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SOUND QUALITY IN WASHING MACHINES

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Abstract
Sound quality has become an important factor in gaining market advantage especially in household appliances. In the present study; the sound quality of different washing machines are determined by constructing a mathematical model through the relationship between objective and subjective aspects of sound quality. This relationship is then extended to include the key design parameters. Eight different washing machine models are selected and psycho-acoustic metrics are determined using sound quality software. This data is then processed by principal components analysis and reduced to a fewer number of variables which still can describe the quality of the sound. Meanwhile, a jury test is conducted with twelve jurors to determine the subjective ratings of the sounds. Then the objective metrics are correlated with the subjective jury tests by linear regression technique to obtain a mathematical model. Graphical methods are used to demonstrate suitable characteristics of sounds that correspond to working stages such as “water intake”, “washing” and “spin extraction” as perceived by the jurors. Finally, the effect of a key design parameter on the sound quality is investigated by using dampers with different characteristics on the same washing machine. The recorded sound samples are processed by our mathematical model to obtain the influence of design modifications on the subjective and objective parameters of sound.

Keywords: Sound quality, psychoacoustics, metrics, jury test, principal components analysis

1 Introduction

Sound quality is “a descriptor of the adequacy of the sound attached to a product” as defined by Blauert and Jekosch [1]. The aim of a sound quality study is to obtain the information about the human perception of a specific sound, by performing series of numerical calculations on the recording of that sound. In order to achieve this, subjective and objective tests are made, and a mathematical model is derived to represent the correlation between objective and subjective properties of the sound. Sound quality metrics are calculated in order to represent the subjective properties of a specific sound. Out of these metrics, “loudness” defined by Zwicker is standardized [2]. The standardization for the others is still in progress. The listening tests performed to obtain the properties relevant to the human perception of a sound are called “jury tests” or “listening tests”. In the sound quality study performed by Sobhi [3] on the washing machine motors and hairdryers, the subjective sound quality metrics and objective jury tests are correlated with each other by the help of linear regression and a mathematical model is obtained. Altınsoy, Kanca and Belek [4] developed an annoyance index for dry and wet vacuum cleaners by correlating the objective and subjective tests by linear regression. Lyon [5] obtained acoustical sensory profiles from an expert jury test by using the descriptors of sound, used principal components analysis to reduce the dimensions of the acoustical sensory profiles and correlated these results with sound quality metrics, and made a linear transformation between the sound quality rating by the consumer jury and the acoustical sensory profiles in order to obtain the sound quality mathematical model. In their sound quality study on hairdryers, Türkdoğru and Belek [6,7] used principal components analysis and neural networks to obtain a sound quality mathematical model. In the sound quality study performed by Bowen [8] on field maintenance equipment, metrics profile is obtained by principal components analysis and then regressed with the subjective tests.

The objectives of the present study on washing machines is to obtain a mathematical model that will be used to predict the sound quality of the washing machines in “water intake”, “washing” and “spin extraction” operation phases. The study consists of four stages; in the first stage the sound recordings are made and the objective metrics are calculated, in the second stage jury tests are made and the subjective data is evaluated, in the third stage the objective and subjective data are regressed to obtain a mathematical model. Finally, effects of a design parameter, the “amount of damping” on the sound quality are investigated.

2 Sound quality metrics

Eight different washing machines are selected for the test and labeled as A to H. The machines are loaded with standard clothes and the “60^{o} cotton” washing program is used. The binaural sound recordings are made during the full washing cycle by using B&K 4100 Head & Torso Simulator and B&K Pulse Multichannel Analyzer in a chamber with similar acoustic properties like a bathroom. Out of these binaural recordings, samples of 5 second duration that represent the corresponding phases are transferred to B&K Sound Quality (SQ) software for the evaluation of the metrics.

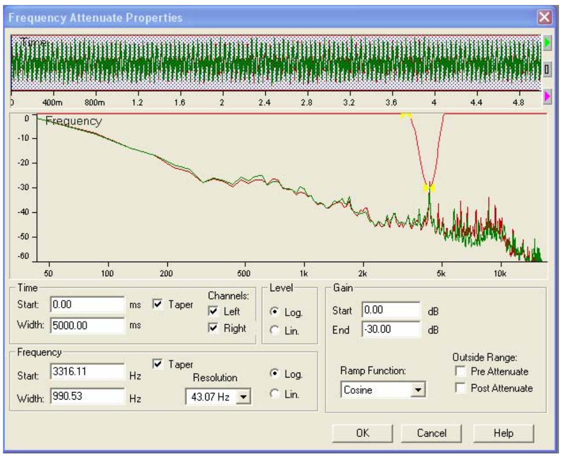

Figure 1 – Frequency attenuate function.

In the SQ software, the sound that belongs to the spin extraction phase of machine C is analyzed and it is noted that there is a dominant pure tone in 4.3 kHz. An additional edited sound "I" is created by attenuating this component by the "frequency attenuate" function of the SQ software as seen in Figure 1.

The calculated metrics are: Zwicker Loudness; Fluctuation Strength; Roughness; Tone-to-noise Ratio; Prominance Ratio; Statistical Loudness (N1, N2, N3, mean); Statistical Instantaneous Loudness (N1, N2, N3, mean); Zwicker Sharpness (N1, N2, N3, mean); Aures Sharpness (N1, N2, N3, mean), where N1=1%, N2=50%, N3=99%.

	Col 1	Col 2	Col 3	Col 4	Col 5	Col 6	Col 7	Col 8	Col 9	Col 10	Col 11	Col 12	Col 13	Col 14	Col 15	Col 16	Col 17	Col 18	Col 19	Col 20	Col 21
Col 1		0.001	0.168	0.101	0.002	0.996	0.999	0.996	0.958	0.998	0.994	0.999	0.873	0.506	0.441	0.517	0.566	0.330	0.188	0.344	0.400
Col 2	0.001		0.609	0.147	0.124	0.008	0.001	0.008	0.049	0.006	0.000	0.002	0.122	0.011	0.001	0.012	0.028	0.050	0.006	0.053	0.101
Col 3	0.168	0.609		0.240	0.290	0.134	0.186	0.135	0.055	0.141	0.219	0.162	0.008	0.095	0.034	0.103	0.163	0.109	0.007	0.118	0.219
Col 4	0.101	0.147	0.240		0.434	0.122	0.083	0.121	0.191	0.117	0.064	0.105	0.266	0.003	0.015	0.003	0.000	0.003	0.002	0.003	0.011
Col 5	0.002	0.124	0.290	0.434		0.000	0.006	0.000	0.006	0.000	0.009	0.001	0.032	0.049	0.023	0.052	0.071	0.077	0.027	0.077	0.118
Col 6	0.996	0.008	0.134	0.122	0.000		0.993	1.000	0.977	1.000	0.985	0.997	0.907	0.481	0.423	0.491	0.535	0.301	0.173	0.314	0.362
Col 7	0.999	0.001	0.186	0.083	0.006	0.993		0.993	0.949	0.995	0.998	0.998	0.858	0.512	0.442	0.523	0.574	0.336	0.189	0.350	0.409
Col 8	0.996	0.008	0.135	0.121	0.000	1.000	0.993		0.976	1.000	0.985	0.998	0.907	0.485	0.426	0.495	0.538	0.305	0.176	0.318	0.365
Col 9	0.958	0.049	0.055	0.191	0.006	0.977	0.949	0.976		0.973	0.928	0.960	0.974	0.411	0.374	0.419	0.448	0.232	0.141	0.242	0.270
Col 10	0.998	0.006	0.141	0.117	0.000	1.000	0.995	1.000	0.973		0.988	0.999	0.901	0.496	0.436	0.506	0.550	0.316	0.184	0.329	0.378
Col 11	0.994	0.000	0.219	0.064	0.009	0.985	0.998	0.985	0.928	0.988		0.993	0.829	0.523	0.447	0.535	0.591	0.351	0.193	0.366	0.431
Col 12	0.999	0.002	0.162	0.105	0.001	0.997	0.998	0.998	0.960	0.999	0.993		0.880	0.515	0.451	0.526	0.573	0.336	0.196	0.350	0.403
Col 13	0.873	0.122	0.008	0.266	0.032	0.907	0.858	0.907	0.974	0.901	0.829	0.880		0.350	0.334	0.356	0.368	0.177	0.121	0.186	0.193
Col 14	0.506	0.011	0.095	0.003	0.049	0.481	0.512	0.485	0.411	0.496	0.523	0.515	0.350		0.983	1.000	0.988	0.959	0.872	0.963	0.943
Col 15	0.441	0.001	0.034	0.015	0.023	0.423	0.442	0.426	0.374	0.436	0.447	0.451	0.334	0.983		0.978	0.943	0.946	0.923	0.946	0.892
Col 16	0.517	0.012	0.103	0.003	0.052	0.491	0.523	0.495	0.419	0.506	0.535	0.526	0.356	1.000	0.978		0.991	0.957	0.862	0.961	0.945
Col 17	0.566	0.028	0.163	0.000	0.071	0.535	0.574	0.538	0.448	0.550	0.591	0.573	0.368	0.988	0.943	0.991		0.941	0.802	0.948	0.958
Col 18	0.330	0.050	0.109	0.003	0.077	0.301	0.336	0.305	0.232	0.316	0.351	0.336	0.177	0.959	0.946	0.957	0.941		0.931	1.000	0.975
Col 19	0.188	0.006	0.007	0.002	0.027	0.173	0.189	0.176	0.141	0.184	0.193	0.196	0.121	0.872	0.923	0.862	0.802	0.931		0.922	0.831
Col 20	0.344	0.053	0.118	0.003	0.077	0.314	0.350	0.318	0.242	0.329	0.366	0.350	0.186	0.963	0.946	0.961	0.948	1.000	0.922		0.979
Col 21	0.400	0.101	0.219	0.011	0.118	0.362	0.409	0.365	0.270	0.378	0.431	0.403	0.193	0.943	0.892	0.945	0.958	0.975	0.831	0.979	

Figure 2 – Metrics correlation matrix (Pearson, R).

Molegro Data Modeller software is used to calculate the correlation matrix. The correlation matrix of the calculated 21 metrics (including the statistical figures) for the spin extraction phase are shown in Figure 2. The dark color boxes represent the higher correlations. The dark rectangular block in the middle represents the metrics related to loudness, and the one in the bottom right hand side represents the metrics related to sharpness. With the help of this figure, it is possible to reduce the number of metrics to be used by taking into account only one representative metric from each of the group of metrics with high correlation. In the scope of the present study loudness, roughness, sharpness and fluctuation strength will be used as primary metrics.

3 Listening tests

3.1 Methodology

The listening tests are performed by using two different methods. For water intake, washing and spin extraction phases, "semantic differential" method is used. However, for the spin extraction phase "paired comparison" method is also used as this phase plays a dominant role in the overall assessment of washing machine sound quality.

3.1.1 Paired comparison test

The paired comparison method involves sequentially listening the sound samples in pairs and rating the most preferred one in the pair. If there are n sounds, there are n(n-1)/2 pairs. There are total of 9 sound samples for the spin extraction phase (recordings of 8 machines and 1 edited sound). 9(9-1)/2=36 pairs are judged by the jury.

3.1.2 Semantic differential test

In semantic differential test, the juror is asked to judge a specific attribute of the sound using a rating scale. The lowest rating of the scale is the lowest perceived magnitude of the attribute, and highest rating is the highest perceived magnitude. The descriptors of sound that can match with the attributes of each working stage of the washing machine are listed in Table 1.

Table 1 – Sound descriptors for three phases.

Water Intake	Washing	Spin Extraction
Loud	Loud	Loud
Sharp	Sharp	Sharp
Rustling	Buzzing	Trembling
Booming	Pulsating	Booming
Hissing	Bubbly	Pulsating
Bassy	Orderly	Fluctuating
Orderly	Booming	Tonal
Fluctuating	Squeaking	Deep
Deep	Fluctuating	Orderly
Soft	Soft	Bassy

Additionally, 3 more attributes “pleasant”, “efficient”, “quality level” and “preference level” are added to the above list of descriptors. A seven point scale which is numbered from -3 to +3 is used for the jury rating. The descriptions of the numbers are; “extremely = ±3”, “very = ±2”, “a little = ±1” and “uncertain = 0”. The semantic opposite descriptors that appear in the tests are used for evaluating the reliability of the jurors.

3.1.3 Equipment used

Listening tests are performed using BOSE Quiet Comfort 2 active noise cancellation headphones and a laptop computer with sound card. The B&K Psychoacoustic Test Bench software is used for the ordered playback of the sounds.

3.2 Paired comparison test results

The results of the paired comparison test, performed with spin extraction sounds is shown in Figure 3 together with the standard deviations.

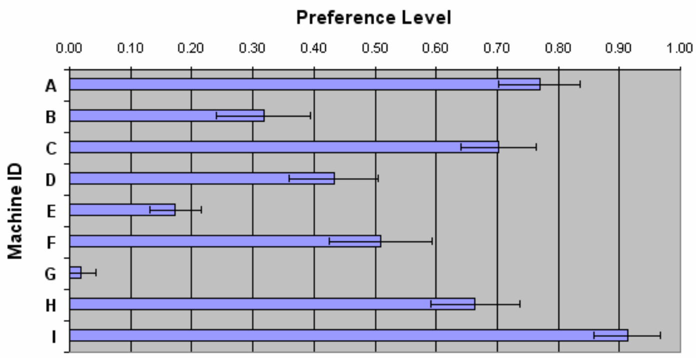

Figure 3 – Paired comparison test, machine ID vs. preference level.

The most preferred spin extraction sound is “I”, which is the edited version of sound “C”. This shows that the attenuation of the high frequency pure tone component in the sound improved the preference level at around 20%. The spin extraction sound of machine “G” is the least preferred sound.

3.3 Semantic differential test results

The correlation matrix of the semantic differential tests gives us the linear relationship between the sound descriptors rated by our jury. For the spin extraction phase, the descriptor correlation matrix is shown in Figure 4.

	Loud	Sharp	Trembling	Booming	Pulsating	Fluctuating	Tonal	Deep	Orderly	Bassy	Pleasant	Efficient	Quality Level	Preference Level
Loud		0.365	0.795	0.967	0.779	0.632	0.105	0.703	-0.618	0.692	-0.794	-0.592	-0.729	-0.760
Sharp	0.365		0.662	0.430	0.532	0.572	0.607	-0.278	-0.676	-0.271	-0.797	-0.765	-0.800	-0.794
Trembling	0.795	0.662		0.866	0.967	0.946	0.443	0.409	-0.937	0.472	-0.929	-0.916	-0.956	-0.929
Booming	0.967	0.430	0.866		0.854	0.730	0.259	0.699	-0.723	0.715	-0.863	-0.699	-0.815	-0.838
Pulsating	0.779	0.532	0.967	0.854		0.963	0.446	0.541	-0.912	0.545	-0.845	-0.881	-0.876	-0.857
Fluctuating	0.632	0.572	0.946	0.730	0.963		0.434	0.396	-0.927	0.447	-0.783	-0.879	-0.856	-0.796
Tonal	0.105	0.607	0.443	0.259	0.446	0.434		-0.176	-0.437	-0.187	-0.537	-0.556	-0.516	-0.584
Deep	0.703	-0.278	0.409	0.699	0.541	0.396	-0.176		-0.293	0.899	-0.275	-0.200	-0.226	-0.264
Orderly	-0.618	-0.676	-0.937	-0.723	-0.912	-0.927	-0.437	-0.293		-0.326	0.867	0.982	0.934	0.888
Bassy	0.692	-0.271	0.472	0.715	0.545	0.447	-0.187	0.899	-0.326		-0.313	-0.203	-0.306	-0.281
Pleasant	-0.794	-0.797	-0.929	-0.863	-0.845	-0.783	-0.537	-0.275	0.867	-0.313		0.902	0.979	0.994
Efficient	-0.592	-0.765	-0.916	-0.699	-0.881	-0.879	-0.556	-0.200	0.982	-0.203	0.902		0.949	0.928
Quality Level	-0.729	-0.800	-0.956	-0.815	-0.876	-0.856	-0.516	-0.226	0.934	-0.306	0.979	0.949		0.976
Preference Level	-0.760	-0.794	-0.929	-0.838	-0.857	-0.796	-0.584	-0.264	0.888	-0.281	0.994	0.928	0.976	

Figure 4 – Semantic differential test, descriptor correlation matrix for spin extraction phase (Pearson, R).

It can be seen that some descriptor pairs have high positive and negative correlations and some have very low correlations. Trembling-pulsating-fluctuating, orderly-efficient-preferable-pleasant groups are in positive correlation within each other. Orderly is in negative correlation with the trembling and fluctuating.

	Loud	Sharp	Rustling	Booming	Hissing	Bassy	Orderly	Fluctuating	Deep	Soft	Pleasant	Efficient	Quality Level	Preference Level
Loud		0.770	0.759	0.480	0.747	0.229	-0.315	0.372	-0.404	-0.678	-0.672	-0.507	-0.430	-0.642
Sharp	0.770		0.964	0.850	0.983	-0.356	-0.461	0.329	-0.846	-0.980	-0.972	-0.918	-0.868	-0.952
Rustling	0.759	0.964		0.909	0.985	-0.321	-0.474	0.433	-0.783	-0.978	-0.953	-0.871	-0.826	-0.907
Booming	0.480	0.850	0.909		0.908	-0.426	-0.306	0.232	-0.720	-0.911	-0.851	-0.830	-0.798	-0.811
Hissing	0.747	0.983	0.985	0.908		-0.322	-0.387	0.337	-0.811	-0.980	-0.951	-0.889	-0.836	-0.909
Bassy	0.229	-0.356	-0.321	-0.426	-0.322		0.599	-0.317	0.731	0.438	0.520	0.689	0.754	0.569
Orderly	-0.315	-0.461	-0.474	-0.306	-0.387	0.599		-0.813	0.632	0.505	0.579	0.603	0.621	0.643
Fluctuating	0.372	0.329	0.433	0.232	0.337	-0.317	-0.813		-0.450	-0.375	-0.403	-0.381	-0.368	-0.402
Deep	-0.404	-0.846	-0.783	-0.720	-0.811	0.731	0.632	-0.450		0.871	0.886	0.947	0.923	0.896
Soft	-0.678	-0.980	-0.978	-0.911	-0.980	0.438	0.505	-0.375	0.871		0.974	0.928	0.885	0.946
Pleasant	-0.672	-0.972	-0.953	-0.851	-0.951	0.520	0.579	-0.403	0.886	0.974		0.963	0.944	0.983
Efficient	-0.507	-0.918	-0.871	-0.830	-0.889	0.689	0.603	-0.381	0.947	0.928	0.963		0.989	0.977
Quality Level	-0.430	-0.868	-0.826	-0.798	-0.836	0.754	0.621	-0.368	0.923	0.885	0.944	0.989		0.960
Preference Level	-0.642	-0.952	-0.907	-0.811	-0.909	0.569	0.643	-0.402	0.896	0.946	0.983	0.977	0.960	

Figure 5 – Semantic differential test, descriptor correlation matrix for water intake phase (Pearson, R).

Figure 5 shows the correlation matrix for the water intake phase. The descriptor groups that have high correlation are: Sharp-hissing-rustling and soft-efficient-preferable-pleasant. The sharp, rustling, booming and hissing properties of the sound are in negative correlation with the preference level. The correlation matrix for washing phase shown in Figure 6 indicates that buzzing and sharp; pulsating and fluctuating are in high positive correlation, whereas booming and soft; buzzing and pleasant are in negative correlation.

	Loud	Sharp	Buzzing	Pulsating	Bubbly	Orderly	Booming	Squeaking	Fluctuating	Soft	Pleasant	Efficient	Quality Level	Preference Level
Loud		0.740	0.786	0.690	0.661	-0.301	0.600	0.416	0.748	-0.697	-0.687	-0.376	-0.626	-0.786
Sharp	0.740		0.916	0.313	0.589	-0.310	0.644	0.738	0.481	-0.634	-0.634	-0.362	-0.525	-0.517
Buzzing	0.786	0.916		0.409	0.664	-0.340	0.680	0.820	0.599	-0.747	-0.838	-0.639	-0.744	-0.672
Pulsating	0.690	0.313	0.409		0.819	-0.320	0.405	0.398	0.896	-0.717	-0.568	-0.130	-0.558	-0.722
Bubbly	0.661	0.589	0.664	0.819		-0.341	0.603	0.690	0.714	-0.799	-0.622	-0.169	-0.570	-0.639
Orderly	-0.301	-0.310	-0.340	-0.320	-0.341		-0.853	-0.417	-0.415	0.713	0.516	0.379	0.521	0.659
Booming	0.600	0.644	0.680	0.405	0.603	-0.853		0.597	0.520	-0.875	-0.708	-0.482	-0.694	-0.800
Squeaking	0.416	0.738	0.820	0.398	0.690	-0.417	0.597		0.577	-0.754	-0.787	-0.566	-0.709	-0.527
Fluctuating	0.748	0.481	0.599	0.896	0.714	-0.415	0.520	0.577		-0.841	-0.817	-0.472	-0.815	-0.873
Soft	-0.697	-0.634	-0.747	-0.717	-0.799	0.713	-0.875	-0.754	-0.841		0.893	0.574	0.886	0.928
Pleasant	-0.687	-0.634	-0.838	-0.568	-0.622	0.516	-0.708	-0.787	-0.817	0.893		0.848	0.983	0.888
Efficient	-0.376	-0.362	-0.639	-0.130	-0.169	0.379	-0.482	-0.566	-0.472	0.574	0.848		0.854	0.649
Quality Level	-0.626	-0.525	-0.744	-0.558	-0.570	0.521	-0.694	-0.709	-0.815	0.886	0.983	0.854		0.907
Preference Level	-0.786	-0.517	-0.672	-0.722	-0.639	0.659	-0.800	-0.527	-0.873	0.928	0.888	0.649	0.907	

Figure 6 – Semantic differential test, descriptor correlation matrix for washing phase (Pearson, R).

By the help of the above correlation matrices, the descriptors are refined. The descriptor groups with high correlation are represented with a single descriptor in order to simplify the model. In future studies, the simplified set of descriptors can be used to shorten the listening tests.

3.3.1 Semantic differential test, preference results

Figure 7 shows the preference levels of the sounds from three phases. Water intake sound of machine “D” is the most preferred one, whereas “F” and “G” are the least preferred. In washing phase, “D” and “G” are the ones that are preferred more than the others that have approximately the same preference levels.

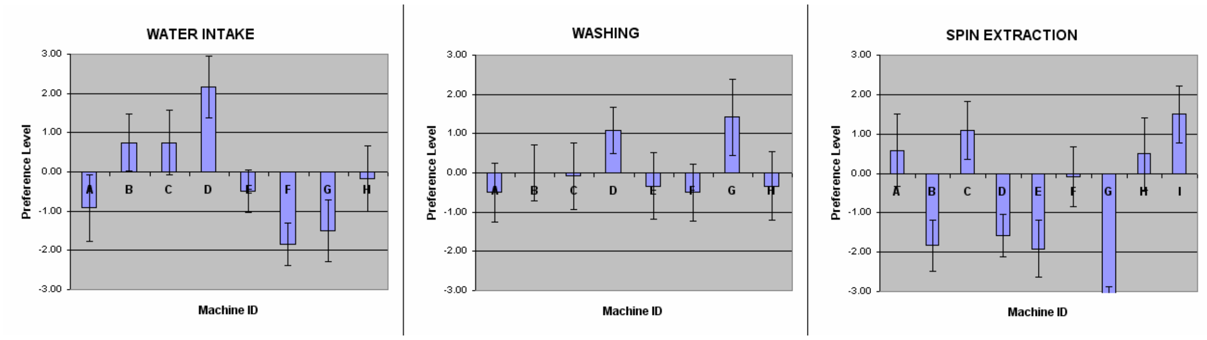

Figure 7 – Semantic differential test, preference level.

Spin extraction semantic differential test results are congruent with the paired comparison test results. The preference level rating results of the two methods are demonstrated together in Figure 8.

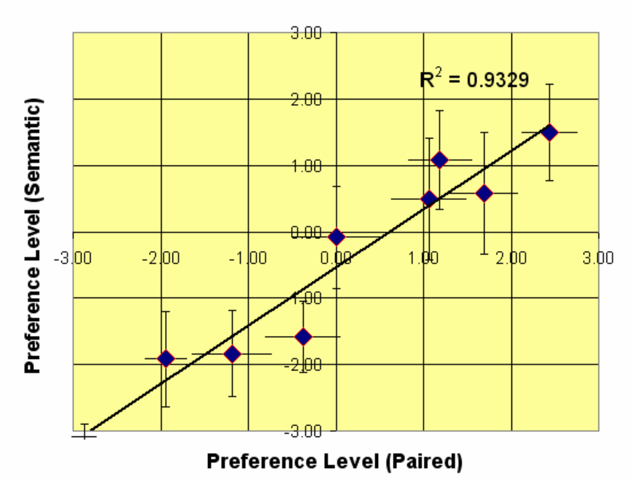

Figure 8 – Preference level; semantic differential test vs. paired comparison test.

4 Evaluating objective and subjective test results

4.1 Principal components analysis

4.1.1 Calculating the principal components

The principal components analysis is performed for all three working phases. For the calculations, the semantic differential test results are used for water intake and washing phases, paired comparison test results are used for spin extraction phase. Mean centered and unit variance metrics matrix is called $\mathbf{X_m}$, jury test results matrix is called $\mathbf{X_j}$. For the spin extraction phase, 4 metrics are used, 8 descriptors are present in the jury tests for 9 sound samples. So, $\mathbf{X_m}$ is (9x4) and $\mathbf{X_j}$ is (9x8) sized matrices.

The covariance matrix of X (nxm) is defined as shown in equation (1).

$$\mathbf{S} = (\mathbf{X}^{\mathrm{T}}\mathbf{X}) / n - 1 \tag{1}$$

As $\mathbf{X}$ is a mean centered matrix with unit variance, $\mathbf{S}$ is the correlation matrix of $\mathbf{X}$. The eigenvalue equation can be written as,

$$\mathbf{S}\mathbf{U}_i = \lambda_i \mathbf{U}_i \quad , i=1,2,\ldots,p \tag{2}$$

where, $\mathbf{U_i}$ is eigenvectors and λ_i is the eigenvalues of the covariance matrix. $\mathbf{U_i}$ eigenvectors are called coefficients vectors of the principal components. Each orthogonal $\mathbf{U_i}$ eigenvectors are the linear combinations of the original variables and contain information on how the variables relate to each other. Then each measurement is projected on an individual axis, where the variance of this variable is the maximum among all possible choices of the axis. The new variables are called z-scores (3).

$$\mathbf{z}_i = \mathbf{X}_i.\mathbf{U}_i \quad , i=1,2,\ldots,p \tag{3}$$

z-scores are the linear combinations of the original variables of $\mathbf{X}$ refined by $\mathbf{U_i}$. As the sum of the variances of the first few principal components is able to represent the reliable percentage of the total variance of the original data, it is not necessary to use all the principal components.

In order to demonstrate the calculation of the principal components (PC) for the spin extraction phase, the metrics and jury test eigenvectors $\mathbf{U_m}$ and $\mathbf{U_i}$ can be calculated as shown in the columns of Table 2 and Table 3, where the rows are the variables (metrics and descriptors).

Table 2 – Metrics coefficients matrix $\mathbf{U_m}$.

	PC 1	PC 2	PC 3	PC 4
Loudness	0.49	-0.51	0.52	0.48
Roughness	0.42	0.63	-0.30	0.58
Fluctuation Strength	0.58	0.36	0.37	-0.63
Sharpness	-0.49	0.46	0.70	0.22

Table 3 – Jury test coefficients matrix $\mathbf{U_j}$.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
Loud	0.39	-0.14	0.48	-0.12	0.60	-0.03	-0.45	0.15
Sharp	0.23	0.58	0.38	-0.13	-0.47	0.12	-0.01	0.46
Booming	0.41	-0.06	0.43	0.14	-0.28	0.00	0.17	-0.72
Pulsating	0.41	0.11	-0.18	0.04	0.39	0.41	0.66	0.13
Fluctuating	0.37	0.24	-0.55	-0.13	-0.08	0.35	-0.54	-0.26
Deep	0.30	-0.50	-0.08	0.62	-0.31	0.13	-0.13	0.37
Orderly	-0.38	-0.28	0.29	-0.20	-0.08	0.80	-0.07	-0.05
Bassy	0.30	-0.49	-0.12	-0.71	-0.28	-0.17	0.15	0.14

Using equation (3), the z-scores can be calculated as shown in Table 4 and Table 5. The columns are the principal components, rows are the samples (machine IDs).

Table 4 – Metrics z-score matrix $\mathbf{Z_m}$.

	PC 1	PC 2	PC 3	PC 4
A	-0.84	2.46	0.57	0.19
B	-0.54	-1.60	0.33	0.58
C	-0.43	-0.20	-0.35	0.10
D	-0.69	-0.32	-0.29	-0.29
E	0.12	-0.84	1.02	-0.36
F	-0.43	-0.98	-0.33	-0.15
G	3.77	0.32	0.05	0.04
H	-1.09	0.63	0.01	-0.14
I	0.13	0.52	-1.02	0.03

Table 5 – Jury test z-score matrix $\mathbf{Z}_j$.

	PC 1	PC 2	PC 3	PC 4	PC 5	PC 6	PC 7	PC 8
A	-2.82	0.83	0.51	-0.35	0.26	-0.11	-0.02	0.05
B	1.74	-1.19	1.27	-0.25	-0.16	0.05	0.03	-0.03
C	-0.93	-1.03	0.20	0.42	-0.10	0.19	-0.02	0.07
D	1.81	1.38	-0.45	-0.21	0.05	0.34	-0.07	-0.02
E	2.06	-0.78	0.08	0.36	0.36	-0.13	-0.04	-0.03
F	0.10	-0.66	-0.76	-0.11	0.11	0.07	0.15	0.01
G	3.09	1.77	-0.17	0.06	-0.21	-0.26	0.01	0.03
H	-3.61	1.53	0.15	0.28	-0.13	0.00	0.03	-0.06
I	-1.44	-1.87	-0.84	-0.21	-0.18	-0.15	-0.07	-0.02

4.1.2 Biplot diagrams

The MATLAB bi-plot command is used to visually demonstrate the contributions of the metrics to the principal components, together with the z-scores of the test data. Each two dimensional graph is a projection of the z-scores to the two of the principal components coefficient vectors. Spin extraction phase bi-plot diagram plotted with first and third principal components of the metrics is shown in Figure 9. Each axis represents the principal components (PC). The blue lines in the graph represent the projections of the principal component coefficient vectors of the metrics ($\mathbf{U}_m$ vectors), red dots represent the z-scores of each sound.

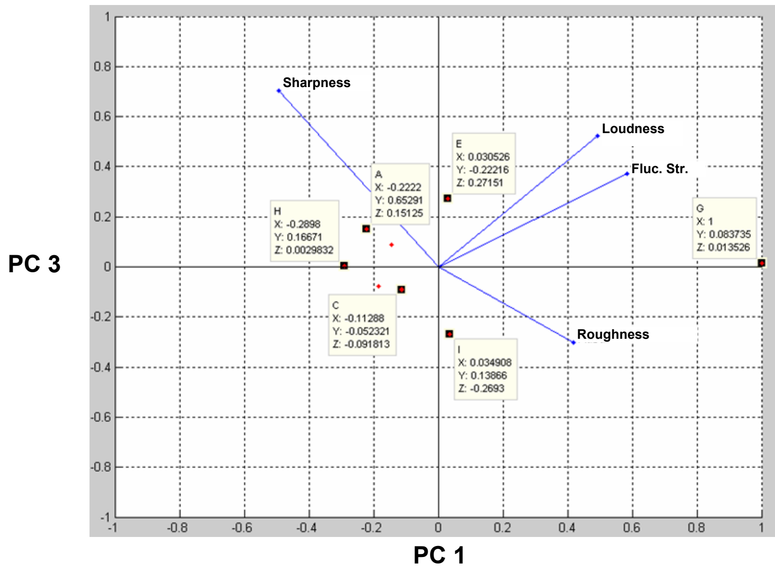

Figure 9 – Metrics biplot diagram for spin extraction phase.

The PC1 has positive contributions from the loudness, fluctuation strength and roughness metrics. The least preferred spin extraction sound “G” seen on the right hand side of the graph, having the highest value of PC1.

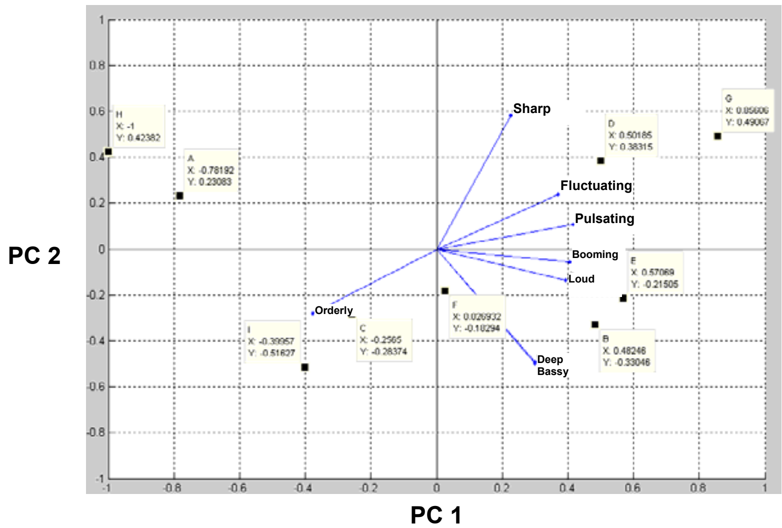

Figure 10 – Jury test bi-plot diagram for spin extraction phase.

Figure 10 shows the bi-plot diagram generated from the jury test results. Again, sound “G” has the maximum values with regard to the projections of sharpness, fluctuation, pulsation, booming and loudness. It can be seen that “bassy” and “deep” descriptors which have similar meanings coincide with each other on the graph. The sound “I” with the highest preference level, located on the opposite side of sound “G”, having highest values in projection with order and low values in projection with sharp, fluctuating, pulsating, booming and loud.

4.2 Linear regression

In order to be able to predict the human perception of sound only by calculating the metrics, it is necessary to obtain a transformation matrix between the objective and subjective tests. In the present study, this is done by linear regression. In equation (4), $\mathbf{Y}$ vector represents the preference level results from the jury tests, $\mathbf{X}$ matrix represents the metrics matrix.

$$\mathbf{Y} = \mathbf{XB} \tag{4}$$

The least squares solution for the transformation matrix $\mathbf{B}$, is shown below in equation (5).

$$\mathbf{B} = [\mathbf{X}^T\mathbf{X}]^{-1}\mathbf{X}^T\mathbf{Y} \tag{5}$$

If the metrics matrix is multiplied with the transformation matrix gathered from the above equation, the predicted preference level vector called $\mathbf{T_t}$ is obtained.

$$\mathbf{T_t} = \mathbf{XB} \tag{6}$$

$$\mathbf{T_t} = \mathbf{-0.732\ X_1 + 0.543\ \ X_2 - 0.609\ \ X_3 - 0.132\ \ X_4} \tag{7}$$

Figure 11 shows the original preference level results from the jury test plotted versus the predicted preference level. The correlation coefficient is $R^2 = 0.93$.

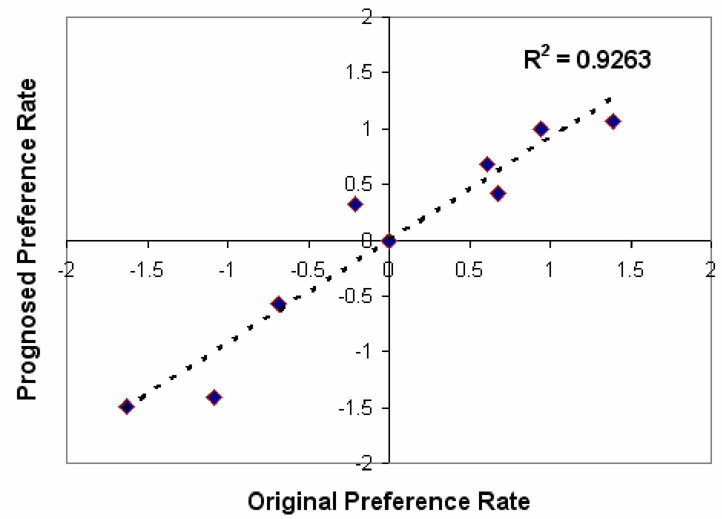

Figure 11 – Original reference rate vs. predicted preference level.

4.3 Investigating the effects of damping on sound quality

Once the SQ mathematical model is developed, it is possible to predict the effects of design changes on sound quality. In the present study, two type of dampers with different damping characteristics are used on the same washing machine and sound recordings are made in the spin extraction phase. The sound quality metrics for the two tests are shown in Table 6.

Table 6 – Metrics calculated for spin extraction phase
with two different dampers AB & AK.

	AB	**AK**
Loudness	22.00	18.80
Roughness	0.50	0.46
Fluctuation Strength	0.96	1.00
Sharpness	1.53	1.60

It can be seen from the above table that the AB damper has higher loudness and roughness values as opposed to lower fluctuation strength and sharpness values.

For the prediction of the preference level of these two sounds the developed SQ mathematical model in equation (7) is applied with the above calculated metrics and the preference level is calculated as -0.82 for AB and -0.88 for AK dampers. Since the metric differences balance each other, there is no significant difference between the two predicted overall preference levels.

5 Conclusions

The mathematical model derived from the linear regression between the objective and subjective tests are shown to be reliable for making prediction for human perception of washing machine sounds. The bi-plot graphs of the principal components generated by MATLAB software is a useful tool to visually demonstrate the contributions of the metrics and the descriptors of sound to the preference level of the sound. This tool can be used to determine the necessary design modifications in order to reach the target sound of a product in the sound quality cycle. Damping is an important design parameter in washing machines. Different dampers have different force transmission characteristics, so they have different effects on the sound quality metrics, especially in the spin extraction phase. Future sound quality tests involving dampers with different characteristics will help the designers to improve the sound quality of the washing machines.

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