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Measurement and Analysis of Dental Handpiece Vibration for Real-Time Discrimination of Tooth Layers

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Abstract— **This paper introduces a real-time tooth layers identification technique which is based on signal processing of air-turbine dental handpiece. The technique will serve as an assistive tool in dental restoration procedures; where the tactile and visual senses of dentists are their only feedback sources, to minimize healthy tooth removal. The vibration of the dental handpiece is measured by two sensors i.e. accelerometer and Laser Doppler Vibrometer. The frequency analysis reveals clean and distinguishable peaks and there are no major differences between the sensors readings. It is found that the first vibration peak in the frequency spectrum of the handpiece corresponds to its angular velocity. This frequency is selected as the feature for the discrimination between enamel and dentin. A qualitative analysis is conducted on air-turbine handpieces to obtain and verify the practicality of our strategy for cutting material identification. The experimental results indicated that the angular velocity of an air-turbine handpiece is changed under different loads. It is shown that the angular velocity reduction matched to the pattern predicted by our qualitative study. Finally, the air-turbine handpiece is tested on a human tooth to investigate the effect of tooth layers in the angular velocity at different supply pressures. The main focus of this analysis is on discrimination of enamel and dentin as the two major tooth components. It is shown that the technique can be expanded to cover other tooth layers as well. Our study shows distinct regions for enamel and dentin on pressure-velocity curves. These curves can accurately differentiate enamel and dentin in a known air pressure supply**.

Index Terms— **Vibration Measurements, Dental Handpieces, Enamel, Dentin, Air-turbine Handpiece**

I. INTRODUCTION

TOOTH is an inhomogeneous body part, and is composed of different layers including enamel, dentin, pulp, cementum, etc. Dentists need to remove infected parts of the tooth to restore its functionality. A dental filling, also called a dental restoration is a process to retain the functionality, integrity and morphology of tooth structure. This process involves removing carries and infections usually with a dental handpiece (a high speed drill), filling the cavity with restoration materials, and forming that before it solidifies. Dental restoration is not just limited to the removal of the infected tooth tissues, but it may also involved removal of the old filling restoration materials. Common dental filling materials do not degrade fast, but external forces by clenching or grinding may result in fatigue, cracks and ultimately failure. The performance of dental restorations is subject to several factors, that includes the restorative materials [1-3], the practitioner's level of experience [4], the type and position of tooth [5, 6], the restoration's shape, size and number of restored surfaces [7, 8], as well as the patient's age [1, 8]. If the old filling collapses, there is a high potential for developing new decay that requires replacing of the old restoration and removing cavities. Replacing of old restorations is still one of the most frequently (60%) procedures in clinical practice [9, 10] which exceeds the restoration of new lesions. This rate has not been declined in spite of continuous dental restoration materials advancements [11]. Replacing a restoration, however, does not exclude the likelihood of the same imperfections and/or new caries occurring around the filling [12].

Dentists are trained to be experts of interpretations of their tactile and visual senses as one of their only tools to manage the tooth restorations as well as other daily dental operations. However, there are cases in dental procedures that tactile and visual senses are insufficient feedback sources to rely. Although dental caries are usually darker than healthy enamel, there are cases that healthy enamel may have a dark appearance [13]. In addition, sometimes carious lesions are the same color as the healthy tooth surfaces. Also, the composite dental restoration materials have the same color as normal tooth. The high speed of the dental handpiece, limitation of oral space, uncontrolled patient factors, and remotely located carries are some of the other factors that affect the accuracy and reliability of tactile and visual senses. In addition, the dentist's fatigue from repeated movements may result in impaired control of the dental handpieces that can easily remove a big portion of a tooth with a small wrist or fingers motion. It can thus be concluded that with current restoration and treatment routines the loss of healthy tooth structure is inevitable [14, 15]. It should be emphasized that tooth structure is one of the few parts that the body has limited healing ability and extensive structure loss will be permanent. An intelligent system that can be integrated with the dentists' expertise in tactile and visual senses and brings the flexibility of selectively removing tooth structure will be highly

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advantageous. As a result, providing online information about the material in the cutting process is the critical component of such intelligent handpieces. Similar to many mechanical devices, analysis of the dental handpiece vibration is a potential source of information to determine the condition of dental bur, turbine, shaft, and bearings.

Studying vibration in dentistry is a wide research field, because the vibration signal is a rich source of information about the status of the operation that can be interpreted selectively to serve in many applications. Regardless of the details, all vibration investigations in dentistry can be categorized in two main topics: (i) vibration analysis of dentistry's instruments such as ultrasonic scalers [16], endosonic files [17], ultrasonic retrograde systems [18], electric toothbrushes [19], dental laboratory vibrator [20], dental handpieces [21, 22]; etc. (ii) vibration analysis of teeth [23, 24], dental implants [25, 26] and dental bonding agents [27]. Dental handpiece vibration analysis is adopted in investigating on some dental related diseases [21], damages [28], achieving a better design for dental devices [29], and dental implants [25].

Vibration analysis of dental handpieces as a diagnosis/identification tool is used by Castellini, *et al*., [23] to propose a noninvasive measurement procedure for the diagnosis of structural defects on human teeth. They concluded that dental defects could increase the resonance frequencies as well as appearance of well-defined anti-resonances. Kocher *et al*., [30] combined the vibration signal of an ultrasonic scaler with fuzzy set to test the suitability of an automatic identification of different tooth layers. They concluded that the application of fuzzy pattern recognition in combination with a dental ultrasonic device was well suited for the classification of tooth layers.

In this paper, measurements and frequency analysis of air-turbine handpieces vibration have been employed for identification and discrimination of tooth layers. Enamel and dentin as the two main tooth components are selected in our studies; however the technique can be expanded to other materials including dental restorations and caries. This study introduces a novel approach that can be implemented in real-time applications. Two sensors, including one contact (an accelerometer), and one noncontact (a Laser Doppler Vibrometer) are employed for measuring vibration signals. In section 2, after introducing the experimental setup, it is shown that there are no major differences between these sensors in our application. However, the accelerometer is selected for the rest of the study considering practical aspects. In section 3, a qualitative analysis is done for air-turbine handpieces modeling. A load identification technique based on the pressure-velocity curves is proposed for cutting material identification. Two sets of experiments are undertaken in this section. In the first one, the parabolic relation of the input pressure and the angular velocity is confirmed practically; and in the second experiment, pressure-velocity curves are obtained for continuous mediums including oil and honey. A similar approach has been conducted on a human tooth in section 4 to discriminate between enamel and dentin. Finally, it is concluded that this technique can be adopted as an effective tool for dental applications in online tooth layer identification.

II. VIBRATION MEASUREMENT OF A DENTAL HANDPIECE

Time domain signal of vibration is a rich source of information, however, in most cases it is affected by noise and disturbances of the surrounding. Moreover, time domain signal is bulky i.e., can be condensed and expressed in terms of fundamental frequencies and their amplitudes. The amplitude/frequency representation of a vibration signal is a more appropriate way of storing and analyzing the information that the signal contains.

For dental headpiece application, the frequency analysis obtained by Fast Fourier Transform. FFT is a capable tool of identifying the frequencies of dominant components in the signal. As it will be shown in the experimental results, the FFT signal is less affected by the noise. An experimental setup has been developed (Figure 1) to collect the vibration signal of dental headpieces, and perform FFT analysis. The setup includes a complete set of an air-turbine handpiece (NSK, MACH-LITE XT M), an accelerometer (DYTRAN 1051V1), a Laser Doppler Vibrometer (LDV, OMETRON VQ-500-DV), a High-speed DAQ card (LDS DACTRON PHOTON II), and a signal processing software for FFT analysis (RT PRO PHOTON). Both the accelerometer and the LDV are high frequency sensors (10k Hz for the accelerometer, and 22k Hz for the LDV). The air-turbine setup is driven by an air compressor (BOSTITCH, 1.8 CFM @ 90PSI). A pressure regulator (SKEANS 150PSI) is also employed to adjust the compressor output pressure.

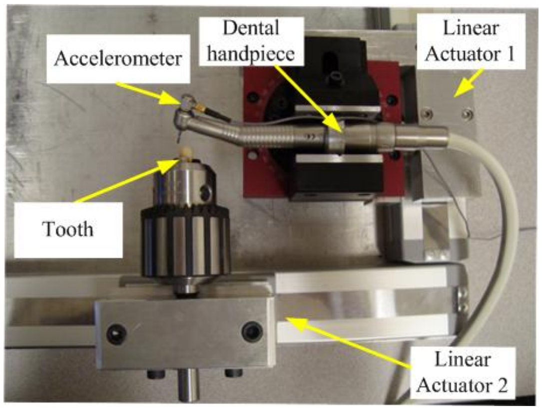


Figure 1: The experimental setup for vibration measurement of handpiece

The vibration signal of the dental handpiece in a wide spectrum i.e. 70 kHz, demonstrates some peaks that are apparently distinguishable from the noise level. These peaks are harmonics of each other, and are proportional to the angular velocity of the air-turbine handpiece. For this study, the location of the first peak (Hz) in the vibration spectrum has been selected as the reference and the spectrum is adjusted to only show the first peak. Figure 2 demonstrates the vibration spectrum of the dental headpiece when it is running free (unloaded). These vibration spectrums are obtained by the accelerometer and the LDV. As it can be seen, both sensors have the same peak frequency in their vibration spectrums. In addition, because the measuring point (on the handpiece) was different for the sensors, it can be concluded that the measurement does not depend on the location. The amplitude differences are due to the fact that the sensors are measuring different vibration variables (acceleration and velocity).

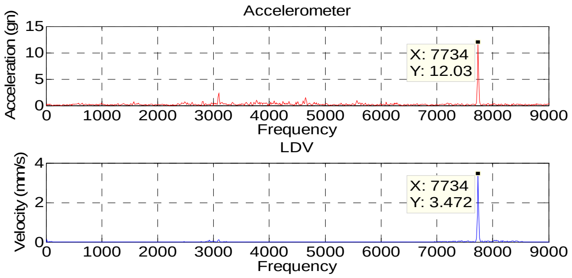


Figure 2: A comparison between measurement of the accelerometer and the LDV while the air-turbine handpiece is in unloaded case

To verify the consistency of the FFT analysis for accelerometers and LDVs, the vibration signal for the loaded dental handpiece is compared. An artificial tooth is selected as the load and the experimental results are depicted in Figure 3.

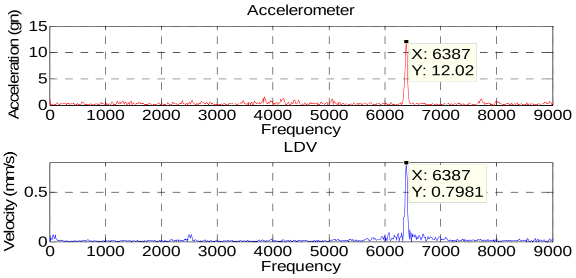


Figure 3: A comparison between measurement of the accelerometer and the LDV while the air-turbine handpiece is in loaded case

Experimental results suggest that both accelerometers and LDVs can be used for this application. Accelerometers are contact sensors with a wide variety of sizes and shapes. They cover a broad range of frequency and recently are available in very small sizes and low weights. LDVs on the other hand, are noncontact high frequency vibration measurement sensors that are working based on the Doppler Effect. These sensing techniques are famous for their high accuracy, and zero vibration interactions to the measurements. Although LDVs are used in dental analysis [23, 31]; they are not suitable for this study. The reason is the transmitted light of LDVs needs to be focused on the vibrating surface while in our application the handpiece is not stationary. Therefore, fixing the light for collecting data while the handpiece is moved for cutting will be challenging. Accelerometers, however, do not have this problem and they are the sole candidate for this study.

III. THE QUALITATIVE ANALYSIS OF A DENTAL HANDPIECE

Air-turbine dental handpieces are conventional pneumatic impulse turbines. These types of turbines are very efficient in converting the potential pneumatic energy to kinetic energy. Different characteristics of air-turbine handpieces such as torque, power, efficiency, flow, etc. have been studied in [32, 33]. Figure 4 shows the schematic of inlet and outlet velocities for an impulse turbine.

The mathematical formula for an air-turbine handpiece is obtained simply by considering the Bernoulli principle [34]:

$$\frac{p_1}{\rho g}+\frac{\tilde{u}_1}{g}+\frac{V_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{\tilde{u}_2}{g}+\frac{V_2^2}{2g}+z_2-h_q+h_s+h_v \qquad (1)$$

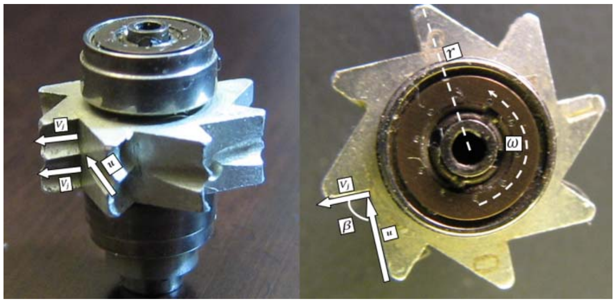


Figure 4: Inlet- and outlet-velocity diagrams for the air-turbine of the handpiece ($\mathbf{u = r\omega}$)

where. p, $\tilde{u}$, z, g and V denote for pressure, internal energy, height, gravitational acceleration and velocity respectively. '1' and '2' indexes display the inlet and outlet of the fluid (air) to the dental handpiece. Also,

$$h_q=\frac{dQ}{gdm}, \qquad h_s=\frac{dW_s}{gdm}, \qquad h_v=\frac{dW_v}{gdm}, \qquad (2)$$

where Q, W_s, and W_v, are the shaft work, work of pressure forces, and the shear work due to viscous stresses respectively. For the air-turbine application, p_1 is the pressure inside the compressor and its velocity V_1 is negligible. p_2 and V_2 are the pressure and velocity of the air just before contacting to the air-turbine (in the handpiece). Also, $\tilde{u}_1 \approx \tilde{u}_2$, $z_1 \approx z_2$, (the height difference between compressor and the handpiece is small). In addition, and h_s and h_v are near to zero because there is no shaft work, and viscous work is negligible. Thus, Equation (1) can be simplified as:

$$\frac{p_1}{\rho}\approx\frac{p_2}{\rho}+\frac{V_2^2}{2} \qquad (3)$$

V_2 is equal to the jet velocity (before contacting the turbine, V_j), and p_1 is the pressure of compressor (p_{comp}). Equation (3) can be simplified as,

$$V_j \approx \sqrt{p_{comp}} \qquad (4)$$

The power equation for this turbine is, [34]:

$$P=\rho\bar{Q}r\omega\big(V_j-r\omega\big)(1-\cos\beta) \qquad (5)$$

$\bar{Q}$, P, ω are flow rate, power and angular velocity. β, and r are parameters that defined in Figure 4 ($u=r\omega$). In unloaded case, the torque of air-turbine handpiece is approximately constant. Thus, the power in Equation (5) only depends on ω. Now, if Equation (4) is substituted in Equation (5), a qualitative relationship between the input (p_{comp}) and the output (ω) can obtained as,

$$\omega \approx \sqrt{p_{comp}} \qquad (6)$$

Based on Equation (6), it can be concluded that the relation between the inlet pressure and the dental bur velocity is parabolic. Fortunately, the pressure (p_{comp}) and the bur velocity (ω) are two components that can be measured easily with a high accuracy. Thus, the validity of the qualitative analysis can be found experimentally. To obtain the curve, the input pressure to the handpiece is varied and the angular velocity of the handpiece in unloaded case (the bur is turning free) is measured for each input pressure. The experimental results are depicted in Figure 5. These results confirm the relation of the angular velocity and pressure in equation (6).

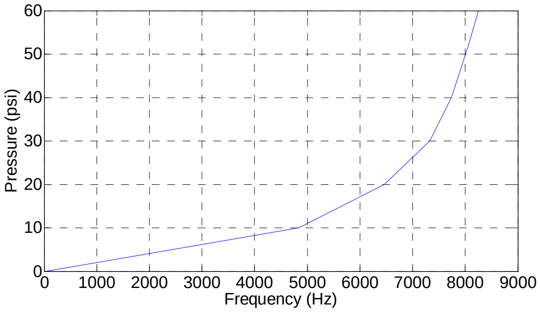


Figure 5: The relationship between input (pressure) and output (velocity Hz) is parabolic when air-turbine handpiece is in unloaded case

The ultimate goal of this study is to employ the FFT of the dental handpiece vibration signal for online identification of the cutting tooth layer. The best scenario to accomplish this is finding a mathematical description for tooth cutting operation. One of the problems in deriving such models is the nature of the problem which makes modeling of the cutting process a complicated task. In additions, different tooth layers, dental cavities, cutting direction, applied forces on the handpiece, and the bur types are parameters that add to the complexity of the mathematical modeling. In the absence of a mathematical model, an experimental model that follows the principles of the air-turbine handpieces is extremely advantageous. In the experimental model, the effect of those parameters that have less contribution to the angular velocity of the handpiece may appear as the deviation from the mean value. The existence of the deviations can not violate the generality of the experimental model as long as they remain inside a boundary and the resulting region will still be distinguishable for different tooth materials.

The identification of the key parameters is the first step in developing experimental curves. The force applied by the handpiece is one of the most important parameters of interest. Dentists intuitively relate that force to angular velocity of the bur and from there they identify the material they are removing at the moment. Here we use the same technique to identify cutting material.

The velocity of the bur is a function of several variables. However, the resistive torque due to the cut and the supply compressor pressure, have the major contributions. The resistive torque is a parameter that depends on the hardness of the material. Generally, softer materials require less torque/force to cut. For this application, the different tooth layers can be related to the bur velocity at various contact postures. To incorporate the effect of the pressure in the tooth-layer/bur-velocity region, experiments can be performed at different pressures when the dental bur is submerged in oil and honey. These liquids are selected, because they produce a continuous contact to the bur (as opposed to solid loads) and they have distinct viscosity (viscosity of oil is 50-100 cP and honey is over 3000 cP). Here, the liquid load can be considered as a resistive force that reduces the bur angular velocity. The experimental results are displayed in Figure 6.

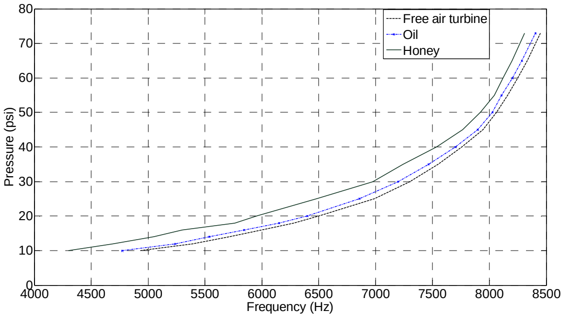


Figure 6: The pressure (psi) versus the velocity (Hz) of the air-turbine handpiece in loaded case (loads are honey and oil). The loaded curves are compared to unloaded curve (the bur runs freely in the air)

As it is observable in Figure 6, for a fixed pressure, the angular velocities of the loaded case (oil and honey) have been reduced compared to the unloaded case (the bur running free in the air.). This reduction is because of the increase in the resistive torque (honey is a more viscous liquid). In addition, similar to unloaded case, the trend for velocity reduction has a parabolic relation to the supplied pressure. These experimental interpretations follow the qualitative insight of the mathematical model given in Equations 1-6.

IV. Tooth Layers Identification Using Handpiece Vibration FFT Signal

The relation of the supply pressure, handpiece velocity and the material cutting resistance was demonstrated in the previous section. In those experiments, the continuous nature of the contact eliminated some of the variables such as contact angle and inhomogeneity of the material. In this section, the effect of different tooth layers on the angular velocity of the air-handpiece as a function of the supplied pressure is investigated. These tests are conducted *in vitro*; however, the results can be extended to *in vivo* experiments.

The experimental analysis is conducted first on Enamel. This layer is the hardest component of the human body which consists of 96% mineral, 1% organic material, and 3% water, [35]. It consists of elongated rods or columns that are formed of hydroxyapatite crystals.

Based on the observation, one of the effective factors in the dental handpiece angular velocity variation is the force applied by hand during the cutting process. Although the force can be related to the angular velocity, it is more preferable to reduce its impact on the measured parameters. A separate investigation needs to be conducted to study the effect of such force. To avoid the force of the hand, the measurements are conduct at the moment of the contact between handpiece and enamel. A small force is required by hand on the handpiece at the contact moment.

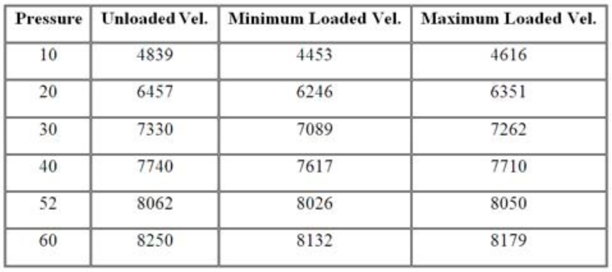
Although almost no forces are applied for the cut, the angular velocity of the handpiece fluctuates in a region with a fixed boundary. Thus, the minimum and the maximum values of the angular velocity were obtained. The experimental results are given in Table 1:

Pressure	Unloaded Vel.	Minimum Loaded Vel.	Maximum Loaded Vel.
10	4839	4277	4453
20	6457	5929	6164
30	7330	6800	7060
40	7740	7411	7582
52	8062	7904	8016
60	8250	8062	8109

Table 1: The velocity ranges (Hz) for enamel in the different pressures (psi)

The experimental analysis confirms a significant velocity reduction compared to the unloaded case. It should be mentioned here that the minimum and the maximum values were obtained after twenty consecutive contacts at each pressure. In addition, another five follow up points were measured for validation of the minimum and the maximum values. In all cases, the results fell within the boundary.

The next tooth layer for investigation is dentin. This layer is a calcified tissue, and is harder than bone, [35]. Similar to the enamel test, the velocity of the handpiece for different input pressures was measured. The contacts were carried out in a short time, and thus, a range was recorded for the velocity in each input pressure. The results are summarized in the Table 2:



Pressure	Unloaded Vel.	Minimum Loaded Vel.	Maximum Loaded Vel.
10	4839	4453	4616
20	6457	6246	6351
30	7330	7089	7262
40	7740	7617	7710
52	8062	8026	8050
60	8250	8132	8179

Table 2: The velocity ranges (Hz) for dentin in the different pressures (psi)

Based on the experimental results that are summarized in Tables 1 and 2, the minimum and the maximum loaded velocities for enamel are less than dentin at each pressure. For example, at input pressure 40 psi, the minimum loaded velocity for enamel and dentin is 7411 and 7617 Hz respectively (7411<7617); and the maximum loaded velocity is 7582 and 7710 for enamel and dentin respectively (7582<7710).

Tables 1 and 2 can be summarized in a Pressure-Velocity curve to represent different regions for enamel and dentin. Figure 7 displays these regions.

As it can be observed in Figure 7, two distinct regions are obtained for enamel and dentin. The exsitance of these regions indicates that by measuring the input pressure and the angular velocity, it can be determined whether the handpiece is working on enamel or dentin. For example, if the input pressure is 40 psi, and the angular velocity is 7500 Hz; then the handpiece is contacting to the enamel. A white zone between the enamel and dentin can also be observed at higher velocities. The zone indicates the area between the enamel and dentin that is hard to recognize during the operation. Luckily, this area is more vivid at higher input pressures that air-turbine handpieces are nominally working. This region can be quite useful for dentists to know if they are working on the transition region between the layers. This will help them to avoid removing the unwanted layer as they approach it.

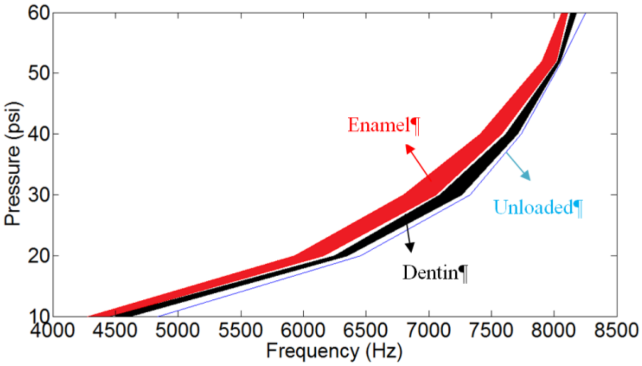


Figure 7: The pressure-velocity curves that indicate recognizable regions for dentin and enamel. The unloaded refers to the case that the dental handpiece has not any contacts.

V. CONCLUSION

This paper introduced a new approach for real-time discriminating of tooth layers. Although the focus was on enamel and dentin identification, without loss of generality, the method can be extended to include other tooth layers. The location of the first peak in the spectrum was selected as the angular velocity of the handpiece. It was shown that the velocity reduction of the air-turbine handpiece was different for enamel and dentin. In addition, based on the input pressure and velocity reduction, some distinct regions were found on P-V curves. These results indicate capability and advantages of the proposed method as a new tool to discriminate between enamel and dentin.

The proposed approach has also the potential to be employed in discriminating dental caries and dental restorative materials from enamel/dentin. In this application, dentists can be notified by a feedback alarm when they mistakenly cut healthy enamel/dentin instead of dental caries or dental restorative materials. Considering all of these facts, the proposed method can be applied to a real-time monitoring system to provide an assistive feedback tool for dentists, and increase reliability of dental operations.

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