potential and nondestructive diagnostics of machinery and metals.

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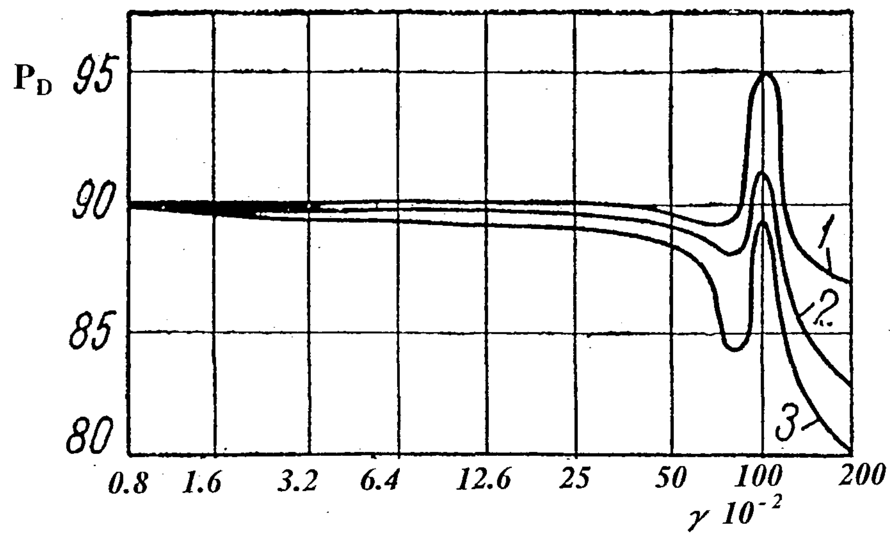

Fig.1 Sound radiation spectrum of plate made from Fe – Cr alloys: 1 – sample # 6 (3.17% Cr); 2 – sample #10 (14.96% Cr); 3 – sample # 11 (18.99% Cr).

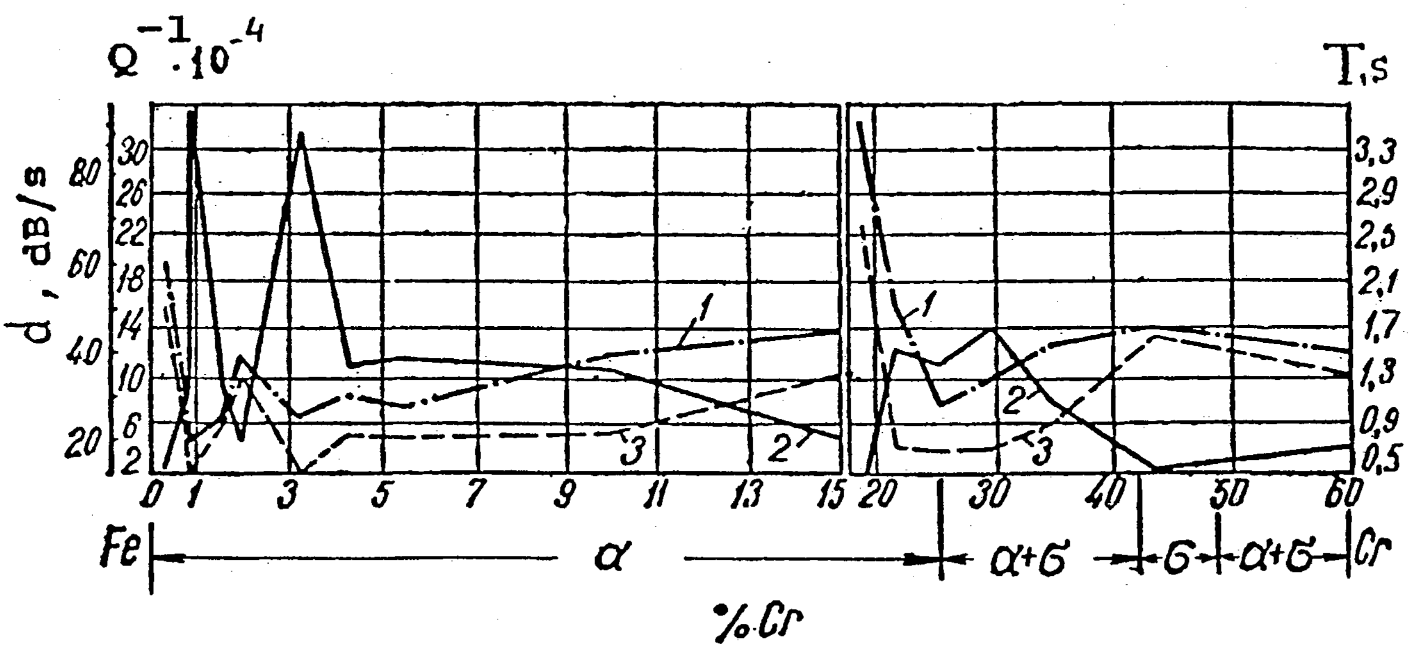

Fig. 2 Change in the rate of the sound attenuation (1), duration of the sound radiation (2), and internal friction (3) of the Iron – Crome alloys

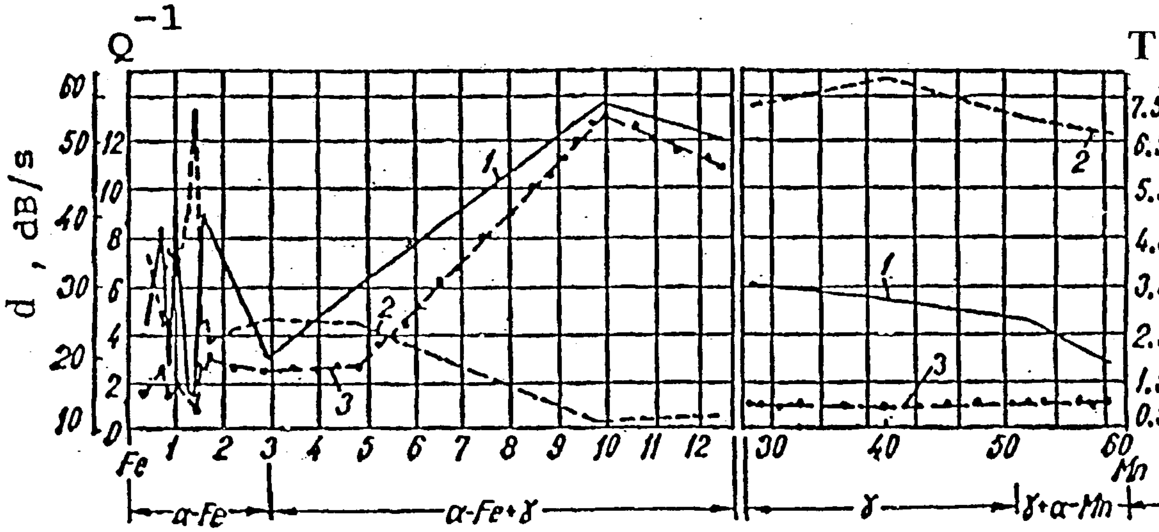

Fig. 3.Change in the rate of the sound attenuation (1), duration of the sound radiation (2) , and internal friction (3) of the Iron – Manganese alloys.