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A COMPARATIVE STUDY ON THE SOUND QUALITY OF WET-AND-DRY TYPE VACUUM CLEANERS

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Abstract : Sound quality of household appliances has become an important parameter in gaining the market advantage. The purpose of present study is to evaluate the sound quality of wet-and-dry type vacuum cleaners comparatively. For this purpose six different vacuum cleaners from different price ranges have been selected and the psycho-acoustical metrics have been evaluated by a sound quality software. Two of these products were from the pilot manufacturer's range: one was with and the other one was without sound quality work done on them respectively. Sound quality of these products were subjectively evaluated by a jury composed of sixteen people. Then the results of the jury test and the psycho-acoustical metrics were correlated by regression analysis. It has been shown that by conducting appropriate sound quality analysis on one of the products of the pilot manufacturer, the annoyance level of the product has been substantially decreased. The sound quality metrics included in this study were: Zwicker loudness, sharpness, fluctuation strength, roughness, tone-to-noise ratio and prominence ratio. Based on this analysis, two annoyance indexes were introduced for the wet-and-dry type vacuum cleaner noise. Thus, the manufacturer is provided by two useful scalar indexes which are function of metric values to assess the relative merit of his product`s sound quality without conducting extensive jury tests.

1. INTRODUCTION

Blauert and Jekosch defined product sound quality as "a descriptor of the adequacy of the sound attached to a product. It results from judgements being performed with reference to the set of those desired features of the product which are apparent to the users in their actual cognitive and emotional situation", [1]. Determination of product sound quality involves both subjective and objective measurements. Currently, the most popular approach defines sound quality of a product with an annoyance or specific index, [2]. Indexes are used to predict human annoyance to product noise and several indexes are defined for specific products and situations. There are some examples of these type of indexes, such as; AVL annoyance index for engine noise quality presented by Beidl and Stucklschwaiger, [3] and refrigerator noise annoyance model developed by May, Davies and Bolton, [4].

Household appliances which play an important role in our daily life should be functional and quiet with an acceptable sound quality. Vacuum cleaners are widely used household appliances and the most disturbing noise sources. Reduction of vacuum cleaner noise has become a main concern of manufacturers in order to comply with European Union directives, [5].

The objectives of present study on vacuum cleaners were; firstly, to assess the result of the sound quality work done on the pilot manufacturer's product by conducting a comparative study on similar units, secondly, to demonstrate whether an index for wet-and-dry type vacuum cleaner annoyance could be developed. The study consisted of four stages, in the first stage recording and the jury test were conducted simultaneously, in the second stage objective parameters were evaluated, in the third stage the correlation between subjective and objective parameters were established, finally two indexes were developed which to reflect the annoyance level for the wet and dry type vacuum cleaner noise.

2. JURY TEST - SUBJECTIVE EVALUATION

Firstly, for the psycological evaluation of the vacuum cleaner noise a number of adjective pairs were selected. In this context it is important to use appropriate terms for expressing the attributes of noise. The selected nine adjective pairs were:

- powerful vs. powerless
- acceptable vs. unacceptable
- booming vs. not booming
- bass vs. high pitched
- comfortable vs. disturbing
- loud-weak
- soft vs. hard
- harmonic vs. discordant
- regular-variable

The jury response was determined by the method of "direct uni-dimensional rating at equal intervals" with a 9 point scale. The method requires first a presentation of the whole range of possible stimuli and an instruction that the subject should use the full range of the scale by assigning the lowest rating to the lowest perceived magnitude of the attribute in question, and the highest rating to the highest perceived magnitude, [6].

Sixteen subjects with normal hearing abilities at an age between 17 and 40 years were selected to participate the jury. The jury test was made in a room which had a volume of 144 m^3 with walls treated by sound absorbing material. A screen was used between the jury members and the vacuum cleaners to hide the identity of the tested units. All units were operated under same conditons during the test. In the jury test a total of six units were used, two of them being identical vacuum cleaners of the pilot manufacturer,(C1 and C2) one was with and the other one was without sound quality work done on them respectively. The jury was asked to test seven different units, however, one unit was repeated twice to assess the reliability of the jury decision. At first, each sound was presented for a short period and a label was given. Then each unit was operated for three minutes and the jury was asked to make an assessment by giving an appropriate scale to that sound. The instruction for the jury was "You will be presented seven different vacuum cleaner's sound. Please listen carefully and select a descriptive number for each adjective pair by using the given scale". The sound of the arbitrarily selected vacuum cleaner, labelled as "B" was presented twice. During the jury test, sound pressure levels were recorded for further analysis.

The repeatability of the jury assessment for unit B is given in Figure 1. The stability of the jury decision seems to be acceptable indicating that the test procedure was sufficiently accurate to yield acceptable overall results.

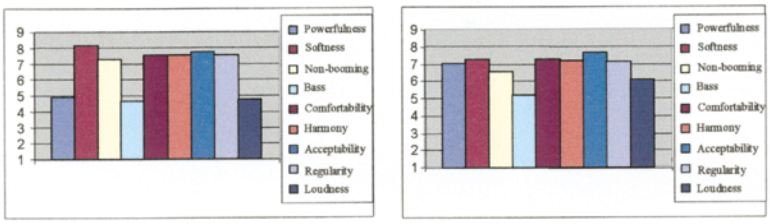

Figure 1. Repeatability of the jury assessment for unit B.

The analysis of the relationship between the attributes of vacuum cleaner noise indicate high correlation between accetability and softness, harmony, boomingness. This relationship is illustrated in Figure 2.

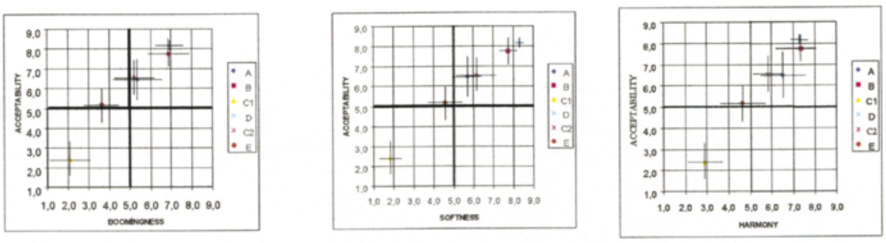

Figure 2. The relationship between acceptability and softness, harmony, boomingness

The results indicated that the jury attributes were the same for powerfulness and loudness, Figure 3. There was no clear distinction between these two attributes, therefore it may be more appropriate to combine these adjectives in the future jury tests for the vacuum cleaners. Similar findings were reported by Kuwano and his friends where loudness and powerfulness produced the same feeling in a cross cultuaral study, [7].

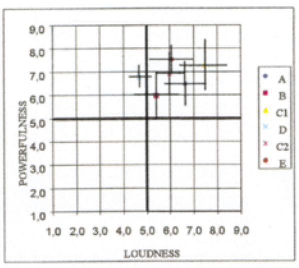

Figure 3. The relationship between powerfulness and loudness.

Based on the results of the statistical evaluation of the jury scores, a "perceived annoyance factor" is proposed. Perceived annoyance factor is inversely proportional with vacuum cleaner's sound quality as expected. Perceived annoyance factor for the six tested units is given in Figure 4.

From results of the subjective evaluation, six vacuum cleaners were divided into three categories for sound quality. These three groups are,

- group 1 vacuum cleaners B and D, "good sound quality"
- group 2 vacuum cleaners C2 and A, "satisfactory sound quality"
- group 3 vacuum cleaners E and C1, "bad sound quality".

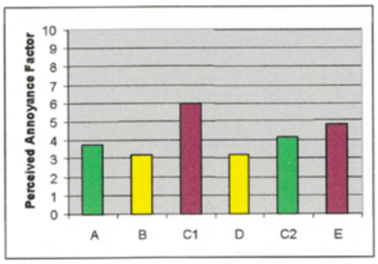

Figure 4. The proposed perceived annoyance factor for the six vacuum cleaners.

Six different vacuum cleaners were selected from different price ranges. Vacuum cleaner prices were normalized based on the price of unit C1. The relative price factors for all the units are; A (0.97), B (1.65), C1 (1.0), C2 (1.05), D (1.23) and E (1.0). As can be seen from Figure 5, through relatively small invesment per unit on sound quality the annoyance factor of C1 is substantially decreased.

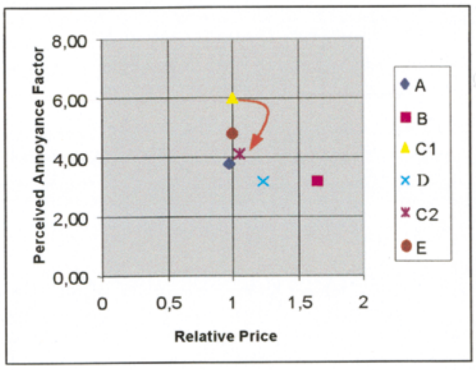

Figure 5. Relative price factor versus annoyance factor.

3. SOUND QUALITY METRICS

During the jury test, vacuum cleaner's 1/3 octave band sound pressure level was measured by a Brüel&Kjaer Type 3548 sound intensity probe and analyzed by B&K Type 2144 analyzer. At the same time vacuum cleaner sounds were recorded using a 1/4 inch condenser microphone on a DAT-Tape. The recordings were then transferred to a PC and objective metrics were determined by using Brüel&Kjaer Type 7698 Sound Quality Software. The sound quality metrics included in the studies were; Zwicker loudness, sharpness, fluctuation strength, roughness, tone-to-noise ratio and prominence ratio. Loudness was calculated according to Zwicker Method described in ISO 532 B, [8] and sharpness values were analyzed based on Aures Method, [9]. Results of the sound quality metrics are tabulated in Table 1.

Table 1. Results of the Sound Quality Metrics

Labels of tested units	Zwicker Loudness [Sone]	Sharpness (Aures) [Acum]	Roughness [Asper]	Fluctuation Strength [Vacil]	Tone-to-Noise Ratio	Prominence Ratio
A	18.9	4.49	0.484	1.63	3.98	10.5
B	15.1	4.08	0.497	1.68	2.08	4.74
C1	29.1	4.94	0.407	1.27	27.4	23.7
D	15.8	4.28	0.482	1.63	3.16	2.4
C2	17.6	4.31	0.511	1.89	13.3	7.16
E	18.5	4.39	0.563	1.64	3.99	1.23

4. CORRELATION BETWEEN SUBJECTIVE AND OBJECTIVE PARAMETERS

In order to establish a link between the sound quality metrics and the perceived annoyance factor regression analysis was performed. The amount of variation in the perceived annoyance factor due to sound quality metrics is given by R^2 statistical value. R^2 values for the "perceived annoyance factor" versus loudness, sharpness, fluctuation strength, roughness, tone-to-noise ratio and prominence ratio are given in Table 2.

Table 2. R^2 values for the perceived annoyance factor in terms of the Sound Quality Metrics

Sound Quality Metric	R^2 values
loudness	0,85
sharpness	0,78
fluctuation strength	0,45
roughness	0,15
tone-to-noise ratio	0,70
prominence ratio	0,53

5. DEVELOPMENT OF THE ANNOYANCE INDEXES

In general manufacturers try to predict the acceptability of their newly developed products in the market. Any useful information that would yield the sound quality of their appliance as a simple scalar quantity, merely by introducing the metrics without conducting a jury test, would decrease their product development cycle. Based on the jury tests and the evaluation of the sound quality metrics it may be possible to introduce an annoyance index for wet-and-dry type vacuum cleaners with an electrical power rating around 1500 W.

Annoyance index can be expressed as a linear combination of sound quality metrics and annoyence index coefficients in the form of equation (1),

$$AI = \sum a_j Q_j \qquad (1)$$

In order to obtain the annoyance index coefficients, following equation has to be solved,

$$\sum Q_{ij} a_j = P_i \quad (i=1,6, j=1,6) \qquad (2)$$

where Q_{ij} = j^{th} Sound Quality Metric for the i^{th} vacuum cleaner,

a_j = j^{th} annoyence index coefficient,

a_1 = loudness coefficient,
a_2 = sharpness coefficient,
a_3 = roughness coefficient,
a_4 = fluctuation strength coefficient,
a_5 = tone-to-noise ratio coefficient,
a_6 = prominence ratio coefficient,

P_i = percieved annoyence factor for i^{th} vacuum cleaner.

Once equation (2) is solved with the values obtained during the test, the annoyance index (AI) can then be expressed as follows:

$$AI = 0.655\ Q_1 - 2.618\ Q_2 + 0.047\ Q_3 + 2.708\ Q_4 - 0.04\ Q_5 - 0.105\ Q_6 \qquad (3)$$

The two sound quality parameters, namely; tone-to-noise ratio and prominence ratio are not that frequently used but on the other hand very useful parameters. They are included in the sound quality software of Brüel and Kjær. By excluding these parameters in the analysis, a second annoyance index in terms of widely used metrics is obtained. The annoyance index equation for the second approach is given by equation (4).

$$AI^* = 0.1\ [Q_1 + Q_2 + 15\ Q_3 + 5\ Q_4] \qquad (4)$$

Comparison of calculated and the measured metrics also yields a high R^2 value of 0.937, Figure 6.

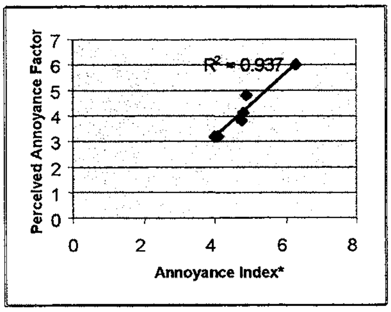

Figure 6. Variation of the Perceived Annoyance Factor with the second annoyance index.

6. CONCLUSIONS AND RECOMMENDATIONS

The major objectives of this investigation were twofold; firstly, to determine whether the sound quality work done on the pilot manufacurer's product was successful, secondly, whether it was possible to introduce an annoyance index that would provide guidance and decrease the product development time for wet-and-dry type vacuum cleaners for the manufacturer. In both objectives positive results were obtained, however, since the units provided by the pilot manufacturer were already designed and already in production all the suggested modifactions could not have been implemented. It is imperatively important to apply the well known "Product Sound Quality Wheel" principle at the design stage in order to come up with the silent product or to achieve the target sound.

Some of the major findings in this study can be summarized as follows:

- Annoyance index is directly affected by Zwicker loudness and increases with loudness, $R^2 = 0.85$. Loudness values vary between 15.1 and 29.1 Sone.
- Sharpness also affects the annoyance index but not as much as loudness, $R^2 = 0.78$. The spread of sharpness values vary between 4.08 and 4.94 Acum.
- Prominence ratio and tone-to-noise ratio both affect the annoyence index with R^2 values being 0.53 and 0.70 respectively.
- Roughness values of all the units are very close to one another (5.18-5.25), no meaningful relationship is observed between the annoyance index and roughness, $R^2 = 0.15$.
- Similar to roughness fluctuation strength values do not have meaningful relationship with annoyance index with an R^2 of 0.45.
- It appears that soft, harmonious and non-booming sound has high acceptability for a vacuum cleaner.
- The sound quality improvement achieved on the unit C2 can be observed in Figure 5. At a moderately low cost the improvement achived in the percieved annoyance factor is quite satisfactory.
- Finally two annoyance indexes are proposed for wet-and-dry type vacuum cleaners first one includes all the metrics while the second index includes loudness, sharpness, fluctuation strength and roughness.
- For the high quality sound the target annoyance index should be below 4.0.
- Manufacturers may use such indexes and can decrease the product design cycle by minimizing extensive jury tests.

The results obtained in this study are valid for a particular class of vacuum cleaners. Cultural differences and tolerances against noise should also be taken into account. Results obtained in one culture may contradict with the results of another culture. The connotative meaning of the concepts of "loudness", "noisiness" and "annoyance" should be normalized by using semantic differentials in different countries. Finally, the results obtained in this study can be further improved by using a sound quality head and torso simulator and a sound quality conditioning amplifier. Increasing the number of brands used in the tests is expected to improve the annoyance index.

7. ACKNOWLEDGMENTS

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