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Spectral changes in the tom-tom related to striking force

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Abstract
This study has investigated the question how the radiated spectra of a tom-tom changes with striking force. Five tom-toms of different size were recorded at four dynamic levels (pp, mp, mf and ff) and their averaged spectra analysed. It was observed that the number of modes excited increase with playing strength, seen in the radiated spectra as a characteristic change in slope for higher frequencies. At louder levels, there is also an initial frequency shift that causes the lower partials to gain width as well as amplitude. Measurements of the contact between drum stick and the drum head showed a decrease in contact time with increasing playing strength.

Introduction
Research on drums is a wide field in which a few selected topics have been studied in detail, like the kettle, bass and snare drum (Fletcher & Rossing, 1991). The theoretical foundations of vibrating membranes are well known since long (Rayleigh, 1877), but many applied cases have still not been examined. An interesting question is whether the radiated spectra of drums change with excitation force like other traditional instruments. An increase in high-frequency content could be expected as it is a common behaviour of most traditional instruments, particularly well studied for the wind instruments and the piano.

In this study, the radiated spectra of drums played at different dynamic levels are analysed. The type of drum examined has been the tom-tom, a common part of the drumset and frequent in many music styles.

Membranes, drums, and pitch
The basic components of a drum are a shell and one or two membranes. The frequencies of the normal modes of vibration for an ideal membrane are given by

\[ f_{mn} = \frac{j_{mn} \sqrt{T}}{2\pi a} \sqrt{\frac{\sigma}{\pi}} \]

where \( j_{mn} \) is the \( n \)th root of the \( m \)th Bessel function, \( T \) the membrane tension, \( a \) the membrane radius, and \( \sigma \) the mass per unit area (see e.g. Morse, 1948). The numbering of these different modes is normally given in the form \((mn)\), where \( m \) denotes the number of nodal diameters and \( n \) the number of nodal circles.

The modal frequencies of an ideal membrane are not harmonically related, which means that they will not give rise to a well-defined pitch. In real drums, however, the frequency relations can be modified. In studies of the timpani, it has been shown that the lowest modes can be shifted into approximate harmonic relations (1:2:3) by enclosing an air cavity (Fletcher & Rossing, 1991). The fact that the timpani is played somewhat off centre also helps in setting the desired modes into vibration, and suppressing the unwanted (inharmonic) modes.

In drums like the tom-tom, the air is enclosed by two membranes and the shell. This gives more complicated spectral patterns of the radiated sound as the two drum heads can vibrate in or out of phase with each other, resulting in a splitting of the lower modes (Table 1). This effect has been reported for the bass drum, and it is claimed that the coupling between the two heads is maximised if the two heads are set to the same tension (Fletcher, 1991). A similar effect has been shown to occur also in the tom-tom (Bork, 1983).

In dictionaries, tom-toms are generally described as drums with approximately the same diameter as depth. Relations varies of course with fashion and taste, but the main difference in design between a tom-tom and a bass drum is size. It would therefore be expected to find a similar behaviour for these two types of drums. In “Some experiments with the bass drum” (Fletcher & Bassett, 1978) it is claimed that the
amplitude of each component in the spectra depends on the strength and the position of the blow. There is also a frequency shift for a hard blow when the deflection of the head is large enough to affect the tension. Fletcher & Rossing estimated this upward shift to about 10\%, or nearly two semitones, for a full blow on a bass drum (Fletcher & Rossing, 1991).

In contrast to the timpani, a tom-tom’s playing spot is normally at the centre of the batter head. Playing at the periphery is used as a means of playing softer, or to achieve a different timbre. Theoretically it should not be possible to set modes with nodal lines through the centre into vibration when striking at that point, but even slight unsymmetries in the drum head will excite such modes (Bork, 1983). To enable a drum to generate more or stronger high-frequency components when played louder, a non-linearity in the excitation process (the contact between drum stick and drum head) must be present. Whatever the nature of this non-linearity, this means that higher order normal modes are excited more efficiently as the dynamic level is increased. An illustrative comparison is the piano, in which a felt hammer with a highly non-linear compression characteristic gives a pronounced increase in high-frequency content in spectra as the dynamic level is increased (Hall & Askenfelt, 1988).

Experiments

Recordings

Five different tom-toms were played single-stroke, each at four different dynamic levels and at two different points on the batter head (centre and periphery). The drums were selected from two drumsets of different types; an older set of jazz-like standard with large, shallow drums (Ludwig), and a newer set with small deep drums of rock character (Premier), see Table 2.

The recordings were made with a professional audio DAT-recorder (SONY TDC D10) in an anechoic chamber, using a high-quality condenser microphone (Brüel & Kjaer 4003 studio microphone) at a distance of 1 m, and at an angle of 45 degrees with respect to a main axis through the centre of the batter head. In order to collect sufficient data for averaging spectra, each drum was played single stroke at least 30 times at each of the four dynamic levels pp, mp, mf and ff, both at the centre and at the periphery (approximately 1/3 radius from the rim).

Table 2. Dimensions of the recorded drums.

<table>
<thead>
<tr>
<th>Drum</th>
<th>Size</th>
<th>Diameter [cm]</th>
<th>Depth [cm]</th>
<th>Ratio dia/depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ludwig</td>
<td>16”</td>
<td>40.5</td>
<td>39.0</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>12”</td>
<td>30.0</td>
<td>20.5</td>
<td>1.46</td>
</tr>
<tr>
<td>Premier</td>
<td>10”</td>
<td>25.0</td>
<td>25.0</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>12”</td>
<td>30.0</td>
<td>25.5</td>
<td>1.18</td>
</tr>
<tr>
<td></td>
<td>14”</td>
<td>35.0</td>
<td>30.0</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Heads: Remo Ambassador
Drumstick: Zildjian 5B

Analysis

The recordings were analysed with the help of a FFT signal analyser (HP 3562A). A preliminary inspection of spectra showed that the main part of the energy was concentrated below 5 kHz, and the following analyses were limited to this frequency range. The bandwidth was automatically set to 6.25 Hz, and the analysis time window for each stroke to 160 ms. The trigger was set at a reasonable level to prevent triggering at several points of the same stroke.

Two full ff -blows at the centre and the periphery of a 12” tom-tom are shown in Fig. 1. The figure shows the characteristic high initial peak followed by a sustained decay with only a few modes left. There is a big difference in amplitude between a stroke at the centre and at the periphery of the batter head. The difference between the softest (pp) and loudest (ff) dynamic level was approximately 20 dB, both when
measured from the peak levels in the waveforms, and in an equivalent continuous sound level measurement \(L_{eq}\). A comparison between a stroke at \textit{ff} and one at \textit{pp} is shown in Fig. 2. The variation in strength between different strokes at the same dynamic level was about 7 dB at the centre. At the periphery, where a small difference in playing position has a larger effect on the sound than at the centre of the head, the variations were generally a bit larger (approximately 12 dB). One bad stroke or two does not have any large effect, as the strong blows dominate the averaged spectral values.

The analysis resulted in 40 spectra of radiated sound (4 dynamic levels x 2 positions x 5 drums = 40 cases) each averaged over 30 strokes.

\[\text{Figure 1. Two blows at ff on a Ludwig 12” tom-tom at the centre of the drum head (left), and at the periphery (right).}\]

\[\text{Figure 2. Two blows on a Ludwig 12” tom-tom at the centre of the drum head, at ff (left) and at pp (right).}\]

### Results

#### General observations

Some very general observations can be made from a first look at the averaged spectra (Fig. 3). The lower modes can be seen separately and clearly, while modes in the higher parts of the spectra blend together, forming a characteristic slope. Most of the spectra show a similar behaviour with regard to how partial peaks and valleys between peaks change with increasing dynamic level. The valleys are sharp and well defined at soft levels, but become more undefined with increasing playing strength. This may of course be the result of increased attack noise, but the partial peaks also increase in width with increasing playing strength (discussed below). This effect helps to “glue” the partials together, forming a continuous spectrum contour.

#### Lower part of spectra

The lower modes do not only gain height (amplitude) with increasing striking force but also some width. This is due to a change in pitch which occurs when the blow is hard enough to add some extra tension to the head. The increase in tension depends in turn on the large deflection of the membrane (Rose, 1978; Bork, 1983). For a \textit{ff}-blow, the change in frequency of the fundamental can be as much as 20 Hz (Fig. 5), corresponding to almost 4 semitones. This frequency shift can be heard when concentrating on this aspect, but it is usually perceived as a characteristic part of a strong impact rather than a glide in pitch. The reason is probably that strong high frequency components, which always are present in a strong blow, partly mask the fundamental during the short initial interval in which tension and pitch descend to their normal values. After the first tenths of a second mainly the ringing fundamental is left at its normal frequency. There are examples of drums where a defined change in pitch at louder playing strengths is intended, but for tom-toms this is normally not the case.

#### Centre and periphery

When comparing strokes at the two different playing positions on the drum head (centre and periphery), the main differences are the peak levels of the weaker modes (Fig. 3 and 4). Most modes are found in both spectra but excited differently. The fundamental is somewhat less dominating compared to the second partial when struck at the periphery. The difference increases with the strength of the blow, but the fundamental is generally a bit weaker than it would be if excited at the centre. This observation is hardly surprising as the fundamental has its only nodal line at the rim.

#### Higher parts of spectra

In the high-frequency part of the spectra there is a considerable change in spectral slope
Figure 3. Averaged spectra of 30 strokes at the centre of a 12” Ludwig tom-tom corresponding to four dynamic levels from pp (bottom) to ff (top).

Figure 4. Averaged spectra of 30 strokes at the periphery of a 12” Ludwig tom-tom corresponding to four dynamic levels from pp (bottom) to ff (top).
Figure 5. Change in pitch for a ff-stroke at the centre of a Ludwig 12” tom-tom. The figure shows the microphone signal, lowpass filtered at 130 Hz (top), and the pitch difference in cents relative to 110 Hz (bottom). The delay between the two curves is caused by the filtering process.

Figure 6. Schematic picture of how spectra changes with the playing strength. The high-frequency slope changes from typically 25 dB/oct at pp (bottom) to 16 dB/oct at ff (top).

Table 3. High-frequency spectral slopes in dB/octave as measured from averaged spectra. See also Fig. 7. For the two pp-values marked with * the slopes did not extend above 3 kHz.

| Dynamic level | PREMIER | | | LUDWIG | | |
|---------------|---------|---------|---------|---------|---------|
| 14” pp        | 27      | 25      | 20      | 23      | 29      | 29      | 22      | 26      | 23*     | 23*     |
| 12” pp        | 22      | 25      | 19      | 19      | 26      | 27      | 23      | 26      | 21      | 21      |
| 10” pp        | 19      | 21      | 14      | 17      | 24      | 24      | 21      | 21      | 16      | 16      |
| 12” mp        | 16      | 17      | 13      | 13      | 20      | 21      | 17      | 17      | 13      | 14      |
| 16” mf        |         |         |         |         |         |         |         |         |         |
| 16” ff        |         |         |         |         |         |         |         |         |         |
Figure 7. High-frequency slope of averaged spectra versus dynamic level for the five recorded tom-toms struck at the centre.

Figure 8. Registration of the contact time between stick and drum head (top), and the acceleration close to the playing end of the drumstick (bottom) for a mf-blow at the centre. A stick mode at about 475 Hz is strongly excited. Estimated arrival of the first reflected wave on the drum head is indicated by an arrow.

Contact times

By applying adhesive copper foil on the drumstick and the drum head the contact time for different strokes was measured electrically. Strokes on a 12” tom-tom were recorded showing decreasing contact time with increasing striking force, which indicates a non-linear contact process (Figs. 8 and 9). Typical values were 8 ms at pp and 5.5 ms at ff, for blows at the centre.

A comparison with the contact times for a stroke on a soft surface (carpet) showed no dramatic changes, which suggests that the release process of the stick is not heavily influenced by reflected waves on the drum head. This behaviour contrasts to the piano where for most notes the
reflected waves on the string are the main cause of hammer release (Hall, 1986; Askenfelt & Jansson, 1993).

An accelerometer attached close to the playing end of the drum stick showed weak traces of reflected waves from the rim (Fig. 8), but it seems that they are too weak to influence the stick motion significantly. Interestingly, these reflections interfere with a strong bending mode of the stick at about 475 Hz. This mode resembles the lowest mode of a free-free bar with an anti-node at the middle and a nodal line close to where the stick normally is held in playing.

![Graph](image)

**Figure 9.** Contact times between drumstick and drum head at four dynamic levels for a Ludwig 12” tom-tom struck at the centre.

**Conclusions**

This study has investigated the question how the radiated spectra of a tom-tom changes with striking force (pp to ff). It was observed that the number of modes excited increase with playing strength. The major finding was a characteristic change in spectral slope for frequencies above 1 kHz approximately, decreasing from typically 25 dB/oct at pp to 16 dB/oct at ff.

An initial frequency shift occurs at loud playing, resulting in wider peaks for the lower partials in the averaged spectra, and also less well defined valleys in between. The shift in frequency can be heard when concentrating on this aspect, and also observed in spectrograms. Normally, however, it is perceived as a component of a strong impact rather than a shift in pitch.

The contact time between drum stick and drum head decreased with increasing dynamic level, from about 8 ms at p to 5.5 ms at f. The release of the stick seemed not to be connected with reflected waves on the drum head. The lowest bending mode of the drum stick at about 475 Hz is strongly excited when held in normal playing manner.

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**References**


