Analysis of handling noises on wound strings

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This study analyzes the handling noises that occur when a finger is slided along a wound string. The resulting noise has a harmonic structure due to the periodic texture of the wound string. The frequency of the harmonics and the root-mean-square amplitude of the noise were found to be linearly proportional to the sliding speed. In addition, the sliding excites the longitudinal modes of the string, thus resulting in a set of static harmonics in the noise spectrum. The sliding excites different longitudinal modes depending on the sliding location.
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1. Introduction

Although the basic vibrational behavior of musical strings is extensively studied in the literature (see, for example the book by Fletcher and Rossing[1]), not much is known about the unintentional handling sounds a musician makes when playing a stringed instrument. Interestingly, musicians, especially in classical music, often tend to avoid making these sounds, but artificially removing them completely will make the music sound unrealistic. This is one reason why synthetic music can sound less lively, or more machine-like, than a real recording.

One approach to correct this machine-like quality in synthesizers is to record a sample library of different handling sounds and trigger a sample whenever a specific sound is needed, as done by Laurson *et al.*[2] On the other hand, a parametric model would provide a more flexible and memory-efficient way of implementing the handling sounds. More information concerning parametric or model-based sound synthesis can be found, for example in the report by Välimäki *et al.*[3] Obviously, before a parametric model for the handling noises can be constructed, an in-depth analysis of the noise type must be presented.

This study analyzes the handling noise generated by sliding the fingertip or -nail along a wound string, thus producing a squeaky sound. This type of handling noise, usually called "fret noise" in the guitar terminology, can be heard often wherever a wound string is played with fingers. For the remainder of the article, this squeaky sound is simply referred to as handling noise.

This article is organized as follows: The measurement setup is described in detail in Sec. 2, and the general structure of the handling noise is explained in Sec. 3. A

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thorough analysis of the time-varying noise components is presented in Sec. 4, while the static noise components are analyzed in Sec. 5. Finally, conclusions are drawn in Sec. 6.

2. Measurement setup

The wound string handling noises on a steel-string acoustic guitar (Landola D-805E) were recorded in the small anechoic chamber at the Helsinki University of Technology. The guitar was placed in the normal playing position (in the player's lap), and the sound was picked up by a microphone (AKG C 480 B, cardioid capsule) 50 cm away from the soundhole along the line normal to the soundboard. The signal was recorded digitally (44.1 kHz, 16 bits) with a sound card (Edirol UA-101) to the hard drive of a Macintosh laptop.

The handling noises were created by sliding the fingertip or -nail along the wound 6th, 5th, and 4th strings. During the measurements, the slide was performed on one string at a time, and all other strings were damped with tape to prevent them from ringing. Although the analysis for only the 6th string is presented in the following, these results were found to apply to other wound strings as well.

3. General structure of the handling noise

The resulting spectrogram in Fig. 1 shows that the noise has a smooth lowpass character with a time-varying harmonic structure. The frequency of these harmonics depends on the slide velocity; a faster slide will lift the harmonics in frequency. This effect was found already earlier in a recent study[4]. Also, the amplitude of the handling noise increases with slide velocity. It can be seen in Fig. 1, that the slide first increases and then decreases its velocity. This is natural, since the finger first accelerates and then decelerates when changing position
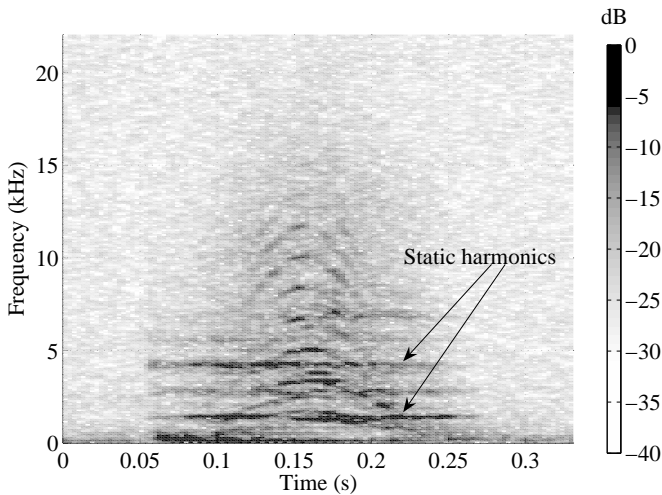
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FIG. 1. A spectrogram of the handling noise created by sliding a finger on a wound guitar string. A 12 ms Hamming analysis window was used with 75 % overlap. The noise clearly has a harmonic structure, where the frequency and amplitude of the harmonics increase with the sliding velocity. In addition to the moving harmonics, static harmonics (denoted by arrows) can be found in the spectrum.

on the string.

The presence of the time-varying harmonics can be explained by the surface texture of the wound string: each time the finger passes over a single winding turn, it will produce a noise pulse. Since the winding pattern is periodic, the resulting sound will be a train of noise pulses, and thus have a harmonic structure. Naturally, a faster slide will shorten the time interval between the noise pulses, thus raising the harmonics in frequency.

In addition to the moving harmonics, less intensive static harmonics can be found in the spectrum. These are illustrated with arrows in Fig. 1. The static harmonics are due to the longitudinal vibration of the string: the finger excites the longitudinal modes while scratching the surface of the string.

With this in mind, the handling noises can be thought of as consisting of an exciter and a resonator part. The excitation, created by the moving string-finger contact, is discussed in Sec. 4, while the resonator, consisting of the string vibrations, is discussed in Sec. 5.

4. Analysis of the time-varying finger-string excitation

4.1. *Harmonic components*

As explained above, an object (finger, nail, or plectrum) moving on a wound string creates a velocity-dependent harmonic force excitation to the string. This

force can be approximated as a periodic pulse train:

$$F(t) = \left[\sum_k \delta(t - t_k) \right] * f(t), \qquad (1)$$

where t denotes time, δ is Dirac's delta function, t_k is the time instant of the kth pulse, and $f(t)$ is the impulse response of a single pulse that is generated when a finger slips from one winding. The operator $*$ denotes convolution. Thus, the excitation force presented in Eq. (1) can be interpreted as a periodic Dirac train filtered by the transfer function of a single pulse. When the sliding velocity is constant, t_k has the form

$$t_k = \frac{k}{d_w v_s}, \qquad (2)$$

where d_w is the wound density (wounds per meter) and v_s is the sliding speed (meters per second).

When the sliding speed varies in time, the harmonic frequencies change. The relationship between the harmonic frequencies and the sliding speed can be given as $f_{Hn} = n v_s d_w$, where $n = 1, 2, 3, ...$ is the mode number. This relation was found to coincide well with the results obtained by tracking the lowest harmonic frequency and the sliding speed on the recordings.

4.2. *Handling noise amplitude*

The amplitude of the handling noise as a function of the sliding velocity is illustrated in Fig. 2. The figure was obtained by evaluating 20 slide events, where the user slid his fingernail the distance of 23 cm on the surface of the string while attempting to maintain a constant sliding speed. The sliding velocity is approximated by dividing the distance (23 cm) by the duration of each slide event. The vertical axis in Fig. 2 denotes the root-mean-square (RMS) value of the slide events, normalized to between zero and unity. It can be seen that the RMS value of the handling noise is approximately linearly dependent on the sliding speed.

It must be noted that, due to the measurement setup, the finger speed could only be kept approximately constant during the slides. However, small variations in the sliding speed average out when the RMS value is taken.

5. Analysis of the string resonances

Naturally, the force exerted by a sliding object to the string excites the transversal and longitudinal vibrational modes. The object can also, depending on its type, damp the string vibrations, especially in the transversal direction.

In other words, for rigid and relatively sharp objects, such as a plectrum, mode damping is minimal, and the transversal vibration plays a major part in the handling
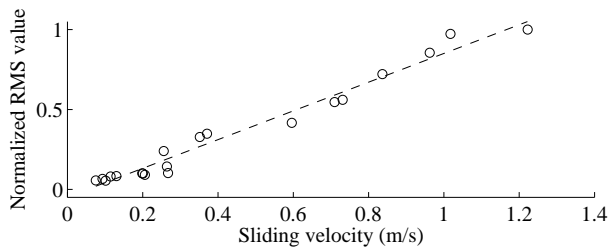
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FIG. 2. Normalized RMS noise value as a function of the sliding speed. The circles denote 20 different slide events performed on the fingernail. The dashed line represents a straight-line fit to the data, where the standard deviation of the residues is 0.053.

sound. The "pick scrape" effect in contemporary electric guitar playing is a good example of this; the player scrapes the plectrum against the string with a long movement, in order to produce a grinding sound with a changing pitch. The pitch change is caused by the change in the string's length from the transversal vibration point of view: the moving plectrum acts as a rigid termination and divides the string into two segments. Since the magnetic pickup is located near one end of the string, it typically registers the vibration of only one of these segments.

On the other hand, a fingertip effectively attenuates the transversal vibrations, so the string vibrates mostly in the longitudinal direction. Since this type of handling noise generation is much more common, the longitudinal mode excitation is considered more thoroughly in the following.

The partial differential equation for the longitudinal string vibration can be formulated as follows[5]:

$$\mu\frac{\partial^2\xi}{\partial t^2} = ES\frac{\partial^2\xi}{\partial x^2} - 2R(f)\mu\frac{\partial\xi}{\partial t} + d(x,t), \qquad (3)$$

where $\xi(x,t)$ is the longitudinal displacement of the string, E is Young's modulus, S is the cross-section area of the string, and μ is the linear mass density. The propagation speed is $c_{\mathrm{L}} = \sqrt{ES/\mu} = \sqrt{E\rho}$, where ρ is the density of the material. Thus, the propagation speed is constant for a given material and does not depend on string tension, unlike in the case of the transverse vibration. The function $R(f)$ is the frequency-dependent frictional resistance. The excitation force density is denoted by $d(x,t)$. When the string is excited at one point x_{exc}, the spatial distribution of the force can be approximated by a Dirac function: $d(x,t) = \delta(x_{\mathrm{exc}})F(t)$. The force acting on the bridge, F_{b}, can be computed as the tension variation at the bridge termination, that is $F_{\mathrm{b}} = ES(\partial\xi/\partial x)|_{x=0}$.

For a given excitation force $F(t)$ at the position x_{exc}, the bridge force can be approximately computed as

follows[6]:

$$F_{\mathrm{b}}(t) = \frac{ES}{\mu L^2}\sum_{k=1}^{\infty}\left\{\frac{k}{f_k}e^{-tR(f_k)}\sin(2\pi f_k t)\right\}$$
$$* \left\{\sin\left(\frac{k\pi x_{\mathrm{exc}}}{L}\right)F(t)\right\}. \qquad (4)$$

The longitudinal modal frequencies $f_k = kc_{\mathrm{L}}/(2L)$ depend on the propagation speed c_{L} and string length L. In Eq. (4) it can be seen that the force signal excites a set of parallel resonances and that the excitation amplitudes depend on x_{exc}. As a special case, those modes that have a node at the excitation point will not be present. In addition to eliminating some harmonics, the excitation position x_{exc} has a strong influence on the general shape of the spectrum. For $x_{\mathrm{exc}} \approx 0$ or $x_{\mathrm{exc}} \approx L$ the first few longitudinal modes are only weakly excited.

The assumption that the static components are originating from the longitudinal vibration is confirmed by measurements. It can be seen in Fig. 1 that the static components have a clear harmonic structure and are around those frequencies where the longitudinal modes are expected when calculated from the physical parameters of the string. Moreover, the frequencies do not change as a function of tension. Instead, they are inversely proportional to string length, being in good agreement with theory. This is shown in Fig. 3. When the string is excited at different positions, the shape of the spectrum changes considerably. Figure 4 shows special cases of exciting the string at half, one third, and one fourth of its length, and leading to the expected result that every second, third, or fourth harmonic is missing from the power spectrum. The time-varying contact noise caused by the string excitation is averaged mostly at low frequencies. This explains the spectral peaks below the first longitudinal modes in Fig. 4.

6. Conclusions and discussion

The handling noises created by sliding a finger on a wound string were analyzed. The resulting noise can be interpreted to be a result of an exciter-resonator system. The moving finger-string contact forms the exciter part: a lowpass-type noise with a clear harmonic structure is created when the finger rubs against the string windings. The harmonic frequencies and the RMS amplitude of the handling noise were found to be linearly dependent on the slide velocity.

The resonator part consists of the vibrational behavior of the string. The sliding contact excites mainly the longitudinal string modes, since transversal vibration is effectively damped by the soft finger-string contact itself. Naturally, different longitudinal modes are excited depending on the finger location. When a harder object, such as a plectrum or bottleneck, is used in the slide, transversal modes will be more significant. Sound examples of different handling noises
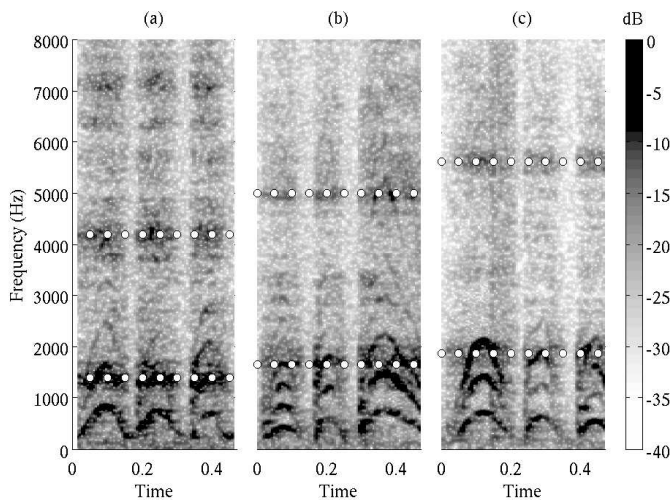
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FIG. 3. Spectrograms of the scratch noise on the damped 6th string of an acoustic guitar. A 23 ms Hamming window with 75 % overlap was used in analysis. The string was scratched with a fingertip, while (a) it had an open length. In (b) and (c), a capo was applied (b) at the third and (c) at the fifth fret. In (a), the dotted white line illustrates the frequency of the 1st and 3rd static harmonics (1400 Hz and 4200 Hz, respectively). In (b) and (c) the white line denotes the frequency where the static harmonics should be located if they were a function of the length of the string. As can be seen, the static resonances coincide well with the dotted lines.
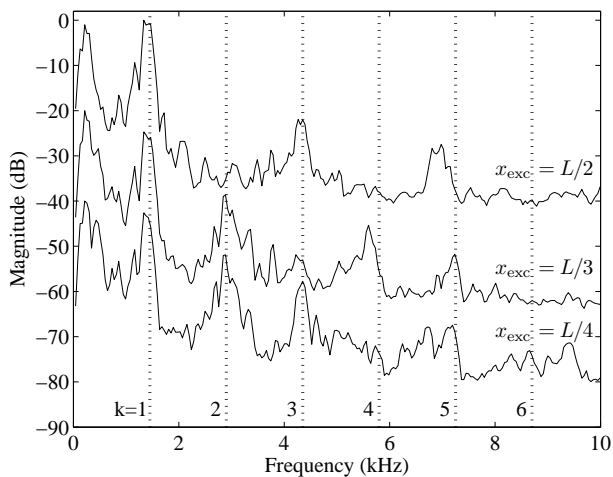

FIG. 4. The averaged power spectrum of the handling noise when the 6th string is scratched at 1/2 (top pane), at 1/3rd (middle pane), and at 1/4th (bottom pane) of the string's length. A magnitude offset of 20 dB was applied to the spectra for clarity. An averaging window of 23 ms was used. The k values and the vertical dotted lines denote the longitudinal mode numbers and locations, respectively.

are available in the companion web-page of this article: http://www.acoustics.hut.fi/publications/papers/jasael-handling-noise.

A simple signal-based model for synthesizing contact sounds on wound strings has been introduced in an earlier study[4]. However, based on the knowledge obtained in this article, a more sophisticated physics-based model for synthesizing wound string contact noises will be presented in an upcoming article on slide guitar synthesis[7]. There, the contact noise between a wound string and the slide tube is synthesized with a noise pulse train -based parametric model. Transversal string vibration is implemented with digital waveguides, and the longitudinal modes are created with static resonators.

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