Toward a psychoacoustically realistic violin physics

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Before one can adequately relate physical theories of vibration of violin strings and bodies, etc., to subjective judgements which purport to distinguish bad, good, and excellent violins, there is need, as is well known, for painstaking psychoacoustical research. The ultimate goal of this must be to locate adequate (and hopefully minimal) sets of physical correlates of the subjective judgements. Our recently-commenced research is concerned both with the physical and the psychoacoustical problems. Some of this work and its background is described informally below. New results are sketchy and provisional as yet, but we think that they are interesting, and hope, at any rate, to generate comment and criticism.

Concert-hall experience, the published literature (e.g. Fletcher & Sanders 1967, Risset & Mathews 1969, Boomsliter & Creel 1972, Mathews & Kohut 1973), and our own work with digital analysis/synthesis, all point to at least three things which must eventually be taken into account by anyone embarking upon the perils of an investigation of 'tone quality' which tries to be relevant to the art of violin playing. These are:

(a) time-dependent effects taking place on the psychoacoustical 'intermediate time scales' (say tens of milliseconds) - examples being vibrato, "articulation" (starting transients), trills and ornaments, and quasi-random fluctuations in bowed-string behaviour (it should be noted that in a vibrato of 7Hz the time scale for the frequency to change substantially is of order $(1/7)$ sec x $(1/2\pi) \sim 20$ ms);

(b) musical (particularly melodic) context, involving substantially longer time scales than (a);

(c) effects due to the concert-hall acoustic (including those due to the directional characteristics of sound incident on the listener). The recent advent of successful 'dummy-head' fully-directional sound recording systems - with concomitant insights into how auditory directional perception works (see e.g. Wettschureck 1972) - opens up possibilities for taking account of (c), which we hope to exploit in due course. For the present discussion, however, we shall artificially restrict attention to (a): our psychoacoustical work so far has been concerned with simple, sythesized vibrato notes and trills, and their subjective evaluation.

It will be temporarily convenient to make the idealization that a violin can be characterized by a well-defined frequency response curve. Published discussion of violin response curves point to two distinct ways in which they are relevant. The first (e.g. Meinel 1957, Meyer 1974, Jansson 1974) concerns fairly large-scale (in the frequency domain) features of the response curve. Important among these, for obvious biological reasons, are features on the scale of vowel formants. It is this large-scale or "coarse" structure which will be reflected, on average, in broad-band spectral analyses of violin sound (such as those using $\frac{1}{3}$-octave filters), and especially in long-time-average analyses. The idea is presumably connected, in some sense requiring clarification by psychoacoustical experimentation, with "timbre" as defined by Plomp & Steeneken (1971) for steady complex tones. This corresponds to the pattern of activity along the basilar membrane, referred to absolute position thereon and perceived with a resolving power of the order of the ear's critical band (roughly a minor third).

The second significant feature of response curves is the "fine structure" (involving local slopes of at least several decibels per semitone) whose interaction with vibrato has been investigated very elegantly by Mathews & Kohut (1973). (An example of the kind of response curve they used is shown in fig.1; apart from the cutoff at

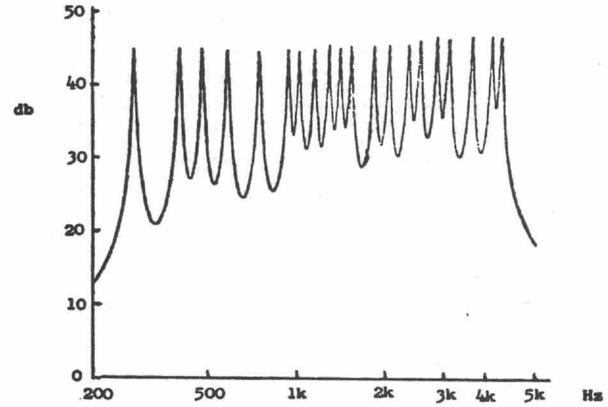

Fig.1. A computer-drawn plot of a response curve of the type used by Mathews & Kohut (1973), corresponding to a case approximating their schematic figure 4c.

5kHz there is no obvious "coarse structure".) We find that fine structure has at least three perceptible effects, of which the first is that already noted by Mathews & Kohut, while the other two seem not to have been mentioned explicitly in the literature:

(i) The frequency fluctuations of vibrato will be accompanied by spectrum fluctuations, as different harmonics move up or down steeply sloping parts of the response curve.

(ii) There will be spectrum fluctuations from note to note of a musical passage, even for semitone or smaller steps.

(iii) There will be reverberation, i.e. sound output will depend on past as well as present string-force input. This is immediately plausible to physical intuition whenever the fine structure is due to high-Q resonances. The time scale of the reverberation may generally be expected to be inversely proportional to the frequency-increment characteristic of the response-curve peaks and valleys, under the assumption that we are dealing with a linear system. One obvious effect upon vibrato tones is to introduce inharmonicity.

Effect (i) has been known to be subjectively important since the work of Fletcher & Sanders (1967). This is adequately confirmed by our own experiments and those of Mathews & Kohut.

We are not aware of any investigations of (ii), apart from a synthesis experiment on trills which we have begun. The subjectively most obvious effect of (ii) upon trills seems to be to make them sound clearer - a violinist might speak of more "brilliance", or "responsiveness" rather than referring specifically to "tone quality". More investigation is needed to check this tentative conclusion. In a melodic context, on the other hand (longer time scales - category (b) above) we should still be prepared for the possibility that effect (ii) might give rise to a change in overall perceived tone quality; Boomsliter & Creel (1972, p.1991) have found that such changes do result from small tempering (of pitch) of the notes of a given melody.

We assessed the role of effect (iii) as follows. First it was observed that one can obtain a linear system whose response curve has fine structure (in a way easy to realize on the small digital computer available to us) by adding to the input signal some feedback from a delay line. Such a response curve is shown in fig.2. This response

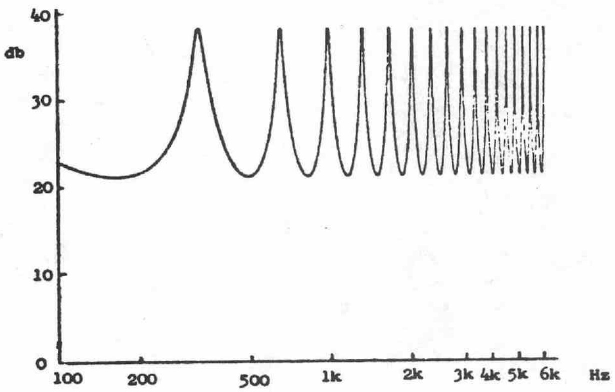

Fig.2. Response curve realized by means of a delay line with 0·003 m sec delay and feedback factor 0·75, giving a peak-to-valley ratio of 17db.

function (with parameter values qualitatively similar to those of fig.1) was used to process some digitally-synthesised 'input' vibrato tones. These were then compared with tones derived from the same input in a "quasi-steady" way, i.e. with the instantaneous output spectrum calculated at each moment from the instantaneous input spectrum, by reading off the response curve, a (nonlinear) process which by definition suppresses reverberation. The difference was subjectively obvious, showing that effect (iii) is clearly perceptible for relevant parameter values.

We think, moreover, that effect (iii) in conjunction with the transients and irregularities of human bowed-string playing, is an important ingredient in the "hollow" sensation reported by Mathews & Kohut (which we have had the opportunity to hear via a tape recording kindly supplied by Dr Mathews). We reproduced the "hollowness" very convincingly by taking input from a real bowed string (using a magnetic transducer similar to Mathews & Kohut's) and processing it linearly via the same delay line with feedback, with parameter values similar to theirs. (The computer program is simple enough to operate in real time, with a 30kHz sampling rate.) Also, using the same parameter values in our pairs of purely-digital syntheses, we found that the syntheses with reverberation seemed decisively more "hollow" sounding than the corresponding quasi-steady syntheses, when heard through headphones (Sennheiser HD 424) to eliminate room-acoustic effects. However the "hollowness" was less obvious subjectively in the computer synthesised, steady (sinusoidal), vibrato tones; we tentatively attribute this to the absence of the transient and irregularity cues of real bowed-string playing. This in itself is consistent with the notion that effect (iii) is a major cause of "hollowness" as these cues serve to excite reverberation themselves.

One unwanted feature of our delay-line response curves for the quasi-steady syntheses is that at high enough frequencies the peaks crowd together closer than the vibrato extent. As a result, quasi-steady syntheses using it tend to have a distracting, unrealistically rapid "tweeting" of high harmonics. We thus made quasi-steady syntheses using a Mathews & Kohut-type response function, that of fig.1, which does not exhibit the effect. These do not sound obviously "hollow". Together with the previously-mentioned experiments this suggest that the causes of hollowness are to be found more in effect (iii) than in the "spectral gappiness" suggested by Mathews & Kohut (p.1624), since the quasi-steady syntheses gives, if anything, more 'gappiness' than if reverberation were present.

The necessity for a compromise (Mathews & Kohut p.1623) between having enough of effect (i) for good "responsiveness to vibrato", but not too much of what we now identify as effect (iii), is probably inescapable for a linear system. There is the intriguing possibility that escape from this constraint could be provided by nonlinear effects, the psychoacoustical importance of which has not, as far as we can see, yet been decisively evaluated. The strongest potential candidate is back reaction of body characteristics onto the bowed string dynamics, and this is one of the topics which we are studying with a computer model of the bowed string with finite bridge impedance (see also Schumacher 1974). As Boomsliter & Creel (1972 p.1992) warn, effects which are small from a physical point of view may not be so to a musician's auditory system.

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