

## The kinematics of musical expression

Author: Neil P. McAngus Todd

The idea that there is an intimate relationship between musical and physical motion can be traced back to antiquity. Classical Greek musical writings by Aristoxenus make reference to rhythmical motion as being with respect to a metrical grid. More recently, Kronman and Sundberg (1987) used regression analysis to model the final *ritardando* of musical performances as motion under constant negative acceleration. In this paper, Todd sets out three goals: 1. to formulate this relationship in a more precise mathematical form; 2. to extend the studies of Sundberg and Kronman to include *acclerandi* as well as *ritardandi* in performances of complete pieces; and 3. to show that the concept of a metrical grid has its origins in the way the auditory system processes rhythm.

Todd begins by relating the study of musical motion to the problems of kinematics and trajectory planning in robotics. In the case of robotics, we speak of the time evolution of the position and velocity of an object with respect to a Cartesian grid. To make the connection to music, we must view a score as being a trajectory in 2-D space. The vertical axis describes a pitch space while the horizontal axis describes a space-like dimension in terms of metrical units or beats, thus defining a metrical grid. We may therefore equate tempo with horizontal velocity (ie: change in metrical position over time).

In the examination of performances of Chopin, Todd plots measured metrical position versus onset time for the first 16 beats. From this it is possible to estimate the tempo as  $v = \Delta x / \Delta t$ . This, however, introduces a discretization error, so Todd opts to use onset times in his regression analysis.

In developing the regression method, Todd notes that performance timing is often characterized by a series of connected *accelerandi* and *ritardandi*, which implies the onset plots would be characterized by a series of alternately concave and convex curves. While this description does characterize the onset plots, I believe it is subtly misleading, because it seems to suggest that the *accelerandi* and *ritardandi* are intentional and a part of expression. Rather, it is merely the fluctuation in tempo – intentional or not – from note to note that causes the alternating concave and convex segments.

Two strategies are used to model the shape of each concave/convex segment. One is derived from motion of a body under constant acceleration, and the other is derived from motion of a body with no acceleration. These are designated as the piecewise linear tempo (PLT) and piecewise constant tempo (PCT) models, respectively. It was found that the PCT model accounted for a very high proportion of the variance of the segments while the addition of the acceleration term in the PLT models accounted for only 3% more of the variance, suggesting that performances with little *rubato* could be accurately modeled by the PCT model.

The next portion of the paper attempts to explain the origins of the metrical grid by presenting a model of rhythm perception in humans. The basic idea of the model is that auditory stimuli are first stored in a time-domain representation which is then analyzed by a frequency-domain process that extracts metrical harmonics from the incoming rhythm. A sensory-motor feedback filter then selects a tactus from the metrical harmonics. The key point is that the a rhythmic event can be associated with a number of cycles of metrical harmonics. This number is independent of the absolute tempo since the ratio of harmonics is an invariant property of a particular rhythm. It is this point that forms the basis of the metrical grid.

Eric Cheng

2.1.06

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Finally, the author makes a distinction between two sorts of motion: a motion associated with the strong underlying beat of a constant tempo, and gestural motion, which is motion on a higher level as associated with tempo rubato. He associates the first type of motion with motor actions of limbs (such as foot tapping) and the second with whole-body motion. In the model of rhythm perception, a sensory-motor process makes such a distinction and assigns the tactus to the metrical harmonic which is nearest the natural foot tapping period of about 600 ms. This was an interesting distinction to make, and it reminded me of the waveform of AM radio where there is an underlying wave with the carrier frequency that is modulated by an envelope wave of much larger frequency. It seems one can examine motion on many different hierarchical levels.

I believe this paper succeeded in achieving all but its last stated goal. While Todd presents a theory of rhythm perception that may account for the notion of a metrical grid, he does little to convince us that this theory has any underlying motivation other than that it explains the notion of a metrical grid. I would have been more convinced had there been more compelling evidence for why we should believe the human auditory system perceives rhythm in this way.