X2. Register Hole Design for Cone Woodwinds. A. H. BENADE, *Physics Department, Case Western Reserve University, Cleveland, Ohio 44106.*—In a woodwind the register hole produces a transition from low to second playing register in two ways. At low dynamic levels the hole must increase the damping of the first mode sufficiently that oscillation cannot be sustained. Oscillation then takes place on the basis of the second resonance peak. At high dynamic levels this effect of the hole is insufficient—intermode cooperation can still sustain the low register oscillation, so that the first mode *frequency* must be suitably shifted relative to that of the second mode to make their cooperation impossible. Optimum hole reactance raises the first mode frequency 25%. For an instrument whose low register half-wavelength is L, having a bore taper $dR/dx=T$, and provided with a (centered) register hole of radius b and effective length $t_e \cong (t+2b)$, the desired frequency shift is produced when $(b^2/t_e)=(\pi/4)^2LT^2$. The damping requirement is best approximated by making the physical length t as small as is mechanically practical (1 mm on a saxophone or bassoon). Oboes and English horns traditionally have vent hole proportions in agreement with this design. Small modifications invariably give trouble. Most saxophones are dramatically improved by reworking the vent holes to the present specification. Similar principles apply to bassoons (and clarinets), but here the multiple use of the vent somewhat compromises the design.

JASA 54(1): 310-311 (1973)

REGISTER HOLE DESIGN FOR CONE WOODWINDS

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1973

In a woodwind instrument it is the function of the register hole to produce a transition from the low register to the second playing register. It does this by altering the acoustical nature of the air column from one which favors the maintenance of oscillations at the low register to one which favors oscillations in the second register. It has been known for about 100 years that for systems like the reed woodwinds and the brasses, oscillation is most favored at a frequency close to that of the tallest input impedance peak as measured inside of the reed or mouthpiece cavity. This was first worked out by Hermann Helmholtz, while Wilhelm Weber supplied a correct account of the effect of the yielding termination of the reed on the input impedance seen by the valve mechanism. Due to the nonlinearity of the flow as a function of the operating control pressure, the Helmholtz-Weber formulation is not quite true, particularly at higher playing levels on real wind instruments. At such levels we find that several of the input impedance peaks can cooperate to form what I refer to as a *regime of oscillation*, in which energy is generated at several harmonically related frequencies and with an exchange of energy of such nature that the net regeneration of this collaborative mechanism can override the Helmholtz-Weber criteria. Let us see briefly what is involved.

Before we do this, however, we should look at SLIDE 1 showing the kind of equipment which is convenient for measuring the input impedance of oboe- and bassoon-type instruments. Here is a device which is based on the driver which John Coltman used in his experiments on the sounding mechanism of the flute. We have a voice coil driving a small diaphragm; there is also a velocity pickup coil close to the diaphragm, and the motional EMF from this coil goes to a servo to maintain constant flow amplitude into what we may call the reed cavity. I will not describe how we objectively determined the proper cavity volume for this replacement of the actual reed. Such a description could have been the subject of yet another paper in this series of reports on our work in Cleveland. Let us turn instead to some data taken with this piece of equipment.

In the lower part of SLIDE 2 we see the input impedance curve belonging to the air column as it is arranged for playing B_4 on a conservatory oboe. This is the B which is played with the left forefinger closing a hole, the rest of the fingers being raised. We observe that there are two more-or-less harmonically related input impedance maxima lying close to 500 and 1000 Hz. The resonance peaks above this are not very tall, and they are quite irregular, as a consequence of the open-hole lattice cutoff frequency, which lies near 1400 Hz. Resonances above this cutoff are killed off by radiation damping. when one plays softly in the low register, the oscillation is based on the tall first peak which is just above 500 Hz. As one plays louder, the second peak (near 1000 Hz) joins the regime of oscillation, and feeds energy to the system.

Opening the register hole does two things to the acoustics of our air column. Firstly, it reduces the tallness of the first peak, so that the second peak is now the tallest of the whole set. The register hole also displaces the first peak to a higher frequency. How do these two alterations modify the behavior of the instrument?

When one plays very softly, which is the domain of the Weber-Helmholtz theory, the oscillation takes place at the tallest peak, producing the desired octave change. We also notice that if an oscillatory regime were tempted to base itself on the first peak, it would find that there is a minimum in the curve at the frequency of the second harmonic so that there is a heavy drain imposed on the oscillation via the transfer of oscillatory energy to the second harmonic component of the tone. Thus all things conspire against an oscillation based on the first resonance peak, and toward one based on the second.

Let us now turn to the next slide. In the lower part of SLIDE 3 we find the in;put impedance curve measured for D_4, which is the six-finger-down note on the same conservatory oboe. We notice at once that the second impedance peak is taller than the first. This extra height of the second and sometimes also the third peak here is quite typical of woodwinds in which the cone is very nearly complete. Instead of having an oscillation preferentially based on the tall second peak, as predicted by the Weber-Helmholtz formulation, one finds that the cooperation between the first, second, and third peaks, which are all harmonically related, gives a net energy input at the low register playing frequency (just above 300 cycles) in an amount which is considerably more than what would be available from a collaboration between the tall second resonance peak and a rather out-of-tune (cooperatively speaking) fourth peak. When one plays very softly, however, particularly on the saxophone, one finds indeed that the instrument has a tendency to make a transition upward to play higher by an octave, basing its oscillation on the tall second peak. However, as one plays loudly the tone reverts back to the low register, as the collaborative effects regain importance.

Let us turn our attention now to the upper part of the diagram which shows the effect of opening the register hole. Here we find that the first and also the third resonance peaks are displaced to higher frequencies, and are made less tall. The little crosses show the frequencies which would have to cooperate with the first impedance peak if an oscillation were to be maintained based on it. Notice the first of these crosses lies at an impedance minimum, which means that there is a tendency to kill off an oscillation based on the first resonance peak, so that the oscillation goes over instead to one supported mainly by peak no. 2 with some help from peak no. 4. On this particular oboe, the third little cross lies on top of peak no. 4, which says that there is a certain residual amount of energy contribution which might be available for maintaining a displaced low register oscillation. This is not a happy situation. This oboe in fact behaves for the musician as though the register hole is too large. If the hole were made slightly smaller, the first peak and its next two harmonics would lie at the positions where the little dots are, and we see that then there would be strong anti-cooperation on all counts, and this in fact agrees with practical experience on a well-arranged oboe.

Let us now turn our attention to an entirely different way to go about obtaining a register change. This other method was in universal use during the Baroque era, and was extensively employed all through the earlier part of the 19th century. As a matter of fact the Vienna oboe of today routinely makes use of this very convenient phenomenon, as does every bassoonist. In SLIDE 4 we see the same B_4 and B_5 transition. The lower part of the curve is exactly as before; the upper shows a double-forked fingering, which has the acoustical effect of leaving the first peak pretty tall, but unable to support oscillation because there are harmonically related dips in the impedance curve, as marked by the small spots. The reed instead chooses to base its oscillation on peak no. 3, which is located here close to the octave B_5. On a Baroque instrument, this peak gives a well-tuned and solid note, and the instrument makes absolutely inexorable transitions to or from it, whether playing loud or soft.

Note added in response to a question raised by R. T. Schumacher, after the reading of this paper:

The lack of a second-harmonic "helper" for the second-register tone is not a source of difficulty, provided that there is not an impedance minimum at this frequency. In other words, the regime of oscillation for the second register is dominated by peak no. 3 with neither help nor hindrance from the resonance curve lying above the cutoff frequency.

Let us draw our general conclusion now. To be effective a register hole must produce a maximum noncooperation between resonance peaks if it is to displace a tone from low register to second register. It must also produce sufficient damping of the first resonance peak that its participation in an oscillation at low playing levels is disfavored. In practice, one finds that 2 or 3% shifts in the detuned frequency of the first peak can be noticed by a player. Craftsmen are quite familiar with the problem of diagnosing and of correcting such size of adjustments. Saxophones customarily use a fairly large-diameter vent hole of a length sufficient to produce proper detuning, but such proportioning gives inadequate damping to the detuned resonance. Vent holes of this type are known to cause all sorts of trouble, so that many saxophones practically ignore their regular keys. Furthermore, there is a great deal of difficulty with the intonation behavior of the instrument as a result of such register holes. If, however, one uses very short holes of small diameter, which optimizes both the low-level and the high-level playing requirements for the hole, one can get marked improvements in the response to the register key, and often considerably reduce the intonation difficulties as well.

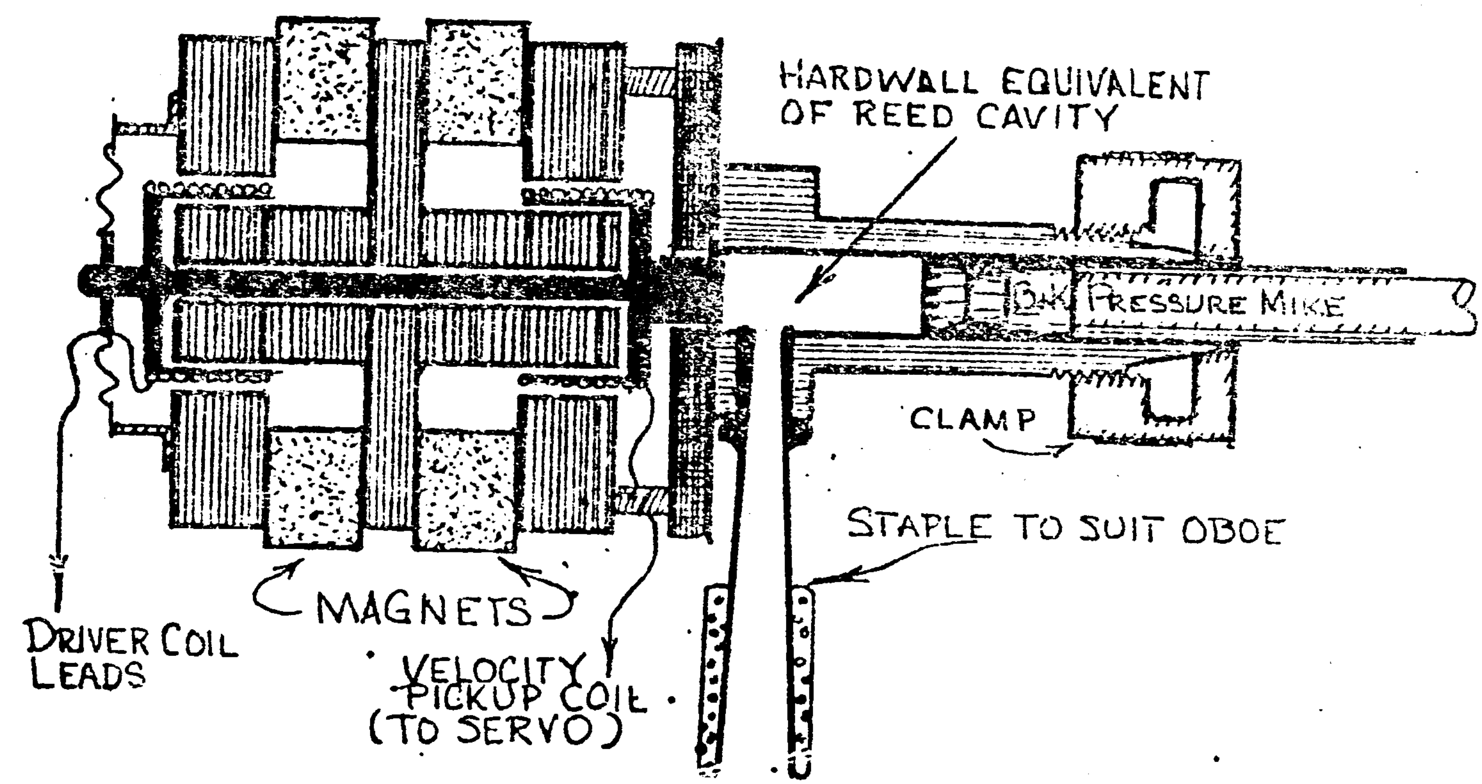

HARDWALL EQUIVALENT
OF REED CAVITY
B+K PRESSURE MIKE
CLAMP
STAPLE TO SUIT OBOE
MAGNETS
DRIVER COIL
LEADS
VELOCITY
PICKUP COIL
(TO SERVO)

FIG 1

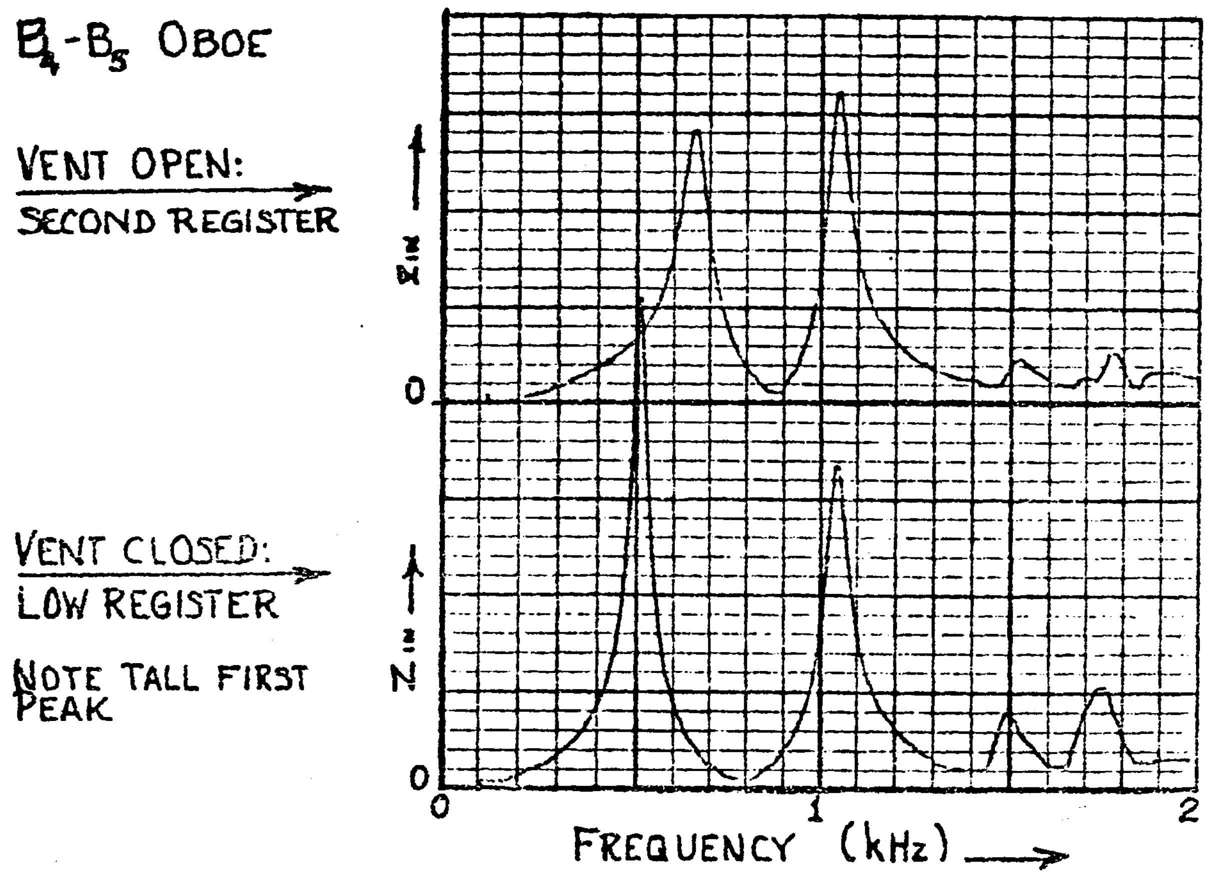
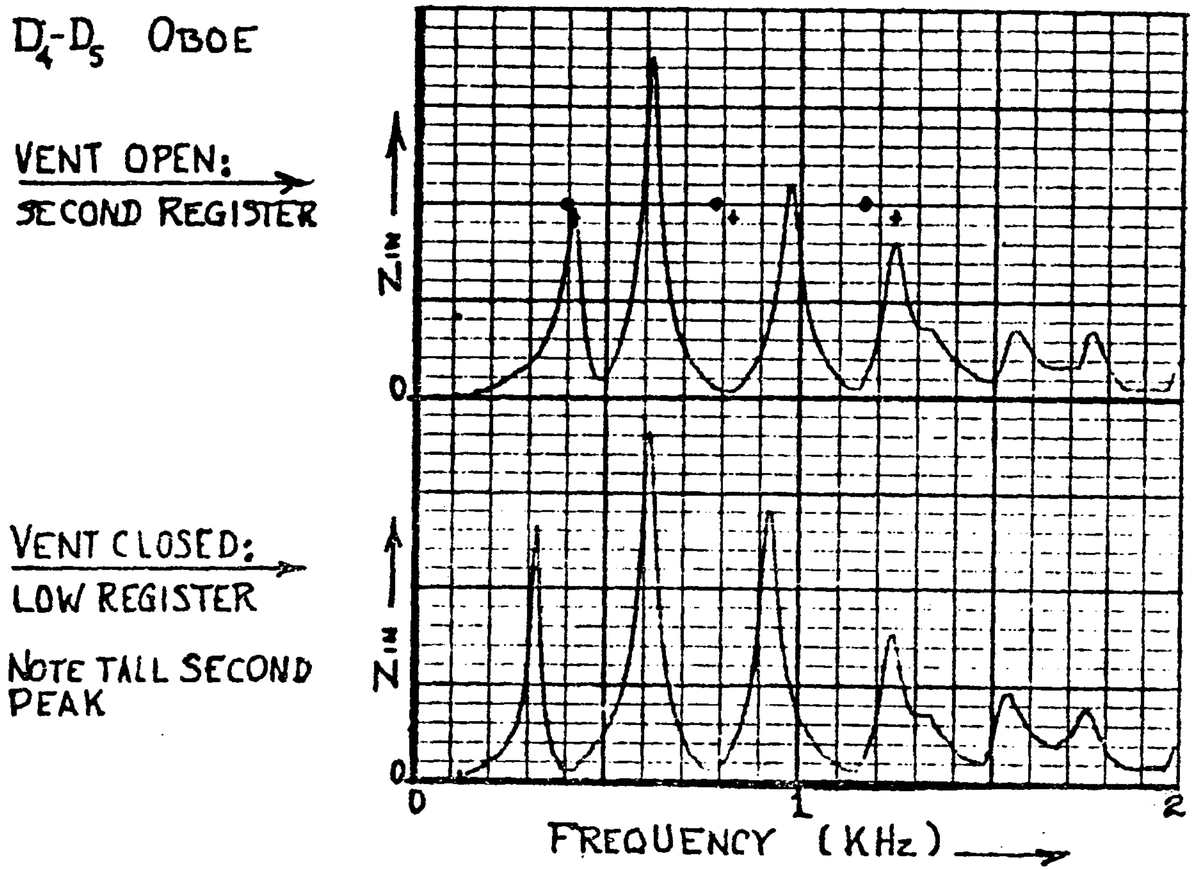
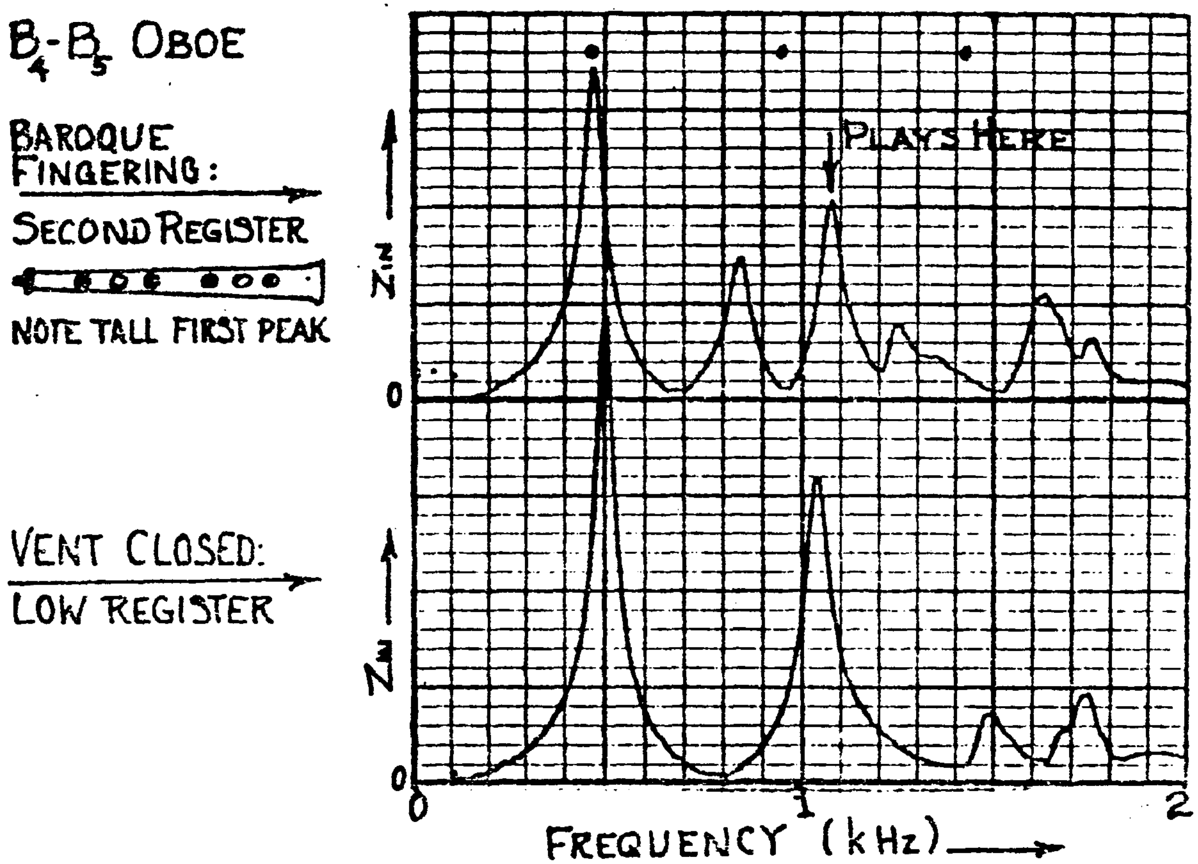

B_4-B_5 OBOE
VENT OPEN:
SECOND REGISTER
VENT CLOSED:
LOW REGISTER
NOTE TALL FIRST PEAK
Zin
0
Zin
0
0
1
2
FREQUENCY (kHz)

FIG 2



D4-D5 OBOE
VENT OPEN:
SECOND REGISTER
VENT CLOSED:
LOW REGISTER
NOTE TALL SECOND PEAK
Zin
0
0
1
2
FREQUENCY (KHz)

FIG3

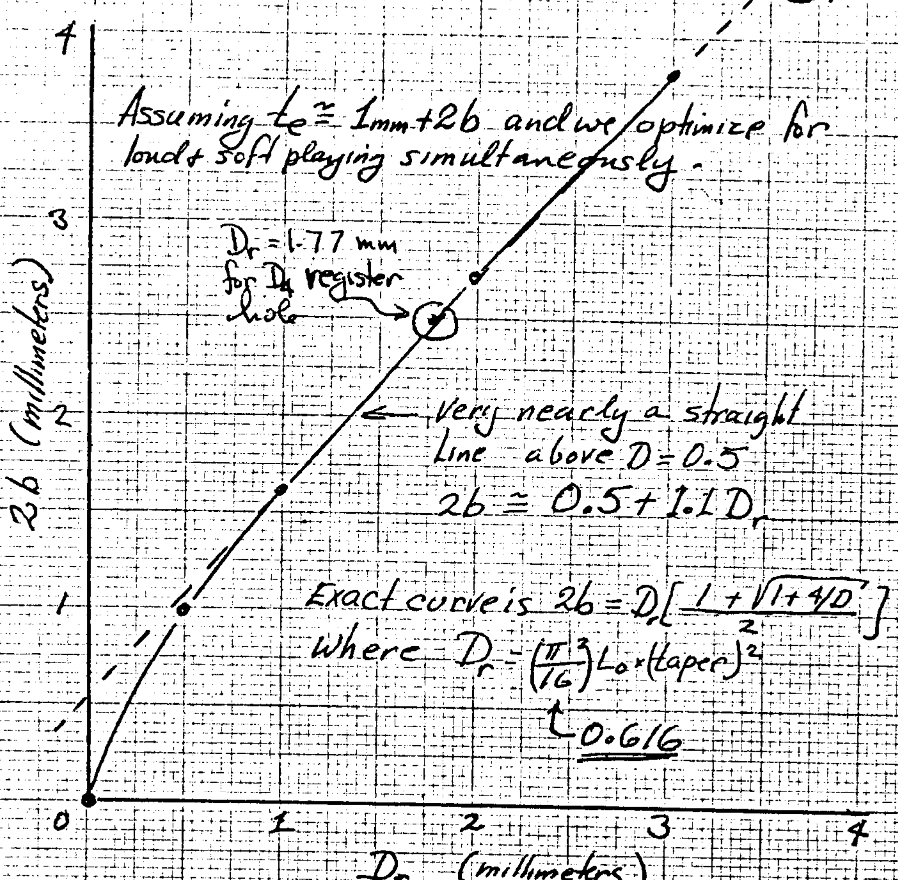


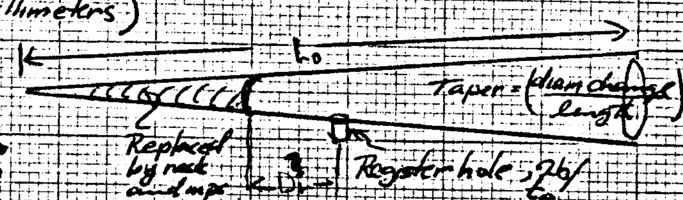
B4-B5 OBOE
BAROQUE FINGERING:
SECOND REGISTER
NOTE TALL FIRST PEAK
VENT CLOSED:
LOW REGISTER
PLAYS HERE
|Z|
0
1
2
FREQUENCY (kHz)

FIG 4

For George Jameson

REGISTER HOLE SIZING FOR A SAXOPHONE:





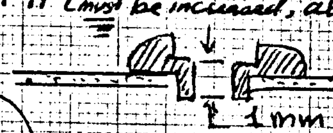
FINAL RESULT:

FOR THE L_o OF THE NOTE TO BE GIVEN A REGISTER HOLE AND THE TAPER OF THE BORE, CALCULATE D_r

USE THIS VALUE OF D_r AND THE GRAPH ABOVE TO FIND THE BEST REGISTER HOLE SIZE.

ARRANGE THAT THE WALL THICKNESS THRU WHICH THIS HOLE IS DRILLED IS 1 MILLIMETER

NOTICE THAT TO SEAT A PAD OR TO PREVENT WATER BUBBLES, THE HOLE MAY HAVE TO LOOK THUS: If t must be increased, always keep (b^2/t_e) constant.



A FINAL WORD: THE EXACT SIZE IS NOT CRITICAL

AHBenade
May 15 1972

NOTE BY V. BENADE: THIS WAS IN JAMESON'S FILE FOLDER OF THE 1973 unpublished paper Register Hole Design — either Benade gave it to him as applicable, or Jameson put the two together.