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DEVELOPMENT OF CUSTOMIZED SOUND MEASUREMENT PROGRAM AND APPLICATION TO PRODUCT NOISE EVALUATION

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Product sound quality and noise improvement have been drawn much attention for the demand of high quality products. The commercial sound measurement tools are generally available but expensive. This work aims to develop the low cost and customized sound measurement program (SMP) and apply to product sound measurement and noise evaluation. First, we discuss the theoretical background for noise evaluation and so forth conceptually layout the SMP for functional design. SMP can do signal processing on sound data and obtain corresponding evaluation index accordingly. SMP is the MATLAB base standalone graphic user interface (GUI) program including the input, spectral analysis, time-frequency analysis, decay rate analysis, and filtering modules. The input module can capture the sound signal via the built-in microphone in computer, import signal data or read wave file. Finally, by using SMP in dealing with product sound and noise evaluation, this work shows several case studies, such as musical instrument sound, dial tone sound, wiper noise, motorcycle vibration and rotary compressor noise. For the sound characteristics of percussion instrument, using SMP can clearly identify the fundamental frequencies and overtone frequencies as well as the decay rate and modal damping ratios. Spectral analysis in SMP can calibrate different dial tone button sounds properly. With the filtering feature, one can differentiate the frequency bands of wiper noise in upward and downward sweeping condition. Case studies also show vibration spectrograms for a motorcycle and the beating sound of a rotary compressor to characterize critical bands. The SMP is not only for diagnosis tools but also capable for quality inspection of products; in particular, the SMP is flexible to expand its module for post processing depending on the need of products.
Keywords: sound, spectral analysis, time-frequency analysis, decay rate, filtering.

1. Introduction

Sound measurement and analysis can help to calibrate musical sound characteristics, to know product noise or abnormal sound, and to control the unwanted noise. Analysis of sound includes time domain method and frequency domain method, such as statistical analysis, decay rate analysis, spectral analysis, time-frequency plot analysis, etc. For sound measurement, one will need the microphone sensor to capture the time history of sound and the FFT (fast Fourier transfer) analyser to obtain sound spectrum and characterize the contents of sound. The commercial available analysers are for general application with multiple complex functions and may be expensive. In practice, one may need the customized and low cost sound measurement and analysis tool to solve the product noise problem. This work shows the development of Sound Measurement Program (SMP) and its applications to practical sound measurement and noise evaluation.

Sound quality evaluation not only deals with the physical sound signal but also refer to physical sensory response. Physical and psychophysical response may have cross effect to each other and make the sound evaluation a complicated subject. In general, one will need fast and precise measurement of sound and effective evaluation method to get corresponding index to characterize the sound or noise, especially the relation to the human perception [1].

For musical instrument sound study, researchers will collect the play sound and analyse to get proper objective indices to link with subjective feel from musicians or experts. Stepanek [2] developed the verbal description measure to musical sound timbre. Sound quality is a complex and involved with multilayer interpretation process. Blauert and Jekosch [3] discussed the sound-quality formation process and characterized four layers of human perception of sound quality. Wang et al. [4] studied the sound response of vibraphone for different playing techniques and interpreted the continuity of sound decay rate, pitch frequency and timbre of sound spectrum by time and frequency domain analysis.

A good sound quality of product becomes the marketing opportunity. The demands on tool and acoustic measure for obtaining sound characteristics of products are important. Ballester [5] adopts objective indices to evaluate human reaction to the hairdryer's noise. Lyon [6] discussed the product design for sound quality from the customer's perception to product engineer's evaluation procedures and techniques. Carletti and Pedrielli [7] performed sound measurement of earth moving construction machines and presented a predictive model for the annoyance conditions. Cerrato [8] briefly reviewed the techniques in investigating automotive sound and vibration quality and presented typical sound spectrum and spectrograms of engine noise as well as tire/road noise and wind noise.

Sound or noise measurement and its analysis majorly base on FFT techniques are necessary for various industries and practical applications. This work develops Sound Measurement Program (SMP) that can perform FFT to get spectral analysis, short time Fourier transform (STFT) to get spectrograms, i.e. time-frequency plot, filtering operation and time history decay rate analysis. Section 2 briefly reviews the theoretical background for noise evaluation. Section 3 shows the SMP layout and its functional design. Section 4 presents several case studies by using SMP to characterize the measured sound response of practical applications.

2. Theoretical development for noise evaluation

This section summarizes the technical background for noise evaluation. The basic physical quantity of sound is the sound pressure, i.e. the atmosphere pressure oscillation due to disturbance and propagated by the air medium. The wave theory has good interpolation of propagating sound signal. A typical sound pressure $p(t)$ is transient and measurable without the effect of P_s the static pressure of atmosphere. P_{rms} is the root mean square value of measured sound pressure and considered the effective sound pressure to obtain sound pressure level (SPL) as follows:

$$L_p = 20\log\left(\frac{P_{rms}}{P_{ref}}\right). \tag{1}$$

P_{ref} is 20×10^{-6} Pa the threshold of audible sound pressure near 1000 Hz. The unit of SPL is dB *re* 20×10^{-6} Pa. In addition, the A-weighted SPL is noted as dB(A) accounting for the human hearing ability in different frequency range and with frequency weighted calculation from SPL.

The powerful tool of FFT is to obtain spectrum from time history data. The superposition of sinusoidal waves is not able to identify their amplitudes and frequencies in time domain. However, one can get Fourier spectrum $P(f)$ in frequency domain by Fourier transform (FT) operation on time data $p(t)$ as well as the reverse operation by inverse Fourier transform (IFT) as follows:

$$P(f) = \Im[p(t)] = \int_{-\infty}^{\infty} p(t)e^{-i2\pi ft}dt. \quad (2)$$

$$p(t) = \Im^{-1}[P(f)] = \int_{-\infty}^{\infty} P(f)e^{i2\pi ft}df. \quad (3)$$

f is the frequency in Hz; $\Im[\ ]$ and $\Im^{-1}[\ ]$ are Fourier transform and inverse Fourier transform operator, respectively. Noted that $P(f)$ is complex number that can be expressed in amplitude and phase angle in frequency domain. In practice, it is not possible to obtain Fourier spectrum from Eq. (2) and neither to perform IFT in Eq. (3). Therefore, Discrete Fourier transform (DFT) and inverse DFT are the practical ways to get digitalized Fourier spectrum or time data as follows.

$$P(m\Delta f) = \sum_{n=1}^{N_t} p(n\Delta t)e^{-i(2\pi\frac{mn}{N_t})}\Delta t, m = 1, 2, ..., N_f. \quad (4)$$

$$p(n\Delta t) = \sum_{m=1}^{N_f} P(m\Delta f)e^{i(2\pi\frac{mn}{N_t})}\Delta f, n = 1, 2..., N_t. \quad (5)$$

Since the DFT is time-consuming numerical process, spectral analysis generally adopts fast Fourier transform (FFT) instead. There are important FFT variables as follows:

$$\Delta f = \frac{1}{T},\ T = N_t\Delta t,\ \Delta t = \frac{1}{f_s},\ f_s = 2\times f_{nyq},\ f_{nyq} = N_f \times \Delta f. \quad (6)$$

Δf is the interval frequency in Hz; T is the time frame for FFT; N_t is the number of time data; Δt is the time interval; f_s is the sampling frequency; f_{nyq} is the Nyquist frequency, just the half of sampling frequency; N_f is the number of effective data in frequency domain, equal to the half number of time data. Knowing any two of above FFT parameters can determine all variables. Proper selection of FFT variables is the important skill for sound and vibration analysist.

Other than Fourier spectrum, auto power spectral density (PSD) function is also of interest as follows:

$$G_{pp}(f) = P^*(f)P(f). \quad (7)$$

$G_{pp}(f)$ is also known as auto spectrum or auto PSD that can take the average operation to reduce the signal random noise and obtain smooth spectrum. In treating a long period of time data, a series operation of FFT on time data or short time Fourier transform (STFT) can produce spectrograms or simply called time-frequency plot or waterfall plot that is useful for machine run-up and coast-down tests to get frequency domain spectrum verse time.

In spectral analysis to obtain Fourier spectrum or auto spectrum from the measured time data, leakage is not avoidable effect, because the signal's frequency will be random values that divided by the interval frequency is not always integer. Therefore, the signal frequency is not exactly predictable by FFT. The weighting function $w(t)$ or called window function needs to apply to original time data as follows:

$$\hat{p}(t) = p(t) \otimes w(t). \quad (8)$$

$\hat{p}(t)$ is the weighted signal to be performed FFT to reduce the leakage effect. $w(t)$ is the weighting window functions [9].

3. Development of Sound Measurement Program (SMP)

With the brief review of signal processing and sound analysis, we will introduce the layout for function design of the SMP. We use ISOC concept to develop the program, i.e. Input, System program, Output and Control Variables (CVs). Fig. 3 summarizes the program flow chart of SMP base on ISOC discussed as follows:

- **Input**: There are three input methods to get the time history data of signal as follows:
  - o **Direct data acquisition** (DAQ). DAQ adopts the default intrinsic microphone in computer, i.e. WINSOUND device, to capture sound response.
  - o **Read the text data file**. The data file is with the extension file name TXT that contains two columns of ASCII code numerical data.
  - o **Read the wave file**. The recorded sound should be in WAV format.
- **System program**: SMP contains the main Program and several subprograms.
  - o **Spectral analysis**: is to obtain auto spectrum from Eq. (7). One can specify different setup of FFT parameters, as listed in Eqns. (6), and select different weighting windows, such as Hanning, Kaiser-Bessel, flat-top and exponential windows.
  - o **Decay rate analysis**: is suitable for original sound history data with decay effect to determine the signal decay rate.
  - o **STFT analysis**: is to obtain the time-frequency plot and can flexibly select the range of time and interested frequency bands to obtain the desired spectrograms.
  - o **Filtering analysis**: is able to do band pass or gate pass filter with flexible selection of frequency range and regenerate the new time history of sound data after filtered.
- **Output**: Users can have direct view on analysis plots and operate zoom in or zoom out as well as denoting observed values on the plot. Users can also choose to capture the data TXT files or convert the measured sound data to WAV files, and vice versa.
- **Control Variables**: the main program and different modules provide flexible selection on signal processing parameter setup to obtain appropriate analysis results.

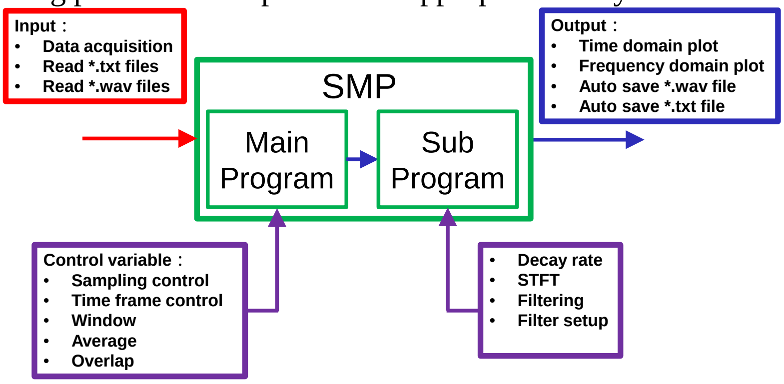


Figure 1: Program flow chart for SMP.

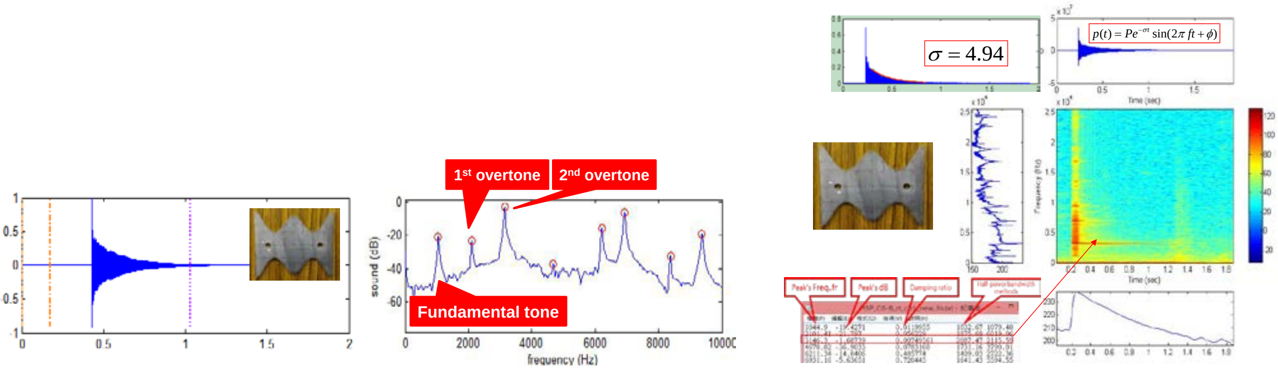
4. Application of SMP to sound/noise analysis.

4.1 Musical instrument sound analysis

Harmonic sound plate (HSP) is a special shape of metallophone design [10] that can produce overtone frequencies with respect to the fundamental frequency being integer ratios and called HSP. Fig. 2(a) and 2(b) shows the time history and spectral analysis of percussion sound of HSP, respectively. One can clearly identify the fundamental and overtone frequencies and get the numerical output for frequencies and peak's dB as well as modal damping ratios as shown in Fig. 2(c).

Fig. 2(c) is the result from STFT analysis. The obtained time-frequency plot or spectrogram can visualize the decay effect of percussion sound. The second overtone frequency has the longest response over time. The third peak frequency 3146 Hz has the smallest decay rate 0.00749. This complies with the decay effect observed in spectrograms. For overall decay effect of percussion, we can use the decay rate analysis program to determine the decay rate σ =4.94.

SMP can help users to identify the fundamental frequency and overtone frequencies of percussion instrument sound and determine if the pitch frequency is correct and its timbre characteristics. The spectrograms can give an overview on time-frequency response for different peak frequency response. The decay rate analysis can characterize the continuity effect of percussion sound.



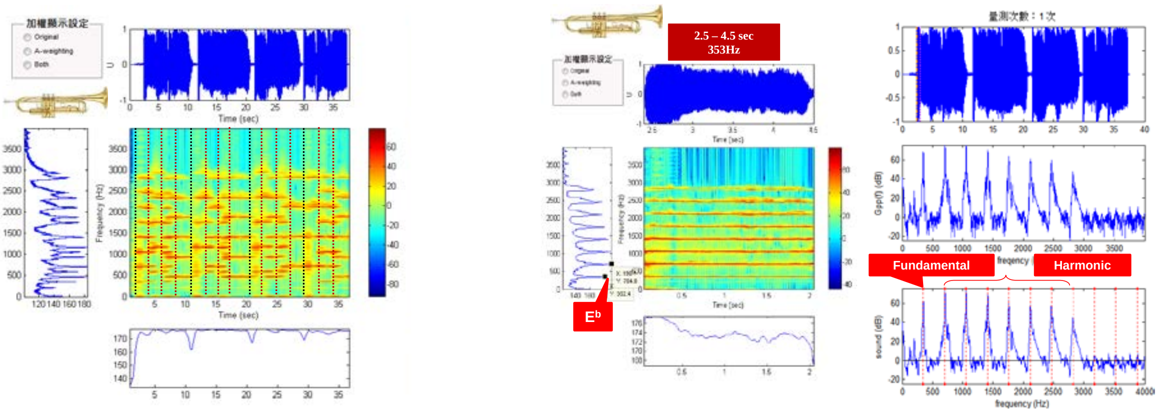
(a) Time history (b) Auto spectrum plot (c) Time-frequency plot

Figure 2: Percussion sound analysis for Harmonic Sound Plate (HSP).

Another example of musical instrument sound analysis is the trumpet sound. Fig. 3 (a) shows the spectrogram for a song about 37.6 sec played by trumpet. One can observe there are four sections in the song. The dotted lines separate each played musical note. One can visualize the peak frequencies for each note.

In order to check the peak frequencies response precisely, we can do in two approaches. One is in STFT program to select the time range and get the spectrograms as shown in the left of Fig. 3(b). One can get the fundamental frequency 352.4Hz, which is the pitch frequency of Note Eb, and those harmonic frequencies consisting of the timbre for trumpet. The other way is to use spectral analysis function in main program menu. One can flexibly select the start and end time of signal data to perform FFT and get the sound spectrum for that period. The right plot of Fig. 3(b) show the fundamental frequency and higher order harmonics with the red dotted line remarks.

One should properly choose the time range for both spectral analysis and spectrograms analysis. For the case of trumpet sound analysis, one can carry on the analysis for any period of sound to calibrate the musical notes and interpret the trumpet timbre.



(a) Time-frequency plot for a song (b) Time-frequency plot for a range of time

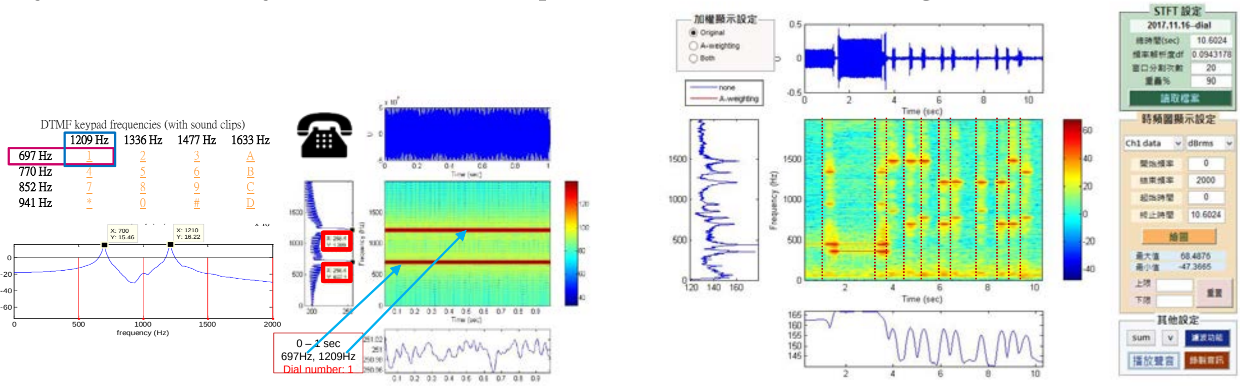
Figure 3: Trumpet sound analysis.

4.2 Dial tone sound analysis

People might be curious about the dial tone sound in dialling different digit number. Actually, there are two frequencies composed of a dial tone number as depicted on Fig. 4(a) that is the spectrograms of dial digit number 1 by STFT analysis program. One can clearly identify the two frequencies are 697 and 1029Hz, respectively, for the ideal dial tone sound. The other way to characterize the dial tone sound is by spectral analysis to get auto spectrum. With the appropriate setup for the FFT parameter, one can obtain the auto spectrum that reveals two peak frequencies as expected.

Fig. 4(b) shows the spectrogram analysis for a series of dial tones for a phone number. At first, the dial tone sound is at 440Hz. The following is digit number 0 for setting up the call. The followings are nine digit numbers' dial tones that are the phone number with a very short period for each dial. One can still observe there are two peak frequencies for each digit number dial tone. From the peak frequency values, one can know what the phone number is.

SMP can play a good role on examining the desired time and frequency domain response for a long length of recorded sound. For the dial tone sound example, users can use either the spectral analysis or STFT analysis to obtain sound spectrum and calibrate what digit numbers dialled.



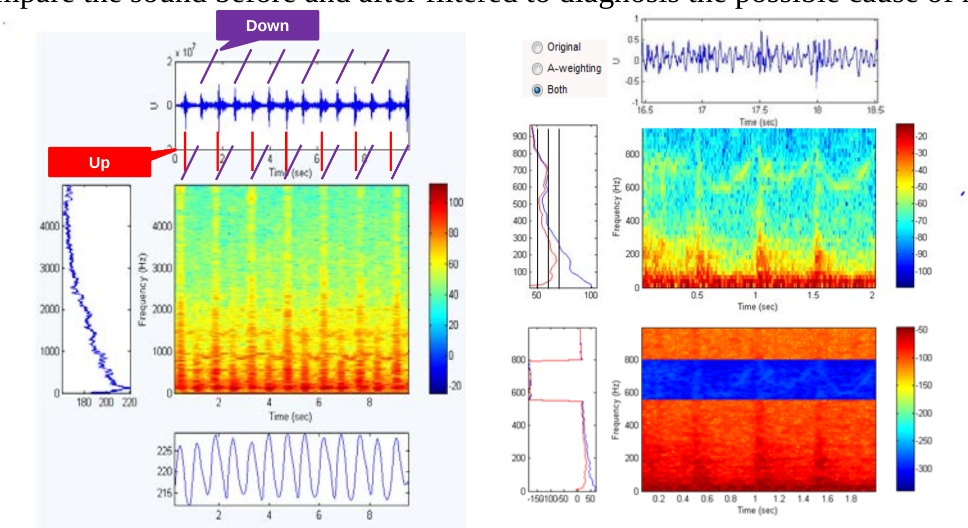
(a) Dial tone sound for digit number 1 (b) A series of dial tones sound for a phone number

Figure 4: Dial tone sound analysis.

4.3 Wiper noise analysis

Wipers are one of components for automobile. Clean and quiet wiping is generally the requirement for good quality of wiper. Fig. 5(a) shows the spectrograms of time-frequency plot for about 10 sec of wiper's sound. From the time history and spectrogram plots, one can easily differentiate the upward and downward wiping and observe the major frequency bands contributing to the wiper sound.

Fig. 5(b) shows the time-frequency plot for the original wiper sound and the filtered sound applied the gate-pass filter at 600-800Hz. The V shape in the spectrogram is from the motor effect sound. With the use of SMP, one can target the critical bands of interest to operate filtering as desired and compare the sound before and after filtered to diagnosis the possible cause of noise.



(a) Upward and downward wiping (b) Filter effect

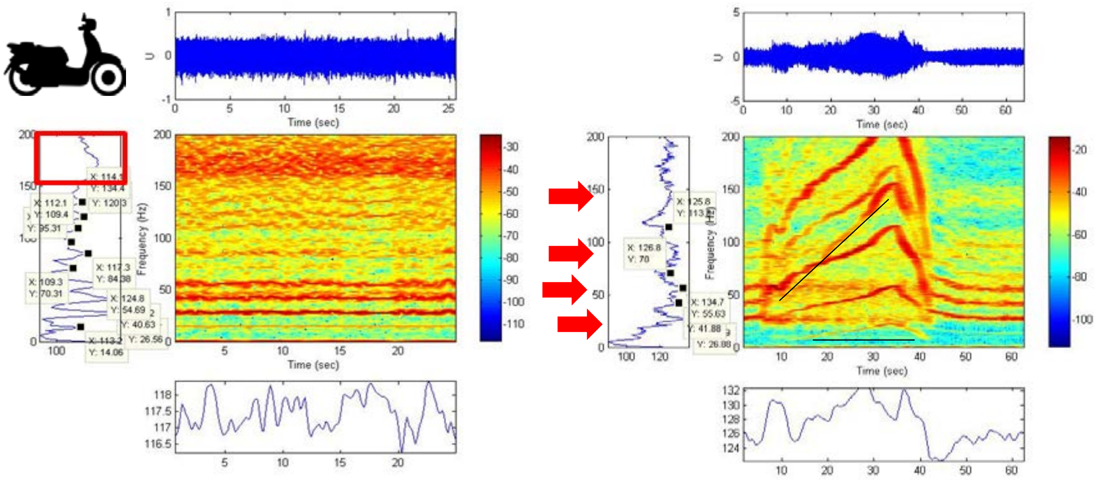
Figure 5: Wiper noise analysis.

4.4 Motorcycle vibration analysis

SMP can also analyse the vibration signal, typically measured by the accelerometer, i.e. acceleration signal. The measured data file must be the TXT file format as described in Section 3. Fig. 6(a) shows the time-frequency plot for the acceleration at the frame of motorcycle in idle condition. There are several peak frequencies referred to the rotating speed frequency as the fundamental frequency, and the rest of harmonics are integer ratios over the rotating speed frequency. The narrow band response around 150-180Hz is present over the time.

Similar to Fig. 6(a), Fig. 6(b) shows the motorcycle in run-up and coast-down conditions. From the spectrograms, one can observe the skew red lines moving up and down for the peak resonance response due to the increasing and decreasing engine speed. After about 40sec, the motorcycle is back to idle condition, and the red lines become the horizontal lines indicating the rotating speed frequency and its harmonics. During the run-up or coast-down stage, one can see the narrow band effect of horizontal lines having high-level of vibration response that may come from the structural natural frequencies effect, as indicated by red arrows.

The spectrograms plot is useful for such a run-up or coast-down test that the rotating speed can vary increasingly or decreasingly, and engineer can easily differentiate the frequencies with peak response either from the structural natural frequencies related or from the rotating speed frequency related. This will help to give a clue for the next action in source or path diagnosis.



(a) Idle condition (b) Run-up and coast-down conditions

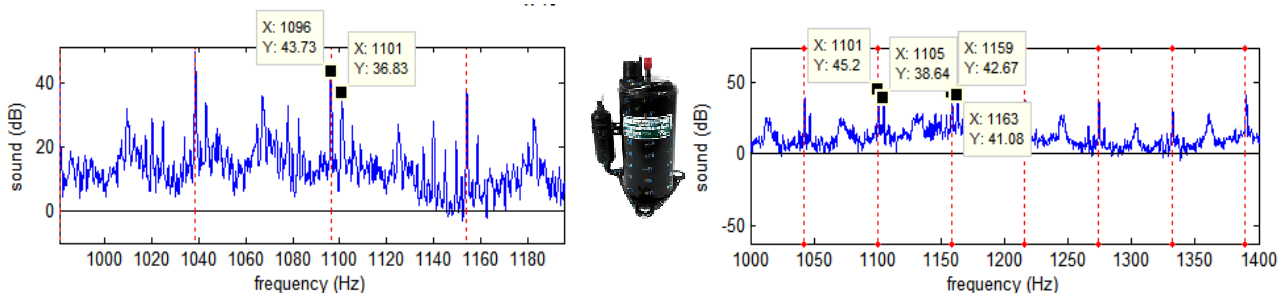
Figure 6: Motorcycle vibration analysis.

4.5 Rotary compressor noise analysis

The rotary compressor used in many applications such as air conditioners for its simple structure is of interest its sound quality. Although most rotary compressors are with low noise level, the abnormal sound may affect the hearing perception. Fig. 7 presents a case study for the rotary compressor with beating sound. With the use of SMP, we identify the beating sound comes from two close frequencies interaction effect.

Fig. 7(a) shows the spectral analysis for the rotary compressor running in steady state, i.e. the constant rotating speed of motor, without abnormal sound. There is the side band frequency at 1101Hz near the harmonic frequency of rotating speed at 1096Hz. The peak value of sound pressure level for the side band frequency at 1101Hz is 36 dB and about 6dB lower than that of harmonic frequency at 1096Hz. This is the acceptable case without the apparent annoyance beating sound.

Fig. 7(b) is the spectral analysis result for the compressor with beating sound at the same operating condition. The sound pressure level of side band frequency at 1163Hz with 41.08dB is very close to that of the harmonic frequency 1159Hz with 42.67Hz. The two close frequencies with relatively equal levels cause the perception of apparent beating sound. With the help of filtering module by eliminating the side band frequency, we listen and compare the original sound and the filtered sound to prove that the high level of side band frequency response actually results in the beating sound effect.



(a) Acceptable normal sound spectrum (b) Abnormal beating sound spectrum

Figure 7: Rotary compressor noise analysis.

5. Conclusions

This work presents the development of low cost, customized Sound Measurement Program (SMP). We introduce the basic principles of background knowledge in developing and applying SMP. SMP is a MATLAB base, standalone and helpful tool and suitable for various types of product noise or sound characteristics analysis. The demonstration cases include musical instrument sound analysis for the percussion HSP and trumpet, telephone dial tone sound analysis, wiper noise analysis, motorcycle vibration analysis and rotary compressor noise analysis. SMP can meet different needs, such as characterizing the product sound and diagnosing the product noise, with functions for spectral analysis base on FFT, STFT analysis to obtain time-frequency plot or spectrograms, filtering analysis and decay rate analysis.

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