Available online at www.sciencedirect.com
ScienceDirect
Expert Systems with Applications 32 (2007) 1004–1010
Expert Systems with Applications
www.elsevier.com/locate/eswa

Automatic timbre quality evaluation in Chinese traditional flute industry

Hui-Jen Yang [a,*], Yun-Long Lay [b], Chern-Sheng Lin [c]

[a] *Department of Information Management, National Chinyi Institute of Technology, No. 35, Lane 215, Sec. 1, Chung-San Road, Taiping City, Taichung Hsien 411, Taiwan*
[b] *Department of Electronic Engineering, National Chinyi Institute of Technology, No. 35, Lane 215, Sec. 1, Chung-San Road, Taiping City, Taichung Hsien 411, Taiwan*
[c] *Department of Automatic Control Engineering, Feng Chia University, No. 100 Wenhwa Road, Seatwen, Taichung, Taiwan 40724, ROC*

Abstract

Since the opening of Chinese economic, a great amount of Taiwanese merchants enter Mainland China for investment. The annual production of bamboo flutes in China is over 4 millions to provide domestic and international consumers. Owing to the great amount of demand, folk instrument industry is one of the attractive investment items. In order to increase the product manufacturing process and promote the product quality, the implementation and application of an automatic timbre evaluation system with spectrum analysis and cluster algorithm to increase the flute quality becomes an important method for Taiwanese businessmen to earn more profits. This research is to implement an automatic timbre quality system to evaluate the timbre quality of Chinese flute in flute businesses. From research data displays that the automatic timbre evaluation system does help the traditional handicraft manufacture classify the timbre quality of flute more effectively.

Keywords: Automatic quality evaluation system; Timbre; Flute; Spectrum analysis; Cluster algorithm

1. Introduction

The bamboo industry is one of 10 big emerging forestry development industries in mainland China. Since 1996, the total annual productivity of bamboo industry has amounted to 20 billion Yuan, is the head of 10 big emerging industrials and also becomes the new benchmark in the Chinese forestry development. Currently, the annual production of bamboo flutes in China is over 4 millions to provide domestic and international consumers need. The sudden appearance of bamboo business has demonstrated the bright future for Chinese bamboo industry. China is the earliest country to use the bamboo as material to make bamboo artwork. The distribution of bamboo in mainland China is over 20 provinces, the cities and the autonomous regions. Among them, there are 20 provinces and 141 counties as main areas to produce the bamboo. The number and area of bamboo occupies around one-fourth all over the world. The types of variety and the broad usages in bamboo have an incomparable superiority with other countries. The bamboo handicraft is the China traditional product, which consumes few resources and has high product economic value. Bamboo handicraft is a potential industry in China at present. The economic value of the bamboo product is generally above 10 times and sometimes even may reach 100 times. The Taiwanese businessman understood the economical pulsation of mainland China, therefore a great amount of Taiwanese businessmen enter the mainland China for investment. In order to increase the product manufacturing process and promote the product quality, the development and application of an automatic

* Corresponding author. Tel.: +011 886 0423924505x7923/7999; fax: +011 886 0423923725.
E-mail addresses: yanghj@chinyi.ncit.edu.tw (H.-J. Yang), layyl@chinyi.ncit.edu.tw (Y.-L. Lay), lincs@auto.fcu.edu.tw (C.-S. Lin).

0957-4174/$ - see front matter
doi:10.1016/j.eswa.2006.02.025

timbre evaluation system becomes an important way to enhance the bamboo flute quality.

In recent years, with the rapid development in computer and information technology, automatic quality management systems have been introduced in many manufacturing industries to improve or guarantee the quality of processes and products of organization (Abbott, 1999; Carvalho, Araujo, & Dourado, 1999; Kuo & Wu, 2002; Swanepoel, 2004; Van Harten, Casparie, & Fisscher, 2000). More recently, manufacturing industries have been applying information and communications technology for both information processing and automatic control. However, little evidence is shown in literature for automatic timbre quality evaluation in the traditional Chinese bamboo flute manufacturing industry. The systematic implementing of an automatic quality control system of Chinese bamboo flute can be useful in guaranteeing the timbre quality of flute to reduce the defect rate. Normally, some kinds of quality evaluation work need well-experienced experts to judge the quality of the products, such as wine taste, jewelry authentication, painting evaluation and so on. By the same token, to evaluate the timbre quality of Chinese bamboo flute relies heavily on the experience of the technician to judge the timbre quality of flute subjectively. To determine the timbre quality of flute is a time-consuming process that requires manual subjective judgment, both by flute musicians and by experienced technicians in flute production factories. In most flute production factories, there are technicians specifically devoted to classifying the type of timbre of flute. The classification process is not uniform, as performing this task depends on the technician's experience, skill, or even on personal emotion or circumstance.

The term "quality" implies a degree of excellence or superiority, value, conforming to specifications, meeting or exceeding customer expectations, suitability and usability of a product (Abbott, 1999; Verdu Jover, Llorens Montes, & Fuentes, 2004). People like to use all of their senses to evaluate quality, such as smell, taste, touch, hearing and so on. Thus, quality is not a single, well-defined attribute but comprises many characteristics or properties relying on the different context, thus, there is no consistent definition of quality in previous studying (Abbott, 1999; Neufeldt, 1988). Some focus on the view of product orientation to define quality and some focus on the view of customer orientation to define quality. Some encompass both concepts; this is the definition applied in this study. In general, quality comprises many properties or features, such as sensory properties (appearance, texture, taste and aroma), chemical constituents, mechanical properties, functional properties, defects and so on (Abbott, 1999). Applying this concept to Chinese flute, a good quality flute should possess the feature not only of accuracy of pitch within the whole key, but also producing a clear note with little effort and having a beautiful sound timbre. From the perspective of manufacturer and performer, testifying the accuracy of pitch in flute is probably not a difficult thing. Whereas choosing or making a satisfactory timbre of flute is probably not an easy task for manufacturers or customers. The attributes of sound timbre are: bright, dark, clear, soft, etc., which are too imprecise to justify. Timbre as assessed by people can not be precisely defined, leaving a high degree of uncertainty depending on an individual's preferences or the unknown influences of individual values on the timbre quality of musical sounds (Kostek, 1999).

Timbre is an auditory attribute considered as a perceptional parameter of sound that is complex and multidimensional. Timbre is the feature of sound that allows people to identify it and distinguish it from other sounds with the same pitch and loudness (Houtsma, 1997). "Timbre" is defined as the quality, which distinguishes two sounds with the same pitch, loudness, and duration (Kostek, 1999). Often timbre is used to refer to the "tone quality" or "tone color" (Ilmoniemi, Valimaki, & Huotilainen, 2004). Thus, the lack of a standard automatic quality control or evaluation system to distinguish the timbre quality may lead to severe economic losses or wrong assessment of products due to the possible misuse of an inaccurate method or unintentional human error.

For decades, the timbre quality evaluation of a flute has been subject to the judgment of experts or professional technicians; experts or professional technicians would blow each flute one by one to test its timbre. This process is labor-intensive and time-consuming and the results are very subjective and non-standardized depending on the preferences of each expert or professional technician. In order to objectively assess timbre quality of flute, there is a need to find a method to make it possible to objectively judge the subjective notions of timbre in Chinese Bamboo flute. With the advent of manufacturing technology toward automation, an automatic timbre evaluation system is necessary to classify the quality of flute. Essentially, the automatic timbre system was used to objectively classify and standardize the timbre of flute in order to be used as an automated evaluation process. The conceptual design of the system in this paper is composed of audio spectrum system, cluster analysis and decision making scheme to judge the timbre types of flute. Initially, a spectrum module is used to collect the features of each timbre as the resources of classification. Subsequently, for exploring the classification of flute, a cluster analysis with K-means algorithm was used to infer the class of timbre feature distribution. Finally, a condition decision algorithm is presented to judge the classification of timbre.

The results reveal that an automatic-timbre-quality evaluation system can not only be employed to support the flute technician in objectively judging the timbre quality with a minimal time and effort, but can simultaneously provide valuable information to prove the timbre quality of the flute and increase its economic benefits.

2. Background and characteristics of flute

As has been pointed out, the aim of the application shown in this paper is to classify the timbre quality of flute automatically. Generally speaking, to make a good quality flute is not an easy task because of the multidimensional and complex nature of the flute itself.

Western musical instrument are often made of metal. Metal is a very versatile material, so it can meet different individual requirements. Therefore, the made-up instrument has a very standard production process. For instance, a western flute has a standard mechanical production process. Thus, its inner tube can be well made with a pure cylinder. However, flute uses bamboo as a material and bamboo is a natural-born material. It is hard for us to make a standardized and unified raw material. The type and age of bamboo material has a large effect on timbre and intensity level (Di-Yin Net, 2005).

As to the timbre evaluations of hard or soft, thin or thick, bright or dark, everyone has different evaluation scales or interests. Thus, the evaluation of timbre in flute is a subjective judgment. However, the attributes of timbre on flute should focus on "sweet, thick, bright, transparent, and soft" (Chen, 2002). Notice that the quality of timbre of flute is based on the musicians' or technicians' subjective judgment. In this paper, four indexes related to timbre in flute are used to estimate the quality of timbre, including sweet, transparent, thick and bright.

Although the study of musical instrument acoustics holds that different musical instruments have different principles of vocal, there are still some common methods. From the perspective of musical instruments, the vocal part and the resonance part should be separated into different system initially, and then their coupling effect should be discussed. The physical characteristics of resonance are usually described by input impedance curve. The impedance measurement was originally designed for measurement of the human vocal tract (Epps, Smith, & Wolfe, 1997). It was used for studies on the Boehm flute, the classical flute, and the baroque flute (Wolfe, Smith, Tann, & Fletcher, 2001; Wolfe & Smith, 2001). The vocal part of tube musical instruments can be separated into two sections with air splitting on the edge of plane surface. The resonance part of a tube musical instrument is the air in its inner tube. The way to measure its input impedance is to place a steady sine wave sound source at the opening of the inner tube. This transmits a sound into the inner tube to test its intensity level. We improve the impedance measurement by adding the spectrum analysis and clustering algorithm to do the automatic timbre judgment.

The blowing hole, vocal part, and body of a Chinese flute is a same piece of a bamboo, thus the method to test the timbre is to blow the flute and check the timbre by ear. Before the flute leaves the factory, the timbre quality evaluation of the flute depends on the manufacturers blowing test. This study is to implement an automatic flute timbre evaluation system. Through this evaluation system, the classification of timbre of flute can be recognized to achieve the goal of automatic measurement.

3. The automatic flute timbre quality evaluation system (ADTQE)

An automatic system for evaluating the timbre quality of flute was designed, implemented and tested. Designing and implementing the system, the spectrum of musical instrument sound, discrete Fourier transform, cluster analysis, and condition decision algorithm were included in this section.

3.1. Framework of ADTQE system

The system, shown in Fig. 1, is composed of personal computer, microphone which was placed approximately 1 cm above the membrane, air pump, air valve, air jet throttle, open–close control valves of the flute finger hole and the fixed mount for the flute. The computer software packages include spectral analysis module, air flow pressure control module to control volume of blown air, open–close control valve module to change the testing tone, and microphone as a musical input device. The ADTQE system has been embedded with a user-friendly software tool using Borland C++ Builder (Deitel & Deitel, 2004) to develop a Windows-based interface system.

3.2. The spectrum of musical instrument sound

The airflow vibration of a tube instrument is similar to the vibration of a harmonic, string instrument. As for flute, there are six finger holes on the bamboo. Pressing closed or releasing among these finger holes will change the wave length of the resonant to produce a different tone. Due to the limited number of finger holes on the flute and its performing limitation, it is necessary to widen the sound domain using the method of changing the blowing pressure.

As for a tube musical instrument, the timbre in the high octave area is harder to control than the low octave area. From a physics perspective, because the tube of a flute in the high octave area is becoming shorter, the sound

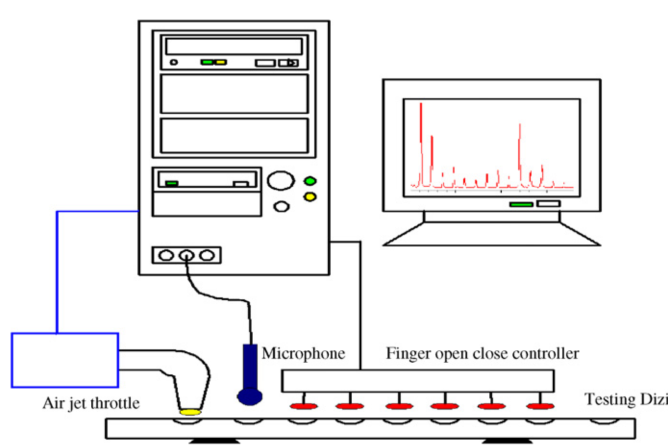

Fig. 1. Framework of the ADQTE system.

vibration will be small. Additionally, after the tube of a flute becomes shorter, it is difficult to vibrate and the number of harmonics obviously reduces. Compared with the vibration of the low octave on the same flute, the timbre of the high octave is tight and dark. In addition, owing to the membrane, the timbre of a flute becomes harmonic and sweet (McAulay & Quatiere, 1986; Serra, 1997).

The signal of a time series could denote $v_s(t)$ the sum of different frequency signals of a sine wave through Fourier transformation. Fourier transformation can process a cyclic signal to produce the spectrum. Including the distributed frequency named as ω_0 fundamental frequency and its harmonics. The critical part of actual signal spectrum is usually restricted within a small range of frequency ω, which is very useful from the perspective of the signal process.

The musical sound signal of Fig. 2 is a wave shape of music tone with fundamental frequency 293.7 Hz. It can be represented as the type of spectrum shown as Fig. 3. These two different kinds of representation form are called time-domain and frequency-domain. The frequency-domain of a signal, denoted as $v_a(t)$, can be represented as $v_a(\omega)$ after the Fourier transformation.

Sound signal through the conversion of A/D (analog to digital circuit) to get the sampled signal becomes the discrete type. Subsequently, using the Discrete Fourier Transform transfers the time-domain into the frequency-domain. Discrete Fourier Transform is the application of the Fast Discrete Fourier Transform. It assumes that there are N sampling points X_n as the transform data to calculate using Eq. (1). Through Discrete Fourier Transform, the spectrum of the sound signal or Periodogram was then acquired. That means the signal of the time-domain transfers into the frequency-domain with frequency components.

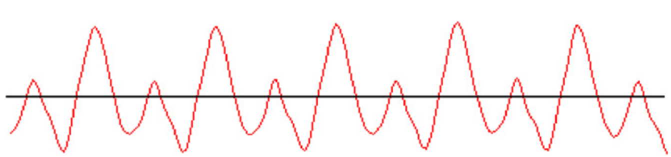

Fig. 2. A wave shape of music tone with fundamental frequency 293.7 Hz.

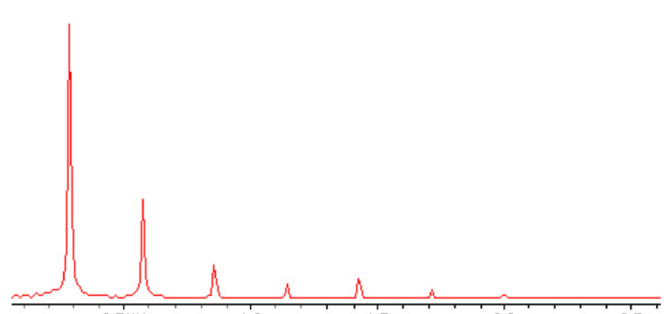

Fig. 3. A spectrum of music tone with fundamental frequency 293.7 Hz.

$$X_n = \frac{1}{N}\sum_{k=0}^{N-1} x_k e^{-2\pi jkn/N}, \quad n = 0, 1, 2 \ldots N-1 \tag{1}$$

3.3. Clustering analysis

A Cluster Analysis with K-means algorithm (Kaufman & Rousseeuw, 1989) was applied to investigate the timbre distribution along the whole pitch of a flute. In the K-means algorithm, giving a set of N M-dimension points, denoted as P_n, was classified into K clusters. The centroid point of the cluster was represented by C_K. The variance of each cluster can be defined as

$$\mathrm{VARC}(L_k) = \sum_{i \in L_k} (P_i - l_K)^2 \tag{2}$$

where l_K is the M-dimensional coordinates of cluster L_K and $P_i - l_K$ is any distance metric set by the user. In order to reduce the variance of each cluster in Eq. (2), it is necessary to move any single point to any other cluster. The total variance is defined by Eq. (3).

$$\mathrm{TVARC} = \sum_{i=1}^{K} \mathrm{VARC}(L_K) \tag{3}$$

To avoid the characteristics of converging to a local optimum in K-means calculation, selecting the initial centroid points must be done very cautiously. The Squared Euclidean Distance was used to calculate the variance of a cluster in this study. In our system, 75 iteration times were calculated as the best classification solution.

4. Experiment method and results

4.1. Materials and experiment operations

Initially, paste the membrane on the flute and then affix the flute on the rack precisely. Adjust the jet throttle to blow in the hole while using a computer to control the air flow volume to the jet mouth. The blowing air intensity will affect the timbre of a flute (Sandell & Martens, 1995). Therefore, the blowing air into the flute must keep a steady speed in each pitch to assure the timbre analysis is under the same blowing pressure. In the example of D tone flute, the open–close control valves of the sound holes slowly goes from completely closed to open from bottom to up. The testing range of sound is from A4 (440 Hz) to B6 (1979 Hz) in D note flute. In order to simplify the representation of the wave data, the intensity of harmonics which were less than 30 dB of the base format were discarded. Each sound within the whole testing domain is extracted by the analog to digital circuit. Then a spectral component is used to analyze the intensity of each harmonic.

Fig. 4 shows the experiment operations of the automatic flute timbre quality evaluation system. It is composed of an air jet mechanism to inject the air into the testing flute while controlling the open or close function of the finger

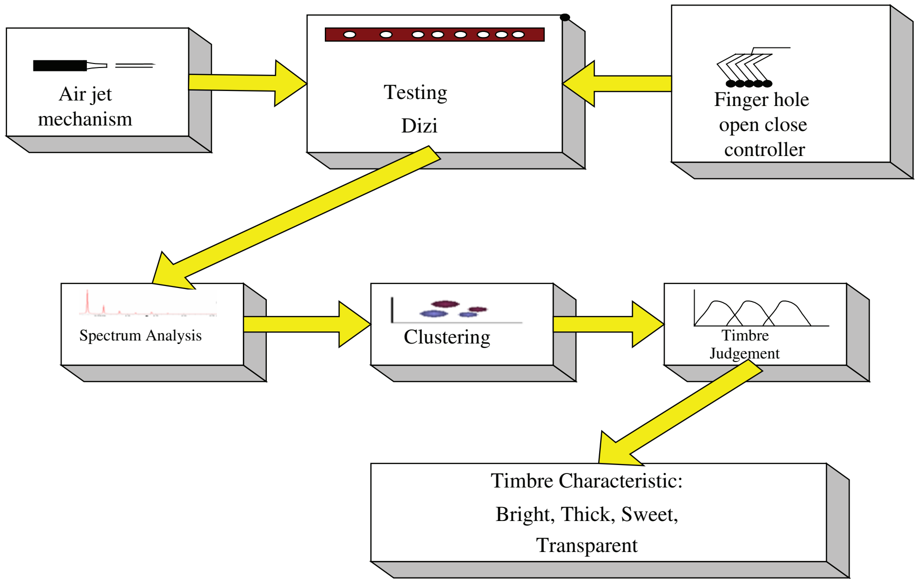

Fig. 4. The experiment operations of the timber quality evaluation system.

hole. A spectrum mechanism was used to extract the timbre features of the flute. A cluster analysis with *K*-means algorithm was used to classify the timbre feature distribution. At the last step, a decision making classifier was applied to judge the characteristics of the timbre features of the flute. These include sweet, bright, transparent, and thick.

4.2. Data acquisition

Initially, in order to get the attributes of the timbre database, 300 good quality flutes were collected by three professional musicians and then a serial number was put on each flute as training samples. Secondly, the automatic testing system gradually blows the musical tone and records the spectral data of each flute using *K*-means algorithm to classify into four groups, shown in Fig. 5, where C1, C2, C3, and C4 individually represented the centroid of four groups. Finally, these flutes were arranged by their serial numbers and three professional musicians blew each type of flute and subjectively gave the suitable timbre classification, where C1 is bright, C2 is sweet, C3 is thick, and C4 is transparent.

Timbre(testing flute feature)=

- Excellent, distance(c0)<0.4 and near(c0);
- Bright, distance(c1)<1.4 or (distance>= 1.4 and near(c1));
- Sweet, distance(c2)<1.4 or (distance>= 1.4 and near(c2));
- Thick, distance(c1)<1.6 or (distance>= 1.6 and near(c3));
- Transparent, distance(c1)<1.6 or (distance>= 1.6 and near(c4));
- Unqualify, distance(c0)>3;

Fig. 5. The rules for defining the class of timbre.

4.3. Timbre range searching

Past research shows that the decision condition algorithm is frequently used to match data corresponding to training data (Holland, 1992; Lee, 1996). As was pointed out in the last Section 4.2, four timbre classifications (C1–C4) were generated to specify each timbre quality respectively. C0(x^*, y^*), calculated by Eqs. (4) and (5), is the center of the 300 original samples. The timbre near C0 is considered to have "excellent" timbre quality.

$$x^* = \frac{\sum_{\text{all } y}\sum_{\text{all } x} x \cdot f(x,y)}{\sum_{\text{all } y}\sum_{\text{all } x} f(x,y)} \tag{4}$$

$$y^* = \frac{\sum_{\text{all } y}\sum_{\text{all } x} y \cdot f(x,y)}{\sum_{\text{all } y}\sum_{\text{all } x} f(x,y)} \tag{5}$$

In order to define the radius of timbre distribution, C0, C1, C2, C3, and C4, the center of each timbre index is judged by three flute musicians who decide the radius of a cluster with the same timbre. The results found that the distance of C0 is 0.4, the coverage radius of C0; the distance of C1 is 1.4, the coverage radius of C1; the distance of C2 is 1.4, the coverage radius of C2; the distance of C3 is 1.6, the coverage radius of C3; and the distance of C4 is 1.7, the coverage radius of C4. Furthermore, no timbre distribution was found when the distance of C0 is over 3. This indicated that if the distance from the testing sample to C0 is greater than 3, the timbre quality is classified as "bad". The decision condition algorithm is used to classify the type of timbre of flute. The following set of rules defining the system is used to specify the class of timbre. If the distance from a testing sample to C0 is less than 0.4 then the timbre of flute is classified as "excellent". Indicating this kind of flute has the quality of sweet, bright, transparent, and thick simultaneously. If the distance from a testing sample to C1 is less than 1.4 then the timbre of flute is classified as ‘‘bright’’. Indicating this kind of flute has the quality of bright. If the distance from a testing sample to C2 is less than 1.4 then the timbre of flute is classified as ‘‘sweet’’. Implying this kind of flute has the quality of sweet. If the distance from a testing sample to C3 is less than 1.6 then the timbre of flute is classified as ‘‘thick’’. Meaning this kind of flute has the quality of thick. If the distance from a testing sample to C4 is less than 1.7 then the timbre of flute is classified as ‘‘transparent’’. Indicating this kind of flute has the quality of transparent. If the distance from the testing sample to all four centers (C1, C2, C3, C4) is larger than 1.7 and the distance from the testing sample to center C0 is less than 3 then the timbre of flute is classified by the nearest distance cluster. If the distance from a testing sample to C0 is larger than 3 then the timbre of flute is classified as ‘‘bad’’. Indicating this kind of flute is unqualified. The pseudo-code of each rule in the decision condition algorithm is shown in Fig. 5.

4.4. Experiment results

After the system has implemented, Min-Chu Musical Instrument Company and Chia-Yin Musical Instrument Company provided 1500 flutes as a testing sample to classify its timbre quality. The experiment period is lasted for three months. Before beginning to test its timbre quality, each flute was assigned an identification number. After testing each one by one with the ADTQE system, the frequency of each index was counted and recorded. The testing results are displayed in Fig. 6, among which 78 are excellent; 459 are bright; 228 are sweet; 315 are thick; 294 are transparent and 126 are bad.

Different tests have been performed with the indexes of sweet, transparent, thick, bright, excellent, and bad to classify the timbre quality of flute with the ADTQE system and the technical support of three musicians. After the ADTQE system classification of 1500 flutes, three musicians individually tested the 1500 flutes one by one to classify the type of timbre. The frequency of each index the musicians classified was counted and recorded by identification number. Due to the large amount of data only summary results are presented in Table 1. As seen in Table 1, the discrepancy between the system and the musicians is minimal. In order to test the difference between ADTQE system and musicians, a t-test was applied and the results are presented

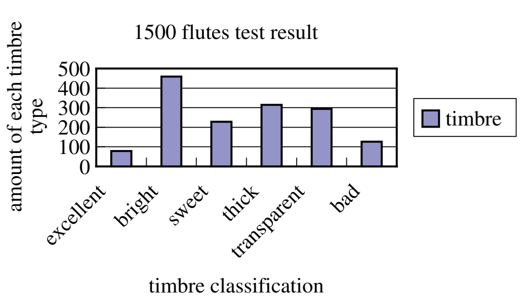

Fig. 6. The testing results of 1500 flutes for ADTQE system.

Table 1
The results of timbre by ADTQE system and three musicians

Timbre	Classifier					
	Excellent	Bright	Sweet	Thick	Transparent	Bad
ADTQE	78	459	228	315	294	126
Musician 1	81	454	230	309	292	134
Musician 2	77	460	225	311	295	132
Musician 3	82	453	223	315	298	129

Table 2
t-Test for timbre classification by ADTQE and three musicians

Independent variables	Mean	SD	t-Value
ADTQE system	2.79	1.33	.125
Musicians	2.76	1.27	

$^{***}P < 0.001$; $^{**}P < 0.01$; $^{*}P < 0.05$.

in Table 2. As expected, the comparison between the system and musicians leads to less significant differences. In other words, there are no significant differences between the system classification and musicians' classification. This result indicated that the classification of timbre quality in the automatic system is valid and accurate. Additionally, an ANOVA test was used to test the classification differences among musicians. The results displayed that there are no significant classification differences among these three musicians ($F = 0.004$, $P = .996 > .000$). This result indicated that the evaluation among three musicians is almost identical.

5. Discussion and conclusions

The function of the ADTQE system in this study was to provide timbre classification of flute that is accurate, precise, and time saving. Several conclusions can be drawn from the obtained results. The ADTQE system has shown to be a useful and attractive tool to classify the timbre quality of flute. However, there are only 1500 flute testing samples, which is not enough to generalize about a large pool of flute. A further study should be pursued using samples of a larger number of varieties coming from different flute factories to increase the usability and validity of ADTQE system. Furthermore, in order to get a more precise classification on the timbre quality of flute, more sample sizes need to be used in the training stage to further improve the accuracy of these experiment results for advanced study. Additionally, the measurement of indexes on sweet, transparent, bright, and thick is very subjective. It is hard to use a scale or instrument to measure these indexes. This study is only in the preliminary stage. Further studies are needed to clearly define the concepts of these indexes.

Due to the characteristics and features of bamboo, it is very difficult to objectively evaluate the timbre quality of flute. Problems are encountered not only within the material of natural-born bamboo, but also in the implementing process, where technicians possibly resist using an automatic evaluation system to judge the timbre quality of flute.

Two possible arguments can depict this. One possible argument is that technicians may always trust that their judgment is better than the system. They may think experience is a key factor in obtaining adequate classification results. The second argument is that technicians would feel they may lose their jobs. Their jobs will be replaced by a computer system. So management should consider how to limit the resistance of technicians to encourage them having intention to use the system as a supportive tool to make their works more efficient and reduce their workload.

Moreover, classifying the timbre quality of flute using traditional human-methods is insufficient to classify the timbre quality that customers want or look for in flute products. Customers differ dramatically in their timbre preferences for flute. Thus, the proposed automatic timbre quality evaluation system was developed to enable the prediction of total timbre quality of flute products.

In short, the ADTQE system can be used as a quality decision tool to classify the timbre quality in Chinese flute industry. At the classifying levels, the system can be used by different technicians who don't need to possess the timbre skill or experience of flute to test the timbre for deciding the timbre quality of flute. This automatic system can improve the speed of the process in the timbre quality testing task to increase productivities and economic benefits for Chinese flute industry. In addition, the automatic system has a uniform standard to classify the timbre quality for a long period of time even 24 hours a day, not like technicians who is easily influenced by the environment, mood, psychological factors, limited energy or other factors during their classification process.

Acknowledgements

The experiments were under the support of Pin-Chung Lin musician in Chia-Yin Musical Instrument Company and Fa-Chang Lin and Shang-Hwa Su musicians in Min-Chu Musical Instrument Company. The author would like to thank and acknowledge these people for their great important support and help.

The author would also like to thank that this work was supported by the National Science Council of Taiwan, ROC under Grant No. NSC-94-2416-H-167-007 and NSC-94-2614-E-167-001.

References

Abbott, J. A. (1999). Quality measurement of fruits and vegetables. *Postharvest Biology and Technology, 15*, 207–225.

Carvalho, P., Araujo, H., & Dourado, A. (1999). An automatic optical sensor for vessels and fibers quality inspection in pulp production. *Computers & Industrial Engineering, 37*, 355–358.

Chen, C.-S. (2002). The summary of timbre of *dizi*. Shanghai Art Graduate School. Available from http://suona.com/instr.htm.03-17.

Deitel, H. M., & Deitel, P. J. (2004). *C How to program* (4th ed.). Pearson Education, Inc., Pearson Prentice Hall.

Di-Yin Net (2005). How to choose a good quality of *dizi*. <http://www.diin.cn/index.asp> Accessed 25.06.05.

Epps, J., Smith, J., & Wolfe, J. (1997). A novel instrument to measure acoustic resonances of the vocal tract during speech. *Measurement Science and Technology, 8*, 1112–1121.

Holland, J. M. (1992). *Adaptation in natural and artificial systems, 1975* (2nd ed.). University of Michigan Press, MIT Press.

Houtsma, A. (1997). Pitch and timbre: definition, meaning and use. *Journal of New Music Research, 26*, 104–115.

Ilmoniemi, M., Valimaki, V., & Huotilainen, M. (2004). Subjective evaluation of musical instrument timbre modifications. Joint Baltic-Nordic Acoustic Meeting, 8–10 June, Mariehamn, Aland, pp. 5–11.

Kaufman, L., & Rousseeuw, P. J. (1989). *Finding groups in data: An introduction to cluster analysis*. New York: John Wiley.

Kostek, B. (1999). *Soft computing in acoustics, applications of neural networks, fuzzy logic and rough sets to musical acoustics, studies in fuzziness and soft computing*. Heidelberg, New York: Physical Verlag.

Kuo, H. C., & Wu, L. J. (2002). An image tracking system for welded steams using fuzzy logic. *Journal or Materials Processing Technology, 120*, 169–185.

Lee, H. M. (1996). Group decision making using fuzzy set theory for evaluating the rate of aggregative risk in software development. *Fuzzy Sets and Systems, 80*(3), 261–271.

McAulay, R. J., & Quatiere, T. F. (1986). Speech analysis/synthesis based on a sinusoidal representation. *IEEE Transaction on Acoustics, Speech and Signal Processing, 34*, 744–754.

Neufeldt, V. E. (1988). *Webster's New World Dictionary* (3rd college ed.). New York: Simon and Schuster.

Sandell, G. J., & Martens, W. (1995). Perceptual evaluation of principal-component-based synthesis of musical timbres. *Journal of The Audio Engineering Society*, 1013–1028.

Serra, X. (1997). Musical sound modeling with sinusoids plus noise. In A. Picciali, C. Roads, & S. T. Pope (Eds.), *Musical signal processing*. Swets Zeitlinger Publisher.

Swanepoel, K. T. (2004). Decision support system: Real-time control of manufacturing processes. *Journal of Manufacturing Technology Management, 15*(1), 68–75.

Van Harten, W. H., Casparie, T. F., & Fisscher, O. A. M. (2000). Methodological considerations on the assessment of the implementation of quality management systems. *Health Policy, 54*, 187–200.

Verdu Jover, A. J., Llorens Montes, F. J., & Fuentes, M. del M. F. (2004). Measuring perceptions of quality in food products: The case of red wine. *Food Quality and Preference, 15*, 453–467.

Wolfe, J., & Smith, J. (2001). Embouchures and end effects in air-jet instruments. In *International congress on acoustics*, Rome, Session 8.

Wolfe, J., Smith, J., Tann, J., & Fletcher, N. H. (2001). Acoustic impedance of classical and modern flutes. *Journal of Sound and Vibration, 243*, 127–144.