Basic Clarinet Acoustics

by

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INTRODUCTION

Careful study of the clarinet demands a rudimentary knowledge of the physical principles involved in producing its sound. We tend to satisfy ourselves with the knowledge gained from private study or the instinctive, trial by error process that has taken us a long way in our journey to become excellent clarinetists. But if we pause for a moment to ask why the solutions we have discovered over the years work, we take some of the mystery away and can perhaps solve future problems in getting ourselves further along in both the technical and musical study of the clarinet. This study of the physical principles is a responsibility we have to ourselves and to our students.

PRODUCTION OF THE CLARINET SOUND

Acoustically, the clarinet works as a "coupled system" with a valve and a resonating chamber. The mouthpiece, reed, and embouchure act as a valve which sends energy into the resonating chamber. The enclosed tube (bore) extending from the mouthpiece to the end of the bell is the resonating chamber which houses the vibrations from the "valve" to create sound. The clarinet's sound is not an amplification of the reed buzzing against the mouthpiece, but is the audible vibration of the forced air inside the resonating chamber. The shape of this resonating chamber is vitally important to the distinctiveness of the clarinet sound. The other woodwind instruments in the orchestra have conical shaped resonating chambers whereas the clarinet has a varied cylindrical shape. This is important not only to the characteristic sound, but to the instrument's overtone series.

VALVE—REED/MOUTHPIECE/EMBOUCHURE

The air column entering the bore of the clarinet must vibrate in order to produce an audible sound. The source of this vibration is the reed. The mouthpiece is shaped with a facing which begins to taper halfway towards its tip and continues this curve all the way to the tip. This leaves a small amount of space between the tip of the reed and the tip of the mouthpiece. In his book, *The Clarinet*, Jack Brymer states,

> The reed of a wind instrument is, in scientific terms, simply a valve—that is, something which opens and shuts, cutting off and re-starting the supply of air to the column inside the instrument. (p. 64)

The reed opens and shuts in the space between the reed and the taper of the mouthpiece. The air pressure supplied by the player and the lip pressure on the reed determine the speed with which the reed will vibrate. The louder one plays, the greater the distance the reed travels to the mouthpiece tip. When playing loudly, the reed actually makes contact with the mouthpiece tip. When playing softly, the reed does not make contact. We produce brighter sounds when air speed and lip tension are higher. This tension and air speed cause a quicker opening and closing of the reed against the mouthpiece. Less tension and air speed reduce the speed and distance the reed travels and create darker sounds. This is because higher vibrations will stimulate more upper partials in a given tone. The lower vibrations will reduce the presence of the upper partials. This also explains why softer reeds create brighter sounds; they vibrate faster with less pressure from the air column and introduce the upper partials in the harmonic series. Interestingly, when very little pressure and very little air speed are used, though the reed will vibrate to a degree, it will not produce a sound.

As stated above, the embouchure and the player's air column act as the energy source to vibrate the reed. In *Horns, Strings, and Harmony*, physicist and clarinetist Arthur Benade explains that energy produced by this process sends "puffs of air" into the resonating chamber. These "puffs of air" act on the physical properties of the bore of the clarinet to create wave forms which produce sound.

CLOSED CYLINDER

The clarinet is distinctive from the other orchestral wind instruments in that its resonating chamber is cylindrical. The overall acoustical system of the instrument is known as a "closed cylinder." It is closed because one end of it terminates with the mouthpiece/reed/embouchure and the other end remains open. It is called cylindrical because of the shape of the bore. In reality, the clarinet is a modified cylinder, having sections of its interior altered to help compensate for intonation problems and to aid in tone production.

Closed cylinders have very specific acoustic properties. Before discussing these, we need to understand the overtone series. For any given note, there are a series of notes higher in pitch which are present in the original note's tone—this is known as the harmonic series. The original note is known as the "fundamental" and each subsequent note is called a "partial." The partials rise numerically from the fundamental pitch, to the second partial, the third partial, and so on. Notationally, the harmonic series for C4 would look like this on the staff:

Figure 1: The Harmonic Series for C4 (from University New Wales "Music Acoustics website)

If you play a low note on the piano and hold down the sustain pedal, you will be able to hear many of the harmonic partials of the note. In other instruments, this becomes more difficult.

The flute, which is an open cylinder, sounds all the partials in its fundamental notes. The closed cylinder does not. Its acoustic properties sound only the odd numbered partials. The chalumeau register encompasses the clarinet's fundamental range. The clarion register sounds the third harmonic. The altissimo notes include both the seventh and ninth harmonics. Think about playing C4. If you press the register key, you are now playing G5, which is an octave and a perfect fifth above the fundamental; the third harmonic of C4. If you lift the left hand index finger, you will play E6, which is two octaves and a major third above the fundamental; the fifth harmonic of C4.

WAVE FORM OF THE CLARINET

The University New South Wales "Music Acoustics" website states:

> To make a sound, we need something that vibrates. If we want to make musical notes (we) usually need the vibration to have an almost constant frequency: that means stable pitch. We also want a frequency that can be easily controlled by the player. In non-electronic instruments, the stable, controlled vibration is produced by a *standing wave*.

A single frequency of sound vibrates in the form of a "sine wave":

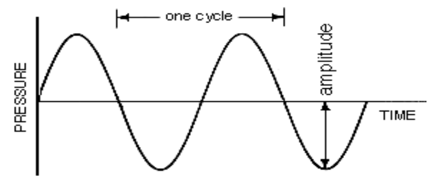

Figure 2: Sine Wave (from "Acoustic Ecology" website)

The combination of two waves traveling in opposite directions produces a "standing wave":

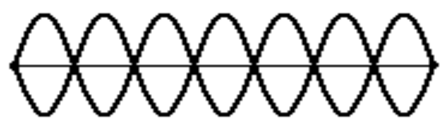

Figure 3: Standing Wave Diagram (from "Acoustic Ecology" website)

In the production of sound, one of these waves travels down the instrument and the other is a reflection which travels back up the instrument. The peak, where there is the greatest distance between the waves is called the "antinode" and is the place of greatest pressure within the wave form. The place where the waves meet (intersecting at the center line) is the "node" and is the point in the standing wave where there is no pressure. The constantly moving wave pulses its vibration between the node and antinode. The wave form of the flute, an open cylinder, would look like Figure 3 if it were vibrating in the seventh harmonic. Jack Brymer states:

> The pulses which form the basis of the vibration in a tube are formed by the compression of the air molecules followed immediately by a rarefaction as the valve of the reed snaps shut. These pulses travel the length of the tube until they meet the open air at the end of it, and one after another they emerge there. At this point they rebound from the outer atmosphere, which reacts against them and sends back a resistance wave (back up) the tube. The interesting factor in this resistance wave is that it is a direct reversal of the pressure points of the outer wave—the compressions have become rarefactions and vice versa. (p. 67)

A closed cylinder such as the clarinet has a very distinct wave form. Unlike the open cylinder flute, the clarinet sound begins at the valve (mouthpiece/reed/embouchure) with the point of greatest pressure in the wave, the antinode. The wave form ends (approximately) at the end of the tube's length—the point of the first open tone hole. If that is E3, the wave ends at the end of the clarinet. If it is C4, it ends just beyond that tone hole as illustrated:

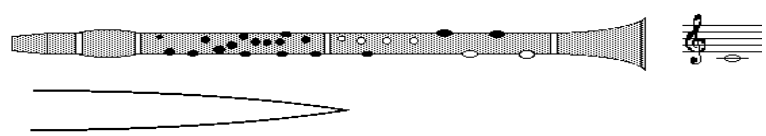

Figure 4: Wave form from fundamental register of clarinet: C4 (University New Wales "Music Acoustics website)

One of the distinctive qualities of the closed cylinder wave form is that the wave in the fundamental (Figure 4) represents only one quarter of a complete wave cycle. This in turn means that in its lower register, the clarinet can play notes much lower than its tube should allow. Compared to the flute, which has a similar length of tube, the clarinet can play a full octave lower.

When the flutist or saxophonist press their register keys, they leap an octave from their fundamental pitch. Since the clarinet only sounds the odd numbered partials, they leap an entire twelfth, skipping the octave altogether. The wave form of this acoustic is quite interesting:

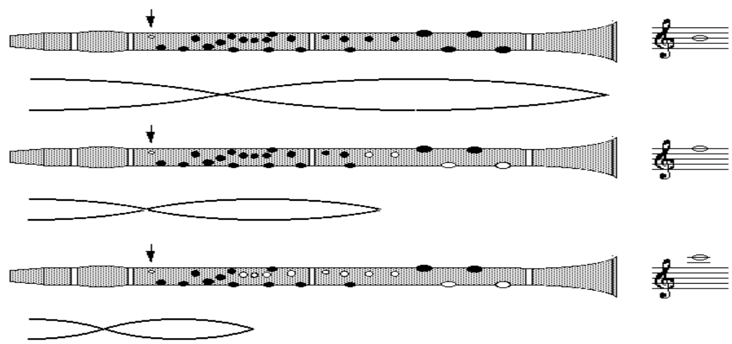

Figure 5: Wave forms from the third partial (clarion) register of the clarinet (University New Wales "Music Acoustics website)

As with the fundamental, the wave form begins at the reed/mouthpiece/embouchure valve with an antinode. The fundamental structure is then destroyed when it passes the register key, creating a place with no pressure, the node. The wave continues on for the length of the tube (ending just past the first open tone hole). Since the fundamental wave form is representative of one quarter the length of a full wave, the third partial is three times that size, or three quarters of the length of a full wave.

CLARINET CONSTRUCTION AND REGISTRATION

Because the clarinet's harmonic system is based upon the odd numbered partials, this created a problem for early clarinet makers. The chalumeau range extends from E3-F#4. When you press the register key, the instrument leaps a perfect twelfth, instead of an octave. When you press the register key with the clarinet's lowest note, E3, you get B4, the first note of the clarion register. This leaves a gap between the chalumeau and clarion registers (G4, G#4, A4, and Bb4), since the last real fundamental note is F#4. To compensate for this gap, tone holes were drilled into the bore above the F4 hole to give the clarinet the ability to play the notes in the gap between the chalumeau register (the natural fundamental register) and the lowest note in the clarion register (the third harmonic register).

Arthur Benade refers to the wave behavior in each of the registers of a woodwind instrument as "modes of vibration." Each register has its own form of standing wave. Figure 4 above shows the vibrating mode of a clarinet note in its fundamental register, the clarinet's first mode, in the standing wave drawing underneath the clarinet. Figure 5 shows the vibrating mode of a clarinet note in its second register, the third harmonic of each of its corresponding fundamental notes. The mode of each subsequent harmonic (fifth, seventh, and ninth) has a standing wave which adds another half-wave (the distance between two nodes which looks like an elipse). So, a note in the fifth harmonic, like C#6 (another harmonic of A3), begins with an antinode, tapers to a node, and has two additional half waves (looking like two elipses). The next mode, the seventh harmonic, has a standing wave with an additional half wave (another elipse). Pressing the register key destroys the integrity of the fundamental at a point around the register key creating a node. It ascends to the level of another antinode and decends to a final node (as in Figure 5). As already stated, the length of the standing wave is determined by the first open tone hole. The standing wave stops just beyond the first open tone hole because of the pressure created by the tone hole. Since the tone hole is not the same size as the bore, there is pressure from outside the tone hole pushing the standing wave a little further down the tube. This is one of the reasons for the flared out bell in the clarinet; it gives the standing wave room to decay. A very simplistic way to look at modes is that each is interrupted by a node in a standing wave. Figure 4 shows the first mode (fundamental); there is only one wave form between the mouthpiece and the first node. Figure 5 shows the second mode (third harmonic) with two areas separated by a node. The third mode (fifth harmonic harmonic) has three areas separated by two nodes. Each successive mode has an additional area separated by a node. The reason for the differences in pressure and feel between the registers is because each mode is characteristically different.

To achieve a clear note in the fifth harmonic (third mode of vibration), a clarinetist takes their left index finger off of its tone hole to destroy the integrity of whichever partial previously played. This first tone hole, in effect, becomes the clarinet's second register key, allowing an easy transition to notes of the fifth (as well as the seventh and ninth) harmonic. The imperfections of this acoustic system show themselves in the clarinet's intonation. Register key placement and size of its bore are a compromise since it also serves as part of the fingering for Bb4. It's bore is too large to be a perfect register key but too small to be a perfect tone hole for Bb4. It's placement is too far from the mouthpiece to be a perfect register key. It exists as it does on the clarinet to give the clarinetist a fighting chance to play the Bb4 in tune while also causing the third harmonic notes to speak clearly. Of practical use, the alternate Bb4 controlled by the right hand index finger is a much better option in terms of its pitch and tone color.

Each of these modes of vibration (registers) have a distinctive sound and feel. One of the greatest challenges to the clarinet student is blending the sound between registers so that the overall effect is seamless. The skilled clarinetist is over time able to compensate for these registral differences with varied air pressure, lip pressure, and finger techniques. But even the most skilled player runs the risk of creating an uneven sound going between registers. The clarinet does have other solutions besides the stock fingerings to make some register changes less challenging. This is where some of our personal responsibility comes into play in developing performance strategies based upon our knowledge of the acoustics of the instrument. There are some alternate fingerings in the fundamental chalumeau range for the first few notes in the third harmonic clarion range. The side keys controlled by the right index finger can produce a B4 and C5, making them fundamental pitches with a standing wave like that in Figure 4. Of more practical use are several notes at the top of the third harmonic clarion register which can make nice substitutions for fifth harmonic altissimo notes. The keys controlling F#4 and the throat tones in the fundamental range are the keys in which one can make an effective C#6, D6, or Eb6. These are best for legato passages which briefly go into the altissimo register from the clarion register. The third harmonic for the fundamental F#4 is C#6. The best fingering to achieve good pitch and tone color is the alternate F#4 using the two first keys on the side of the clarinet. An excellent place to use this might be in the long clarinet solo that finishes the "Adagio non troppo" movement of Nielsen's *Fifth Symphony*. D6 has two options, the Ab4 key and the third key on the right side of the clarinet. The true third harmoni of Ab4 is Eb6, but due to the positioning of the key and the presence of the thumb over its hole to lend stability to the standing wave, it produces a flat D6 sound—too flat for practical use. The side key works well, though. An example of its use might be in the opening clarinet solo of Rimsky-Korsakov's *Capriccio Espagnol*. Eb6 has two good options with the A4 key and the fourth side key on the right side of the clarinet. Again, the third harmonic of A4 is E6, but because of the key positioning and the covered thumb hole, makes for a responsive, good sounding Eb6. A great place to use this fingering is in the opening clarinet solo at letter B in the first movement of Brahms' *Symphony #3*. Using these choices, especially as substitutions for fifth harmonic altissimo notes, can make certain passages sound and work better. It is our responsibility to know about these options and use them where the music demands.

REASONS FOR MULTIPLE FINGERING CHOICES

There are two primary reasons that multiple fingering choices produce the same note. The first is because the upper portions of the third and fifth harmonic ranges extend beyond the lowest note in the next harmonic range. The throat tones in the fundamental range exist to bridge the gap between the chalumeau and the clarion registers. It is not necessary to bridge the gap between the clarion and altissimo registers, so those keys offer the clarinetist additional choices for fingerings. The upper portion of the fifth harmonic range also has some options for notes normally played in the seventh harmonic range, but these notes have significant pitch problems.

Another reason for multiple fingering choices has to do with "cut off frequencies." As mentioned before, the standing wave actually extends beyond the first open tone hole. Since the tone holes are not as large as the diameter of the bore, the standing wave will vibrate further down the bore. The pressure is great enough that many notes have cross fingerings such as the G#5 fingering using the register key, thumb, and first two fingers of each hand covering their respective tone holes. There are many combinations like this that work, but it is dependant upon the amount of reflective pressure coming back into the clarinet's bore from the first open tone hole in the tube. Another example would be Bb5 using the register key, thumb and first finger of each hand. Cross fingerings were especially important to early clarinetists, who had very few keys on their instruments.

FUNDAMENTAL NOTES AND THEIR RELATIVE NOTE IN EACH MODE

NINTH HARMONIC (Fifth Mode of Vibration-Altissimo Register)	B C
SEVENTH HARMONIC (Fourth Mode of Vibration-Altissimo Register)	G* G#*A* A#*
FIFTH HARMONIC (Third Mode of Vibration-Altissimo Register)	C# D D# E F F#(G G# A)
THIRD HARMONIC (Second Mode of Vibration-Clarion Register)	B C C# D Eb E F F# G G# A Bb B C (C# D* Eb*E*)
FUNDAMENTAL (First Mode of Vibration-Chalumeau and Throat Registers)	E F F# G Ab A Bb B C C# D Eb E F F# G Ab A Bb

This chart shows the fundamental pitches on the clarinet (bottom row, lower to higher from left to right) and the subsequent notes in each mode of vibration directly above the fundamental. The notes within parentheses are not normally used. The notes with asterisks deserve special attention because they have significant intonation problems. These intonation problems are caused primarily by the compromise in placement of register keys and tone holes in the clarinet. Generally, today's clarinets are adjusted so that the twelfth between chalumeau C4 and clarion G5 is good. The twelfths below C4-G5 are generally narrower (sharper in the fundamental/flatter in the third partial) and the twelfths above C4-G5 are wider (because of the sharpness at the top of the third partial). Because of the acoustic of the instrument, the low E3 and F3 are significantly lower than the other low chalumeau notes.

In the third harmonic range, the altissimo notes normally played in the fifth harmonic range have significant pitch and resistance problems. C#6 is the most stable but flat unless you use the two side keys as an alternate fingering. D6 as fingered like G4 (throat tone) is not only flat but very unstable in the resistance created by the sound wave. This is because of the very short space the standing wave has to vibrate and because of the tone hole's proximity to the register key. It is much better to create a D6 by adding the side key to the fingering for C6. Eb 6 is incredibly flat to the point that this partial is better used as D6—a half step lower—in very fast technical passages. E6 shares the same problem as Eb6; by playing this note with the A4 fingering, it is a half step too flat. This fingering works well for Eb6.

The fifth harmonic range starts with C#6 in relatively good pitch and becomes progressively flatter the higher one goes. For D6-F6, a clarinetist adjusts for this by pressing the right hand key for fundamental Ab3. This raises the pitch leaving the subtleties of pitch to the player to adjust with their embouchure. F#6 requires venting further up the horn to bring its pitch up. Normally, the right hand fork key solves this problem. G6-A6 are too flat and too shrill for practical use in the fifth harmonic range.

In the seventh harmonic range, all the tones listed above are very flat. They are unusable as they exist. The clarinetist solves this problem by learning this register a half step flat; each fingering we use in this register is acoustically the fingering for the note one half step lower. The notes become progressively worse as the pitches rise. The G6 in the seventh harmonic range is barely useable and most clarinetists must find a more suitable substitute. The G# is so flat, that a clarinetist must open the right hand index finger key and instead press down the middle finger key to make the note in tune. The A is so flat, it is unusable as a relative to B in the fundamental. The A# is so flat that it functions as an A with the assistance of a resonating key like the low F# key to make it tenable. To use the A# in the seventh partial, one can still base it on the C fundamental, but must lift the thumb key to bring the pitch up properly.

CONCLUSION

Understanding these basic principles about the acoustics of the clarinet are important in how we approach the instrument. This information takes some of the mystery away from many issues including reed qualities, mouthpiece choices, creating smooth transitions between registers, and fingering choices. One of the first, most practical applications relates to fingering choices. All clarinets have their own pitch idiosyncrasies beyond the natural tendencies of the instrument, especially in the higher range of the instrument. The knowledge gained from understanding cut off frequencies, for instance, gives us the tools we need to discover better fingerings for our own unique instrument.

Further study of the acoustic properties of music and the clarinet will help make us better clarinetists. As with any discipline, we should continue to analyze our problems and their solutions with the question “Why?”. For many of our musical problems, this question will lead us to acoustics.

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