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Some Acoustical Principles of Flute Technique

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The flute is a very individual instrument, its sound depending in great measure upon the exact way in which the air jet from the players lips strikes the edge of the flute embouchure hole. Some players learn a good lip technique relatively easily but for others it is a constant struggle, and it is sometimes difficult for a teacher to explain exactly what should be done to improve the situation. Even for more advanced players there are constant problems in striving for flexibility and nuance of timbre, and the variety of individual flute tones amongst professional players attests to the diversity of possible solutions.

Much of the beauty and individuality of a musical sound depends upon the way in which it is attacked and released and upon the fluctuations associated with the vibrato. Indeed, when deprived of their characteristic attack transient, many instruments are almost unrecognizable — try playing a tape recording backwards! Despite this, the steady tone quality is of immense importance, and it is impossible to produce a beautiful sound unless the basic steady tone is itself well developed and controlled.

During recent years our knowledge of the acoustical principles governing tone production in wind instruments, and in flutes in particular, has increased very greatly, although there still remain many questions to be settled. An excellent account of our present understanding of the acoustics of the flute has been given recently in these pages by John Coltman[1] and detailed references to the literature can be found there, as well as in a recent book by John Backus.[2]

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The purpose of the present article is to take up several aspects of flute performance technique which were not covered in Dr. Coltman's paper and to show how, by understanding the principles underlying some of the effects we try to produce in performance, we may perhaps make their attainment easier. I would not claim that this approach should supplant traditional teaching methods, but it may serve as a useful adjunct to the more instinctive approach generally adopted.

Basic Acoustical Problems

The simple motion of a flute as a cylindrical tube, effectively open at each end, in which standing waves can be excited by directing an air jet across a mouth-hole, is familiar enough not to require detailed discussion. The possible vibration modes of the pipe form an approximate harmonic series which we can explore for ourselves by fingering low C (C^4)[3] and then, by appropriate blowing, sounding not only C^4 but C^5, G^5, C^6, E^6, G^6 and perhaps even a note close to $B\flat^6$. Which note sounds depends upon lip position and blowing pressure. A similar series of notes can be produced starting from any fundamental, though the number of notes we can produce with one fingering becomes fewer as we ascend the scale.

Obviously, one of the most basic skills in flute technique is to learn to control just which note of this series will actually sound. However, we must recognize that whenever a note is played, all the higher overtones in the series for that note are excited to some extent. Since the relative intensities of these harmonics determine the timbre of the sound, it is important to be able to control them within certain limits.

In addition to these tonal qualities, a player must be able to vary the sounding pitch slightly (to keep in tune with other instruments) and must also have control of the loudness of his sound. To make matters even more complicated, he should be able to control each of these variables independently of all the others, a nearly impossible task.

For the experienced player, all of these adjustments are instinctive and he thinks about them little more than we think of the necessary muscular adjustments we must make to keep our balance while running or walking. But for the beginner or even for the experienced player meeting a new technical or interpretive difficulty, it is often a great help to understand the physical principles involved in bringing these variables under control.

These problems and their practical solutions have of course been discussed by flute players (and writers) for hundreds of years. Hotteterre[4] in *ca.* 1700, Quantz[5] in 1752 and Boehm[6] in 1871 all wrote on the matter, and their books are well worth the attention of a modern flute player. Quantz's book is an indispensable

1. John W. Coltman, "Acoustics of the Flute," *The Instrumentalist*, XXVII/6 (January, 1972), 36-40; XXVII/7 (February, 1972), 37-43.

2. John Backus, *The Acoustical Foundations of Music* (New York: W.W. Norton & Co., 1969).

3. I am using the U.S.A. Standard Notation in which the notes of the octave beginning at C ≃ 16 Hz are given superscript 0, the lowest C on a piano is C^1, etc.

4. Jacques-Martin Hotteterre, *Rudiments of the Flute, Recorder and Oboe* (1707), trans. by P.M. Douglas (New York: Dover Publ., 1968).

5. Johann Joachim Quantz, *On Playing the Flute* (1752), trans. by E.R. Reilly (London: Faber and Faber, 1966).

6. Theobald Boehm, *The Flute and Flute Playing* (1871), trans. by D.C. Miller (New York: Dover Publ., 1964).

text on the interpretation of baroque music, but his remarks on embouchure and tone production are also of great interest. Modern methods for the flute[7] also give attention to lip technique and to blowing, but all of these treatments are from a practical rather than a theoretical standpoint.

Most of these writers give reasonably similar directions for the proper control of flute sound, though they differ in their emphasis. Here we shall look at what is actually done by a representative group of flute players and examine some of the physical reasons behind the methods they use.

Octave Selection

The generally taught method of producing high notes on a flute, or of selecting one of the higher possibilities for a given fingering, is to push the lips forward and to blow a little harder. Quantz maintained that the change in lip position was the prime necessary action and disagreed with his contemporaries Vaucanson and Corrette who advocated "doubling the wind" for the second octave.

The acoustical principle involved in this process was discussed by Coltman.[8] Briefly it is as follows. The air jet from the player's lips, if undisturbed, would strike centrally against the sharp edge of the flute embouchure hole. If the air jet is deflected inwards, it increases the air pressure in the tube near the embouchure hole, but if it is deflected outwards, the tube pressure is lowered. The motion of the jet is, however, controlled by the sound vibrations in the tube, which cause air to flow in and out of the embouchure hole and thus deflect the jet. There is, therefore, a close coupling between the jet and the tube and, if everything is adjusted correctly, energy will be fed from the jet to the air column and the flute will sound.

The critical thing about this adjustment is the time taken for any deflection of the jet to travel across the embouchure hole and interact with the edge. This time clearly depends both on the distance involved (the jet length) and on the jet velocity, which in turn depends on the blowing pressure. Measurement and calculation show that the most efficient blowing situation occurs when this travel time is just about half the period of oscillation of the tube tone (i.e., about 1/880 seconds when we play $A^4 = 440$ Hz).[9] If the jet travel time is very far from this value then the fundamental will not sound. In particular, if the jet length is decreased or the blowing pressure increased so that the travel time is halved, then the upper octave will sound.

Actually, there is a reasonable amount of flexibility in this adjustment, and both the jet length and the blowing pressure can be altered a good deal before the note ceases to sound or breaks to the octave. In addition, the player apparently has the option of either pushing his lips forward to halve the jet length, or else increasing the blowing pressure by a factor of four (because the jet speed varies as the square root of the pressure) to sound the upper octave. What does (or should) he actually do?

Before answering this question, we should point out that the theory outlined above is oversimplified and reality does not quite follow these simple linear relations. If the jet length is too great, for example, it is almost impossible to reduce the travel time sufficiently, using extra pressure, to cause the octave to sound, probably because of spreading of the jet. With this sort of reservation in mind, however, the theory does produce a very useful guide.

In normal playing, a performer on the flute probably wishes to produce both a note and its octave with the same sort of loudness and timbre and, of course, in tune. If he leaves his lips fixed and simply blows much harder, the upper note will be too loud, because the air jet has a great deal more energy, and probably sharp, for a reason we will consider presently. He can reduce the size of his lip opening to correct the loudness, but this may still leave an intonation problem. Conversely, if he simply pushes his lips forward, then the three-octave compass of the flute will require an eight-fold change in lip-to-edge distance. This means a great variation in embouchure hole covering and considerable problems of intonation, loudness and timbre.

Measurements I have made on a number of professional and advanced amateur flute players show a remarkable consistency in the method actually adopted. This method represents a combination of all three possibilities suggested above. Thus, to produce a note one octave higher than that being played, the air pressure is doubled, the jet length reduced to about 0.8 of its previous value by pushing the lips forward and the area of the lip opening is reduced by about 30 percent.

Leaving aside the question of lip opening for the moment, we see that these measurements are almost exactly in agreement with the theory. The doubling of air pressure reduces jet travel time by a factor of 0.7 and, in combination with the jet length reduction by a factor of 0.8, the travel time is reduced to 0.56 times or very nearly half its original value.

Figure 1 shows a series of photographs of lip positions, while Figures 2 and 3 show the ranges of blowing pressure and jet distance measured. Pressure curves for individual flute players usually lie in the central shaded region of the figure but a few players use consistently higher pressures for fortissimo and lower pressures for pianissimo, the overall variation being confined to the total shaded area. In cases where the blowing pressure is varied in this way, there is a distinct change in tone quality from one end of the dynamic range to the other. The jet length curves vary only a little from one player to another.

Two other observations are worthy of note. The first concerns the angle from which the jet strikes against the edge of the embouchure hole and the second the variation of the lip opening with pitch.

From the first series of photographs in Figure 1 we see that the air jet is directed down towards the edge at an angle between about 25° and 40° to the horizontal, the shallower angle being used for low notes. Most flute players also use a shallower angle for loud than for soft playing but this depends somewhat on lip shape

7. For example, Walfrid Kujala, *The Flutist's Progress* (Winnetka, IL: Progress Press).
8. Coltman, "Acoustics of the Flute."
9. 1 Hertz is equal to 1 cycle per second.

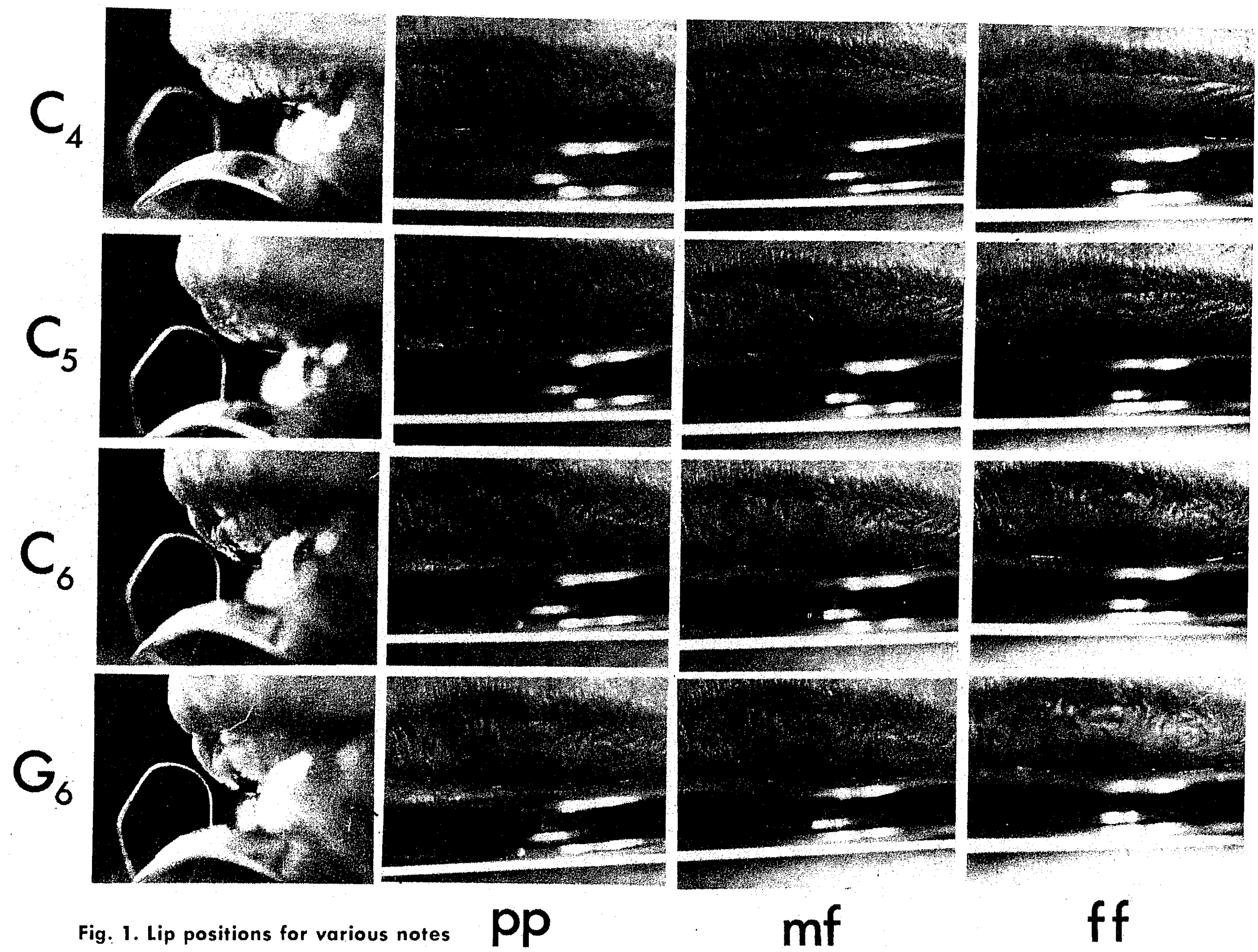


Fig. 1. Lip positions for various notes over the compass of the flute from low C to high G. In the first column the fine wire shows the edge of the embouchure hole.

The reason for the variation in lip opening is largely so that the upper notes, with high blowing pressure, will not be too loud in relation to the lower notes. In all cases the lip opening is approximately an ellipse with width about 15 times its height. The dimensions vary typically as shown in Figure 4. It is likely that some of the individuality of flute tone is determined by the exact shape of this lip opening and this in turn depends on lip shape and the position of the teeth. We should therefore treat these curves only as a guide and not try to reproduce them blindly.

Control of Pitch

The flute is nominally built to play a perfect, equally tempered scale and we might say that it is being played "in tune" when this has been achieved. In fact, however, string players tend to play in Pythagorean rather than either just or equally tempered intonation, pianos have stretched octaves, and any sort of ensemble playing always involves continuous adjustment of intonation to

Fig. 2. Range of blowing pressures used for different notes and dynamic levels by a selection of flute players. Measured curves are always of nearly the same shape and lie within the shaded region shown, most players within the dark region.

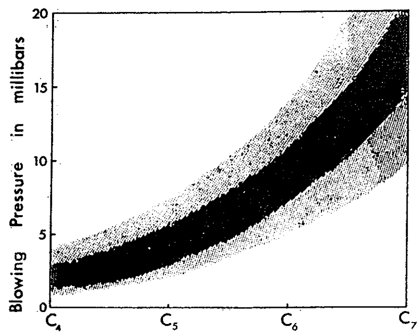


Fig. 3. Lip-to-edge jet lengths used by a selection of flute players.

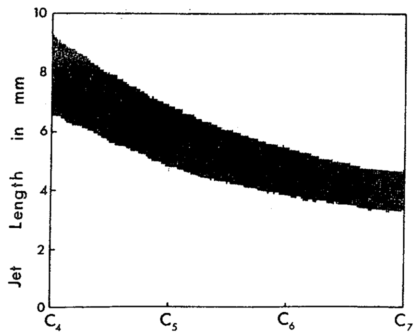
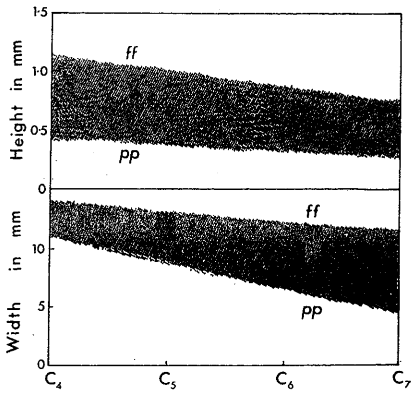


Fig. 4. Dimensions of the lip opening as a function of pitch and dynamic level. The opening is in all cases nearly an ellipse with axial ratio between 10:1 and 20:1.



produce a musically satisfactory result.

The theory and experiment outlined by John Coltman shows that if a flute player simply blows harder, without making any other adjustment, the pitch of the note sounded will rise. Essentially, this is because the airstream vibrations always reach the cutting edge a little early and effectively "hurry" the pipe oscillation. We might expect the same result for the same reason if the lips are pushed forward to shorten the jet length, but often just the opposite occurs and the note gets flatter. Depending on exactly how the push forward is achieved, the protruded lips can cover up more of the flute embouchure hole, resulting in a flattening effect which more than compensates for the sharpening produced by the shorter jet.

The usual methods taught for flattening a note (turn the flute inwards, blow down into it, or lower the chin) or sharpening one (turn the flute out, blow across it, or raise the chin) probably produce the desired effect on the pitch by altering the amount of embouchure hole uncovered. If the placing of the flute against the lip is also changed, or varies from one player to another, then this affects not only the general pitch level but also the timbre of the sound.

Control of Volume

It is not possible to change the loudness of playing a flute without affecting the timbre of the sound. This may not be a disadvantage but it should be, at least to some extent, under the control of the player. For a simple change in volume, the goal should be to keep the timbre as nearly as possible the same.

To change the loudness of the sound produced by the flute we must change the amount of energy communicated from the jet, and this means a change in the total air flow. This could be produced either by changing the blowing pressure, while making appropriate lip adjustments to keep the note in tune, or by altering the size of the lip opening to change the cross sectional area of the jet.

Measurements show that when the player attempts to keep a similar tone quality for loud and soft notes, he uses a constant blowing pressure and varies the size of his lip opening. A clear set of photographs to illustrate this is shown in Figure 1, and the general range of variation is depicted graphically in Figure 4.

It is interesting to note that in no case (for a good flute player with a clear tone) does the width of the lip opening greatly exceed that of the embouchure hole (about 14 mm), nor does the height of the lip opening exceed about 1.3 mm. Obviously an opening wider than the embouchure wastes air and probably produces unwanted breath noise. We might have expected, however, that a jet more than 1.3 mm in thickness would have had more power and produced a louder sound than a 1.3 mm jet. However, the larger lip opening and thicker jet simply produces a dull *mf* sound with little intensity. The reason for this is that the thicker jet is less responsive to the tube vibrations and so produces a tone with less harmonic development.

It is, of course, possible to reduce loudness still further by reducing blowing pressure, but this is more likely to affect the upper harmonics than the fundamental. It is more useful, therefore, to consider this as a controlled change in timbre.

Control of Tone

The last aspect of flute technique that I wish to discuss is that of tone or timbre. The general sound of the flute is determined by its design, particularly by the diameter of the tubing used. The note D^5, for example, sounds vastly different when played on a standard flute, an alto flute or on a piccolo. Even for a given note on the flute at a set dynamic level, there is still a good deal of subtle variation possible. Let us leave a discussion of vibrato until later and consider just the character of the steady tone.

The main factor determining tone quality is the relative strength of the harmonics present in the sound. The flute is generally thought of as producing a rather "pure" sound with few harmonics, and many of the standard texts show oscillograms or sound spectra to indicate this. It may be that styles of flute playing have changed considerably in the last fifty years or that analysis techniques have improved, but our ideas on this point require revision. Analysis of a standard "rich" flute tone on low notes shows a relatively weak fundamental tone and considerable strength in harmonics up to at least the tenth. On low C^4 played strongly, in fact, the second, third, fourth and fifth harmonics are all stronger than the fundamental. The situation changes as we go to higher notes. In the middle octave the fundamental is strongest with harmonics up to about the sixth being important, while in the top octave the fundamental is clearly dominant and only harmonics up to the third occur in appreciable strength.

Theoretical analysis and experimentation with adjustable organ pipes shows that, for a pipe of given diameter, harmonic development is favored if the air jet is thin and has sharp boundaries and if the jet travel time is less than the half-period value we discussed before. Harmonic development is also favored if the pipe is sounding strongly rather than weakly.

When applied to the flute this means that to produce a tone rich in harmonics we should use a lip opening which is a long thin ellipse, rather than a wide ellipse of equal area. We should tend to use a slightly lip-forward position to reduce the jet length, and we should use high air pressure, though stopping short of overblowing in both these latter adjustments. Conversely, a longer than normal jet length, a rounder lip opening and a lower blowing pressure will all reduce the harmonic development of the sound.

Some of these parameters vary considerably from one flute player to another, and this contributes to the individuality of flute tone. For a given performer, blowing pressure, lip opening shape and, to a lesser extent, jet length provide the major possibilities for adjustment. Stretching the lips to thin down the elliptic opening and increasing slightly the blowing pressure yields a more intense sound, while a relaxed embouchure and a lighter blowing pressure makes for a lighter, quieter tone. All these adjustments can be overdone, of course, and too round a lip opening or too low a wind pressure leads to dullness, while too tight an embouchure and too high a blowing pressure gives a strident sound. Within these limits, however, there is room for quite a degree of subtle tone variation.

Another component of the tone which needs to be under control is the amount of breathiness or air noise produced. This is most pronounced, of course, during the articulation at the beginning of a note and here it is a necessary component of flute sound. During the steady part of the note, however, we want to reduce it to the lowest level possible. Too thin a jet encourages wind noise, as does stray air not reaching the embouchure edge. In general, therefore, we should strive for a regularly shaped lip opening which is less in width than the flute embouchure hole. Again, there is a good deal of individuality in this and we should not seek undue uniformity.

Vibrato

Vibrato is not strictly part of the steady sound, but it is useful to discuss it briefly here. There are actually three variations of sound involved in a normal vibrato — a slight variation in pitch, a variation in loudness, and a variation in harmonic content. For a string instrument, the pitch variation is the main feature of the vibrato; but for wind instruments this is of less importance and variations in loudness and harmonic content predominate.

Measurements of blowing pressure in the mouth suggest that this fluctuates by about 20 percent above or below its mean value in the course of a typical note with vibrato. The resulting fluctuation in sound level is typically something like a factor of two, but much more important is the fluctuation in tone quality. Thus, while the amplitude of the fundamental varies by only about 20 percent, the amplitudes of the third, fourth and fifth harmonics, which are as strong as or even stronger than the fundamental, may vary by more than a factor of six, following the pulse of the vibrato. The associated pitch variations are, in contrast, very small. We should therefore characterize a flute vibrato as predominantly a timbre vibrato, rather than either a pitch or a loudness vibrato (see Figure 5).

Conclusion

In this article I have discussed some of the basic factors influencing the production of sound from a flute. What I have not done, however, is to discuss the muscular adjustments which are most appropriate to control these factors, and this is, of course, of even greater importance to the flute player.

It seems that there is sometimes quite a difference between what we think we are doing in the matter of embouchure control and what we are actually accomplishing. In itself this is of no importance at all unless we try to enforce a uniform approach on all our pupils. I hope, however, that a rather deeper understanding of what we are trying to do may help us all. ■

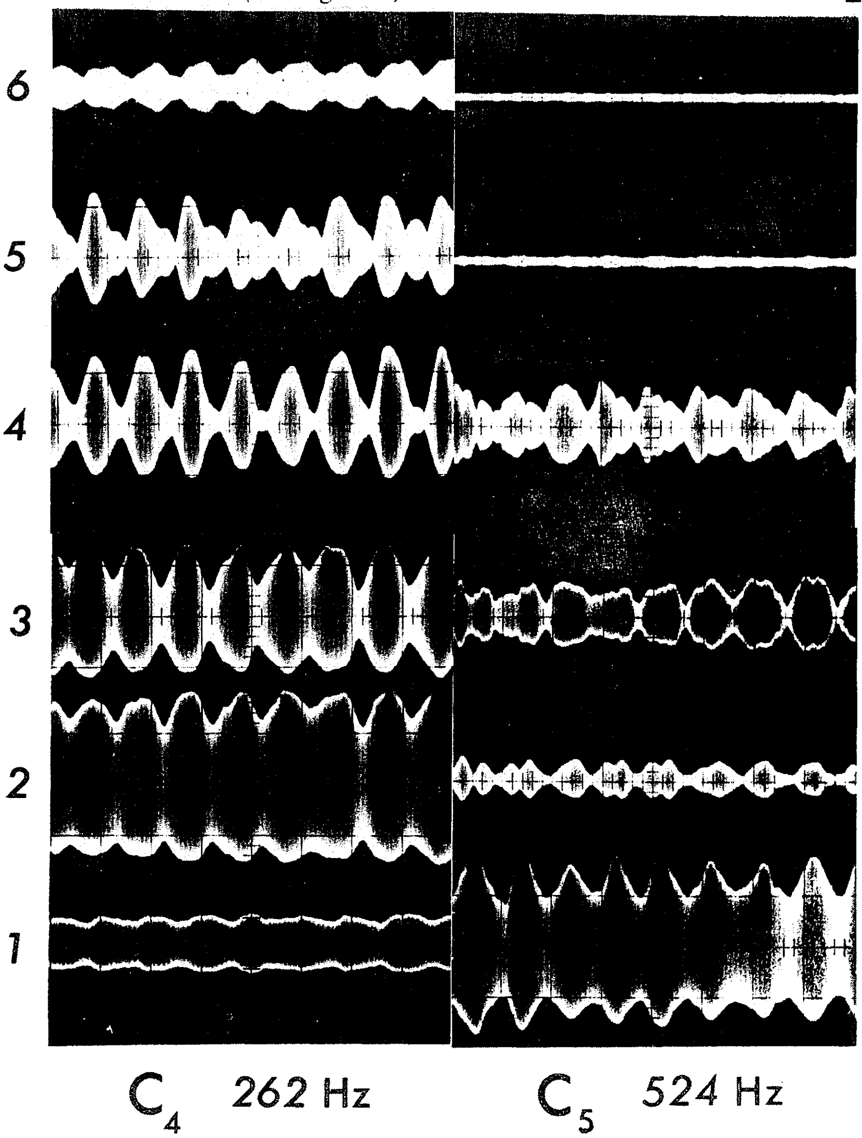


Fig. 5. Harmonic structure and vibrato on the notes C^4 and C^5. The relative amplitude and time variation of each of the first six harmonics is shown, the pulse of the vibrato being 5 per second in each case.