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ANALYSIS OF FRICTIONAL SOUND USING RADIATION EFFICIENCY

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Abstract

Whenever dry sliding occurs, frictional sound is generated. Past works focus on frictional vibration as the main cause of frictional sound, but no consideration is given to the sound radiation properties of the system under investigation. In this paper the use of the radiation efficiency is proposed as a simple method to quantitatively relate frictional sound, frictional vibration and the radiation properties of the system. The graphical representation of this relationship is a frictional sound map, which can be used to compare sounds generated in different systems and sliding conditions from viewpoints of frictional vibration and radiation efficiency.

Using this approach, three systems with friction elements of aluminium, brass and steel were studied. It was found that although the tribo-system with aluminium had the same sound power as the one with brass, aluminium generated higher frictional vibrations which were radiated less efficiently, compared to brass. The tribo-system with steel elements had the lowest sound power, because it generated lowest frictional vibrations, which were radiated with efficiency close to the efficiency of the brass tribo-system. The presence of a thin lubricant film reduced the friction induced vibrations of the tribo-system with brass, but did not affect the radiation efficiency.

INTRODUCTION

Whenever two surfaces slide against each other friction takes place, wear occurs and sound is generated. In most cases of interest to engineers this sound is not desired and is therefore termed 'noise'. Automotive brakes are a typical example of systems where high level of frictional noise is a problem. Brake noise has been extensively studied in the past [1-3], but still there is no commonly accepted explanation of its generation mechanism.

A few studies on the basic mechanism of frictional sound generation in model systems were conducted in the past [4-5]. They focused on the friction-induced vibrations, but the effect of sound radiation properties of the system under investigation on frictional sound was not considered.

In this paper the use of radiation efficiency is proposed as a simple method to relate quantitatively frictional sound, frictional vibration and the sound radiation properties of the system. The graphical representation of this method is a frictional sound map, which can be used to compare sound generated by different systems and under different sliding conditions. To illustrate the method several tests with three common engineering materials – aluminium, brass and steel have been conducted.

EXPERIMENTAL APPARATUS AND METHOD

Experimental Apparatus

The tests were conducted on a specially designed reciprocating tester (Fig.1). Frictional sound is generated by the contact of a pin with hemispherical tip (tip radius 4 mm) on a flat bar. The bar specimen is attached to a moving stage. The stage is moved by magnetic screws, rotated by a stepping motor. Magnetic screws allow for non-contact transmission of axial force, therefore reducing the noise levels generated by stage motion. The motor is located in a separate compartment with heavy walls covered with sound-absorbing material on the inner side. The motor base and its compartment are placed on a table top vibration isolator. The test chamber was designed with heavy walls to prevent noise entering from outside and sound-

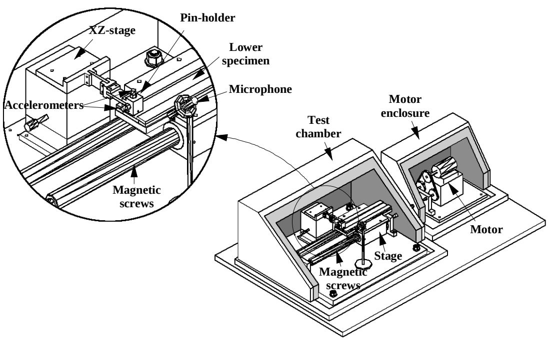

Figure 1. Experimental apparatus

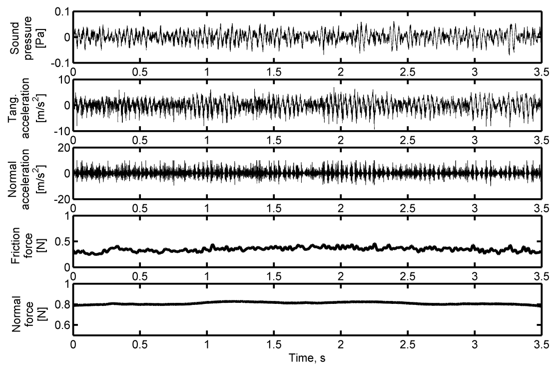

Figure 2. Example of acquired signals

absorbing material on the inside to reduce sound reflections and create free field conditions. Normal load is applied by the elastic deformation of a leaf spring when the XZ-stage is lowered down. Vibration is measured in tangential and normal direction by two B&K 4393 accelerometers mounted onto the pin-holder. The sound is measured by a B&K 4190 free-field microphone. It is placed at about 8 cm from the center of the pin-holder, its axis at an angle of about 45° to the direction of sliding and 45° to the plane of stage motion. Normal and tangential forces are measured by strain gauges on the leaf springs. The signals from the sensors are amplified and data is acquired into a notebook computer by a data acquisition card. An example of the acquired raw data is shown in Fig. 2.

Experimental Method

Three pins and three bars made of aluminium, brass and steel were used in the tests. The bars were all finished with emery paper with the same grain size, but had different surface roughness, although the average profile slope had similar values. All the pins were mirror polished and had similar surface roughness and profile slope. Tables 1 and 2 summarize the material properties and the roughness data for the bars and pins used.

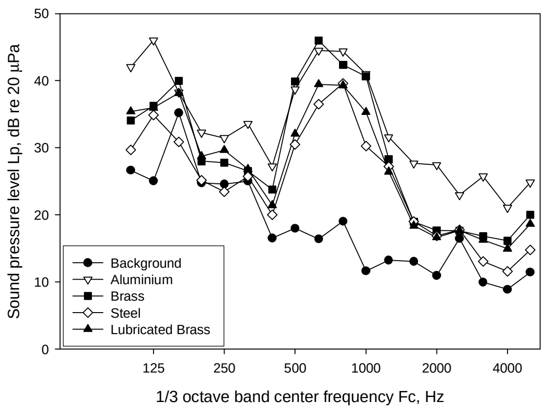

Figure 3. Frictional sound and background

At least three repetitions were done for each pin sliding against a bar made of the same material, under applied normal load 0.8 N and sliding speed 20 mm/s at room temperature and humidity. Before the tests, background noise generated by the stage motion at 20 mm/s was measured. Comparison of the 1/3 octave band frequency spectra of this background and the frictional sound generated in contact (Fig. 3) reveals that the frequency range in which the signal-to-noise ratio is highest is from about 0.5 to 2 kHz. In the further analysis only this frequency range is used when determining both sound and vibration averages. For the sound data correction for the background is applied.

Table 1. Material properties

Mat. Property	Alum.	Brass	Steel
Young's modulus, GPa	70	103	193
Density, g/cm^3	2.68	8.39	7.93
Hardness, RV	66	108	296
Poisson Ratio, ν	0.33	0.4	0.27

Table 2. Specimen surface properties

Spec.	Surface property	Alum.	Brass	Steel
Bar	Rq, µm	1.66	0.86	0.63
	Avg. Profile Slope	0.19	0.17	0.14
Pin	Rq, µm	0.04	0.06	0.03
	Avg. Profile Slope	0.03	0.03	0.02

Analysis Method – Radiation Efficiency for Frictional Sound Map

To evaluate the effect the system has on the generated sound it would be needed to relate frictional vibration and frictional sound. For sound radiated from a vibrating object the relation between mechanical vibration and radiated sound is given by the so-called radiation efficiency, σ, [6]:

$$\sigma = \frac{P_a}{\rho c S v_{rms}^2} \quad (1),$$

where :
P_a is the sound power radiated by the radiating object, W,
ρc - characteristic acoustic impedance of air, kg/(m^{2}s),
S – radiating area, m^2,
v_{rms} – the RMS velocity of the radiating surface, m/s.

The expression in the denominator of eq. (1) is the same as the sound power generated by a large rigid surface with area S, vibrating with a RMS velocity v. Radiation efficiency can be interpreted as the ratio of the sound power of the vibrating object to the sound power of such a surface, having the same radiation area and vibrating with the same RMS velocity.

As in the case of frictional vibration there are normal and tangential components v_n and v_t respectively, the velocity vector is:

$$\vec{v}(t) = \vec{v}_n(t) + \vec{v}_t(t) \quad (2),$$

and then the RMS velocity of frictional vibration is:

$$v_{rms} = \sqrt{v_{n_{rms}}^2 + v_{t_{rms}}^2} \quad (3).$$

For the denominator of eq. (1) we introduce the term *potential sound power* P_p and by taking into account eq. (2) and eq. (3) above it is given by:

$$P_p = \rho c S \left(v_{n_{rms}}^2 + v_{t_{rms}}^2 \right) \quad (4).$$

This quantity describes the potential of a frictional element with radiating area S, to radiate sound when vibrating with normal v_{nrms} and tangential v_{trms} RMS velocity.

In order to use eq. (4) some justified simplifying assumptions would be needed. The mass of the sliding stage with the attached bar specimen is many times higher than the mass of the pin-holder with pin. The vibration of the sliding stage is negligible compared to the pin-holder vibration. It is justified to assume that the sound is radiated from the pin-holder only. The largest dimension of the pin-holder, about 2 cm, is much smaller than the wavelength of a sound wave with frequency 2 kHz (the upper limit of the frequency range of interest), which is 17 cm. Thus it can be assumed that the pin-holder radiates as a simple point source in the frequency range of interest. The large top surface of the stage acts as a reflecting surface and doubles the radiated power. The radiating area of the pin-holder is the sum of the normal and the tangential cross-section area and in this case is 936 mm^2. The value of the RMS velocities can be easily obtained from the vibrations of the pin-holder after integration of the acceleration data.

The airborne sound power of the tribo-system can be calculated as the sound power of a simple source on a reflective surface is given by:

$$P_a = \frac{p_{rms}^2}{\rho c} 2\pi R^2 \quad (5),$$

where:
p_{rms} is the RMS of the measured sound pressure, Pa
R – the distance between the microphone and the center of the source, m.

Now eq. (1) can be rewritten as:

$$\sigma = \frac{\frac{p_{rms}^2}{\rho c} 2\pi R^2}{\rho c S\left(v_{n_{rms}}^2 + v_{t_{rms}}^2\right)} \quad (6),$$

or simply

$$\sigma = \frac{P_a}{P_p} \quad (7).$$

If the values of eq. (7) are expressed as levels, then the logarithmic radiation efficiency becomes:

$$10\log_{10}\sigma = L_{wa} - L_{wp} \quad (8),$$

where L_{wa} and L_{wp} are the airborne and the potential sound power levels.

RESULTS AND DISCUSSION

Results for the overall sound pressure and vibration levels in the frequency band 0.5 – 2 kHz are presented in Fig. 4 to Fig. 6. The sound pressure generated during sliding of aluminium pin on aluminium bar was the same as the sound pressure generated by the brass on brass combination and had a level of 49 dB. The frictional sound generated by steel on steel had a level of 42 dB, 7 dB lower than aluminium and brass. These frictional sounds were generated by normal and tangential vibrations with velocity levels shown in Fig. 5. The normal vibration velocity levels were higher than the tangential for steel and brass but lower for aluminium. Compared between materials, the vibration velocity levels were highest for aluminium, lower for brass and lowest

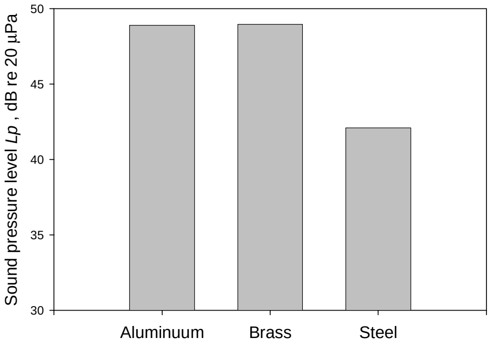

Figure 4. Overall (0.5 – 2 kHz) sound pressure levels.

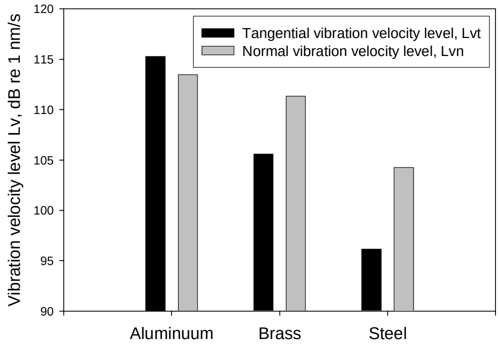

Figure 5. Overall (0.5 – 2 kHz) vibration velocity levels.

for steel, as seen from the combined vibration velocity levels plot (Fig.6). The combined velocity levels are obtained from the summed normal and tangential velocity RMS values as described in eq. (3), which is equivalent to adding the normal and tangential velocity levels. The combined velocity level is 117dB for Aluminium, 112 dB for brass and 105 dB for steel.

In order to explain these results and the effect the change of material has on the vibration generation and on the sound radiation properties of the system we will use the airborne and potential sound power defined earlier, and use eq. (7) and eq. (8) to calculate the radiation efficiency. A plot of the results is shown in Fig. 7.

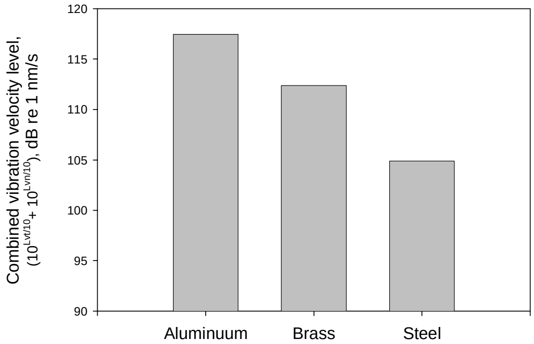

Figure 6. Combined normal and tangential vibration velocity levels.

The horizontal axis of this plot represents the potential sound power level, a quantity obtained from frictional vibration measurements. The vertical axis represents the airborne sound power level, obtained from frictional sound measurements. The inclined contour lines represent the logarithm of the ratio of the airborne to potential sound power, which is simply the difference of the respective levels. This ratio indicates how efficiently are frictional vibrations radiated as sound. To refer to this graphical representation of eq. (8) we will use the term 'frictional sound map'. Knowing any two of the three quantities related by the frictional sound map, the third one can be determined. This map can be used to evaluate quantitatively the contribution of frictional vibration and system's sound radiation properties (described by the radiation efficiency) on the measured frictional sound.

From the frictional sound map (Fig. 7) for tests with aluminium the tribo-system sound power was 34 dB, the potential sound power due to frictional vibration was 53

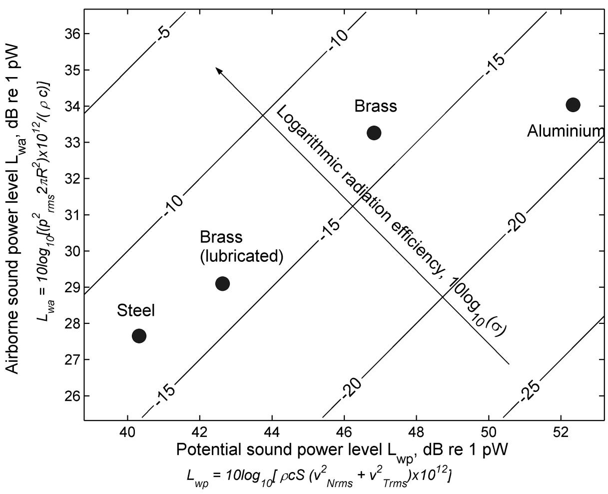

Figure 7. Frictional sound map

dB of which 17 dB did not become airborne in the process of sound radiation from the system.

The tribo-system with brass sliding pair had potential sound power of 46 dB, 7 dB lower than the tribo-system with aluminium. However, it radiated 5 dB more efficiently and as a result the sound power of a tribo-system with brass was approximately the same as the one with aluminium.

Tribo-system with steel specimens generated lowest potential sound power due to frictional vibration – 40 dB. It radiated sound just a little more efficiently than brass and as a result had the lowest sound power of all the three tribo-systems – 28 dB.

An interesting observation is that by using bars made of three different materials and finished with the same grain size emery paper, we observed that the largest change of potential sound power was 12 dB, while the largest difference in radiation efficiency was only about 5 dB. Whether this large difference of potential sound power was the effect of material or the effect of difference in the surface roughness should be the point of future inquiry.

From eq. (7, 8) and the frictional sound map it is obvious that reduction of the sound power radiated by the tribo-system can be achieved by either reducing the potential sound power (through the radiation area or through the frictional vibrations) or by reducing the radiation efficiency.

Because the differences of the potential sound power are larger than the radiation efficiency differences for the three materials, this suggests that reduction of the vibrations generated at the contact can be an effective approach to reducing the sound generated by aluminium or brass specimens.

Because brass is much more likely to be used as a material for a friction pair, it was attempted to reduce the vibrations generated at the contact by introducing lubricant at the contact. A thin lubricant film of grease was applied, which was then wiped away, so that boundary lubrication conditions could be obtained. In these conditions we measured: sound pressure level: 43.5 dB; vibration velocity levels - tangential 100 dB, normal – 105 dB, combined 107 dB. As a result of reduced frictional vibration, the potential sound power was reduced by about 4 dB. The airborne sound power was only about 2 dB higher than that of steel, while radiation efficiency of the system remained unchanged.

It can be seen that the radiation efficiency characterises the acoustic properties of the tribo-system and is independent of the surface condition. If we extend this result to surface roughness, we may speculate that if different the surface roughness would produce the same level of vibrations, a system with a frictional element of steel or brass would always be noisier than a system with frictional element made of aluminium.

CONCLUSIONS

1. A frictional sound map which relates quantitatively frictional sound, frictional vibration and the radiation efficiency of the tribo-system is proposed. The map can be used to explain quantitatively changes in frictional sound under different conditions by changes in frictional vibration and radiation efficiency.

From sliding tests with three mirror polished pins made of aluminium, brass and steel and three bars made of the same materials and surface finished with the same grain size emery paper it was found that:

2. The sound power of a tribo-system with aluminium frictional pair was almost equal to the sound power of one with brass friction pair, 33 – 34 dB re 1 pW, and was 5 -6 dB higher than the sound power of a system with steel frictional pair.
3. Friction-induced vibrations, measured by the combined normal and tangential velocity levels, were highest for aluminium – 117 dB (re 1 nm/s), lower for brass – 112 dB (re 1 nm/s), and lowest for a sliding pair of steel – 105 dB (re 1 nm/s).
4. The radiation efficiencies of tribo-systems with brass-on-brass and steel-on-steel frictional pairs were almost equal (-13.5 and -12.5 dB), and were 5 - 6 dB higher than the radiation efficiency of a tribo-system with aluminium sliding pair (-18 dB).
5. Introduction of a thin lubricant layer of grease in the case of brass frictional pair reduced the friction-induced vibration by 6 dB, measured by the combined normal and tangential vibration velocity levels. Also the sound power of the tribo-system was reduced by 4 dB, and was only 1.5 dB higher than the sound power of a system with steel sliding pair.
6. The radiation efficiency of the tribo-system was unaffected by the presence of a thin lubricant film.

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