A thermodynamics-like theory of annoyance

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A theory of annoyance is developed by supposing a psychological system of a man. Mathematical expressions of the psychological system are derived in a similar way of thermodynamics. An application of the theory to the community response of the bullet train noise is also performed.

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1. INTRODUCTION

How a man responds to a noise has long been studied by many authors, and is still an important subject to study. One of the difficult points to study it is that the psychological effects of a noise would be affected by the psychological state of the man who perceives the noise, so that we may not distinguish the only effects of the noise on the man.¹⁾

Annoyance is one of the subjects which have a problem of this kind.²⁾ That a noise makes a man annoyed does not always mean that the A-weighted sound pressure level (ASPL) of the noise is very high. One would sometimes feel annoyed even when the ASPL of a noise is low if he dislikes that kind of the noise and/or he does not like the man who operates the noise source. We should, therefore, estimate one's psychological tendency on the noise and/or the noise source to determine annoyance of a noise.

The purpose of this paper is to develop a systematic theory of annoyance by making use of the basic idea in thermodynamics.³⁾

2. EQUATION OF STATE

We will introduce new internal variables describing a supposed psychological system of a man: one is psychological strain (R), and the other is hate-ness (H) on a noise which forces the man to complain about the noise. Using R and H we define annoyance (A) by

$$f(H, R) = A. \quad (1)$$

Let's imagine a system in equilibrium state where R and H are stable, respectively, under a constant external stimulus of noise. In this system annoyance A takes a constant value by Eq. (1). We say that this system equilibrates with the external stimulus of noise. This system should have its own energy. We will call it psychological (or internal) energy. If we make the external stimulus of noise stronger a little, the annoyance A of this system would necessarily increase as the noise becomes stronger. Also the psychological energy of this system would increase a little. The increment of the psychological energy should cause R and/or H to increase. R should increase if H is fixed, and inversely H should increase if R is fixed. After a while the system would get to a new state characterized by A' , R' , and H' which equilibrates with a new external stimulus of noise. Then A' could be described by

$$f(H', R') = A'. \quad (2)$$

Now let's return to the previous state with H , R , and A expressed in Eq. (1). Differentiating Eq. (1) we get

$$dA = \left(\frac{\partial A}{\partial H} \right)_R dH + \left(\frac{\partial A}{\partial R} \right)_H dR. \quad (3)$$

The discussion after Eq. (1) means

$$(\partial A / \partial H)_R > 0, \quad (4)$$

$$(\partial A / \partial R)_H > 0. \quad (5)$$

Eqs. (3)~(5) show

$$(dH)(dR) < 0 \quad \text{for } dA = 0. \quad (6)$$

It would be, therefore, reasonable to assume

$$HR = g(A) \quad (7)$$

where $g(A)$ is a monotone increasing function.

Next we will consider to measure A . To do this we assume that $g(A)$ is a linear function of A . Then we could determine the value of A by

$$A = 100 \times \frac{HR - (HR)_{A=0}}{(HR)_{A=100} - (HR)_{A=0}} \quad (8)$$

where

$A = 0$: not annoyed at all,

$A = 100$: extremely annoyed.

To simplify the following discussion we put the condition

$$(HR)_{A=0} = 0. \quad (9)$$

Then Eq. (8) leads

$$HR = KA \quad (10)$$

where $K = (HR)_{A=100}/100$.

3. ENERGY CONSERVATION LAW

In the previous section we introduced a new variable: psychological (or internal) energy (E) of a psychological system. Let's imagine a psychological system surrounded by an external stimulus of noise. A small amount of increase of the external stimulus of noise would make the psychological energy increase as much as $d'Q$, and a small amount of work of the psychological system make the energy decrease as much as $d'W$. As a result the psychological energy changes as much as dE in total. Thus we get

$$dE = d'Q - d'W \quad (11)$$

where $d'Q$ ($d'W$) is not total differential but a very small amount of Q (W), while dE is total differential. We will define $d'W = HdR$ for the work of the psychological system to get

$$d'Q = dE + HdR. \quad (12)$$

4. NOISE CAPACITY

In the following we will regard annoyance A and psychological strain R as independent variables of a psychological system, so that we may define

$$H = H(A, R), \quad (13)$$

$$E = E(A, R). \quad (14)$$

Differentiating Eq. (14) we get

$$dE = \left(\frac{\partial E}{\partial A} \right)_R dA + \left(\frac{\partial E}{\partial R} \right)_A dR. \quad (15)$$

Substituting Eq. (15) in Eq. (12) we find

$$d'Q = \left(\frac{\partial E}{\partial A} \right)_R dA + \left\{ \left(\frac{\partial E}{\partial R} \right)_A + H \right\} dR. \quad (16)$$

We assume $(\partial E / \partial R)_A = 0$ in Eq. (16) to get

$$d'Q = \left(\frac{\partial E}{\partial A} \right)_R dA + HdR. \quad (17)$$

When $d'Q$ makes the annoyance A increase as much as dA , we can define noise capacity (C) of the psychological system by $C = d'Q/dA$. Thus from Eq. (17) we get

$$C = C_R + H \left(\frac{dR}{dA} \right)_{\text{process}} \quad (18)$$

where C_R is the noise capacity for the process with $dR = 0$, and is defined by $C_R = (d'Q/dA)_R$. Further if we keep H fixed for the process of the psychological system, we may define another kind of the noise capacity (C_H) for the process with $dH = 0$ by the expression

$$C_H = C_R + H \left(\frac{\partial R}{\partial A} \right)_H. \quad (19)$$

5. SOME USEFUL EXPRESSIONS

Differentiating Eq. (10) we have

$$HdR + RdH = KdA. \quad (20)$$

For the case $dH = 0$ Eq. (20) is reduced to

$$H(\partial R / \partial A)_H = K. \quad (21)$$

Eq. (19) together with Eq. (21) gives

$$C_H - C_R = K. \quad (22)$$

As K should be positive, Eq. (22) means $C_H/C_R > 1$.

Let's consider the case of $d'Q = 0$. For the case $d'Q = 0$ Eq. (17) becomes

$$C_R dA + HdR = 0. \quad (23)$$

Eqs. (21)~(23) make the relation

$$\frac{dH}{H} + \frac{C_H}{C_R} \frac{dR}{R} = 0. \quad (24)$$

By integrating Eq. (24) we find

$$HR^r = \text{const.} \quad (25)$$

where $\gamma = C_H/C_R$. Combining Eq. (10) with Eq. (25) we find other expressions

$$AR^{r-1} = \text{const.}, \quad (26)$$

$$AH^{(1-r)/r} = \text{const.} \quad (27)$$

where both of the constants of Eqs. (26) and (27) depend on K . We assume that both of K and γ are common to different psychological systems. Then, applying Eq. (27) to two different psychological systems, we have

$$\frac{A_1}{A_2} = \left(\frac{H_1}{H_2} \right)^{(r-1)/r}. \quad (28)$$

So far in this note we have developed a new theory of annoyance. The way to deduce the mathematical expressions in this note is very similar to the one of thermodynamics. There is, therefore, much correspondence in the mathematical form between thermodynamics and the present theory developed above. The correspondence is shown in

Appendix for the convenience of the reader.

6. APPLICATION

We apply Eq. (28) to the community response of the bullet train (or Shinkansen train) noise which was investigated by T. Sone *et al.*⁴⁾ in July of 1972 along the New Tokaido Line and the New Sanyo Line. Result of γ 's at 80 dB (A) and 75 dB (A) of the train noise is listed in Tables 1 and 2, respectively. Here we have regarded the positive rate of each item of their investigation as the expectation value of the psychological variable H of the theory presented above. The scores of the annoyance as well as other four items are originally listed in Table 3.11 of the publication by Sendai-shi which appears in Ref. 4). The numerical values of H_1 , H_2 , A_1 , and A_2 in Tables 1 and 2 of this note are quoted from the publication. However some of them are not the numbers quoted exactly but the ones calculated by interpolation or extrapolation based on the data available in the publication of Sendai-shi. Tables 1 and 2 show that the numerical values of γ 's of the item "Disturbance of hearing" are very different

Table 1 Numerical result of γ at 80 dB (A) of averaged peak level of the train noise from both tracks (Case I) or from near track (Case II). Suffices 1 and 2 of H indicate New Sanyo Line and New Tokaido Line, respectively. For Case I annoyance employed is $A_1 = 86.67$ and $A_2 = 70.00$, and for Case II $A_1 = 80.00$ and $A_2 = 60.00$.

Item	Case I			Case II		
	H_1	H_2	γ	H_1	H_2	γ
Interference with sleep	60.00	35.00	1.66	56.67	23.33	1.48
Disturbance of hearing	76.67	70.00	-0.74	70.00	55.00	-5.18
Disturbance of children's life	50.00	23.33	1.39	50.00	16.67	1.35
Startle	47.14	30.00	1.90	45.71	20.00	1.53

Table 2 Numerical result of γ at 75 dB (A) of averaged peak level of the train noise from both tracks (Case I) or from near track (Case II). Suffices 1 and 2 of H indicate New Sanyo Line and New Tokaido Line, respectively. For Case I annoyance employed is $A_1 = 70.00$ and $A_2 = 53.33$, and for Case II $A_1 = 63.33$ and $A_2 = 45.00$.

Item	Case I			Case II		
	H_1	H_2	γ	H_1	H_2	γ
Interference with sleep	40.00	15.00	1.38	40.00	—	—
Disturbance of hearing	60.00	46.67	-12.11	53.33	35.00	5.30
Disturbance of children's life	33.33	4.00	1.15	30.00	—	—
Startle	31.67	10.00	1.31	30.00	3.33	1.18

from those of the other items, on the contrary the numerical values of γ 's of the other three items are close to each other and agreeable to the restriction $\gamma > 1$. It would mean that the item "Disturbance of hearing" is far from expressing the psychological variable H of the theory developed in this note, while the other three items are favorable to express the variable H . Thus the theory has well explained the relation, in a unified manner with a common constant γ , between the annoyance and the other three items about the attitudes to the train noise investigated in two different communities.

7. SUMMARY

We have developed a thermodynamics-like theory of annoyance introducing a psychological system of a man in it. We have applied the theory to the community response of the bullet train noise. We have found that the theory would be plausible to explain the community response.

APPENDIX

The correspondence between thermodynamics and the present theory is as follows:

present theory	thermodynamics ³⁾
H	$\leftrightarrow P$ (pressure)
R	$\leftrightarrow v$ (volume)
A	$\leftrightarrow T$ (temperature)
K	$\leftrightarrow R$ (gas constant)
$HR = KA$	$\leftrightarrow pv = RT$ (equation of state)
E	$\leftrightarrow U$ (internal energy)
$d'w = HdR$	$\leftrightarrow d'w = pdv$ (work of a system to the outside)
$d'Q$	$\leftrightarrow d'Q$ (thermal energy from

the outside)

$d'Q = dE + HdR$	$\leftrightarrow d'Q = dU + pdv$ (first law of thermodynamics)
C_H	$\leftrightarrow C_p$ (specific heat at constant pressure)
C_R	$\leftrightarrow C_v$ (specific heat at constant volume)
$C_H - C_R = K$	$\leftrightarrow C_p - C_v = R$
γ	$\leftrightarrow \gamma$ (ratio of C_p to C_v)
$HR^\gamma = \text{const.}$	$\leftrightarrow pv^\gamma = \text{const.}$ (Poisson's law)
$AR^{\gamma-1} = \text{const.}$	$\leftrightarrow Tv^{\gamma-1} = \text{const.}$
$AH^{(1-\gamma)/\gamma} = \text{const.}$	$\leftrightarrow Tp^{(1-\gamma)/\gamma} = \text{const.}$
$A_1/A_2 = (H_1/H_2)^{(\gamma-1)/\gamma}$	$\leftrightarrow T_1/T_2 = (P_1/P_2)^{(\gamma-1)/\gamma}$

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