THE NX CLARINET, 1983

Material used for four talks that A. H. Benade gave in 1983 about his NX clarinet design:

February 11, 1983	Massachusetts Institute of Technology
April 7, 1983	Case Western Reserve University
May 13, 1983	Acoustical Society of America, spring meeting
September 16, 1983	Oberlin College

Abstracts for all four are included here, plus transparencies. Because there are subtle differences in the abstracts, all four are given here.

The set of 14 transparencies were made for the MIT talk, and probably the entire set was shown at the next two presentations. However, for the talk in the fall, where the audience was mainly music students, 5 of the transparencies were redrawn to use slightly more informal terminology and to emphasize playing, rather than physics. The introductory slide from the first set was also used, unchanged.

MIT Department of Mechanical Engineering, 11 February 1983

THE PHYSICS OF A NEW CLARINET

Arthur H. Benade, Case Western Reserve University, Cleveland, OH

The clarinet (or other woodwind) player demands smoothness of response, wide dynamic range, clean articulation, good carrying power, stability of pitch, and suitable tone color from his instrument. In the past few years it has become possible to systematically relate these musical virtues to the acoustical properties of the instrument. Acoustically the instrument is an oscillator with nonlinear feedback, giving coupled production of energy at several frequencies, and having wide-band radiation and dissipation behavior governed by a nonperiodic lattice of open and closed holes on a subtly shaped air column.

Cooperation between scientist, craftsman and musician has led to the development of dependable procedures that guide the adjustment of instrument proportions. It has also deepened our understanding of the musical and acoustical nature of early instruments. This in turn has suggested new avenues of scientific inquiry, and new ways to mitigate traditional shortcomings of the instrument itself.

The first part of the talk will briefly outline these matters with the help of various "player's demonstrations." The basic features of a new clarinet design will next be described and demonstrated. This instrument came into being with a two-fold purpose: to force the scientific/engineering issue of whether it is indeed possible to produce a design "in cold blood" and, if so, to provide the musician with a workable instrument requiring little change in his technique, but which reduces the problems and strengthens the virtues of his familiar clarinet. Such a design proves possible. It is not difficult to make and maintain, and it is very forgiving of reeds. Players tend to respond to it with enthusiasm.

COLLOQUIUM

THE PHYSICS OF A NEW CLARINET DESIGN

7 April 1983, Physics Department, Case Western Reserve University
Room 301, Rockefeller Bldg.
Coffee will be served at 4:00 P.M.

The clarinet (or other woodwind) player demands smoothness of response, wide dynamic range, clean articulation, good carrying power, stability of pitch, and suitable tone color from his instrument. In the past few years it has become possible to systematically relate these musical virtues to the acoustical properties of the instrument. Acoustically the instrument is an oscillator with nonlinear feedback, giving coupled production of energy at several frequencies, and having wide-band radiation and dissipation behavior governed by a nonperiodic lattice of open and closed holes on a subtly shaped air column.

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OBERLIN COLLEGE

CONSERVATORY OF MUSIC

September 16, 1983

The Musical Physics of a New Clarinet Design

Professor A. H. Benade

Case Western Reserve University

The clarinet (or other woodwind) player demands smoothness of response, wide dynamic range, clean articulation, good carrying power, stability of pitch, and suitable tone color from his instrument. In the past few years it has become possible to systematically relate these musical virtues to the acoustical properties of the instrument. Acoustically the instrument is an oscillator with nonlinear feedback, giving coupled production of energy at several frequencies, and having wide-band radiation and dissipation behavior governed by a nonperiodic lattice of open and closed holes on a subtly shaped air column.

The first part of the talk will present a nontechnical outline of these matters with the help of various "player's demonstrations." The basic features of a new clarinet design will next be described and demonstrated. It provides the musician with an instrument which reduces the problems and strengthens the virtues of his familiar clarinet. It is mechanically simple, full toned and docile, requiring little adaptation by the player. The good features of early 19th-century clarinets (bell taper, bore and register hole relation, and low complex-flow interaction effects) had a major influence on the design of this instrument, whose adjustment was guided by formal playing-condition diagnostic techniques.

Session MM. Musical Acoustics II: General

9:05

MM4. Musical/acoustical design of the NX clarinet. A.H. Benade (Case Western Reserve University, Cleveland, OH 44106)

A simple, failsafe mechanism separates the $B_4\flat$ tone hole function from that of a single register hole. This permits redesign of the clarinet's acoustics as follows. Accurate alignment (<5¢) of mode 1 and mode 2 resonances over the entire low register scale becomes possible, assuring good tone and response in the low register. The register hole is sized such that the "off-node" pulling up of pitches at both ends of the second register scale just offsets the effect of embouchure slackening needed to give best tone and response via reed resonance effects. Register hole dissipation is also reduced. A suitable taper angle plus a set of small vent holes lower down, let the conical bell function as an accurate impedance and radiation surrogate for an extended tone hole lattice. Dissipation via adjacent-hole, and hole entrance-exit interaction effects and turbulence are minimized by systematic relocation of holes at the upper end (zigzag around the tube), by reproportioning for maximum tone hole length/diameter ratio on all holes (especially at the lower end of the bore), and by systematic rounding of all sharp edges on the tone hole and joints. The instrument is mechanically simple, full toned and docile, requiring little adaptation by the player. The good features of early 19th century clarinets (bell taper, bore and register hole relation, and low complex-flow interaction effects) had a major influence on the design of this instrument, whose adjustment was guided by formal playing-condition diagnostic techniques.

PROPERTIES OF A GOOD INSTRUMENT

(1) Full steady tone . . .
(suitable spectrum, small FM/AM noise)

(2) Clean start and stop
(controllable articulation .. dependable

(3) Wide dynamic range.
(stable and controllable)

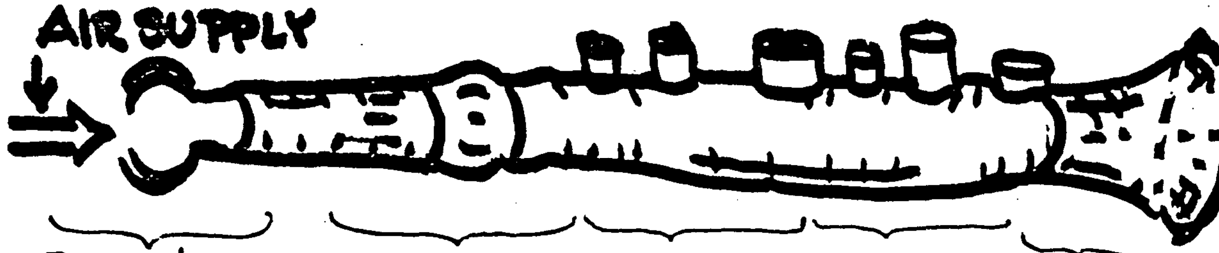
(4) { Pitch flexibility without loss of tone
Tonal flexibility without loss of pitch

(5) Large muscular efforts control
Small musical changes, but
with preservation of (2), (3) and (4)

{ Permits fine control
Protects from small glitches

It **Wants** to do your bidding!

WHAT IS A WOODWIND ?



THE AIR COLUMN HAS NORMAL MODES
Well specified at all frequencies
LINEAR .... (except damping (later)

SUPERPOSITION HOLDS

THE REED { MOTION PRETTY LINEAR
FLOW CONTROL NONLINEAR

WITHOUT THIS NONLINEARITY
THE INSTRUMENT IS USELESS
(UNPLAYABLE)

ONLY

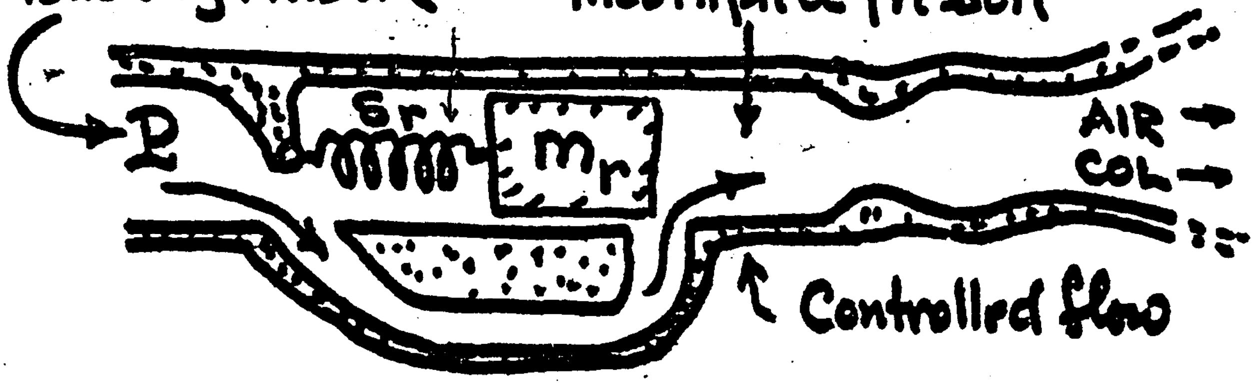
TWO GENERIC AIR COLUMN SHAPES WILL "TALK NICELY" WITH A REED

CYLINDER — Clarinet

CONE — Oboe, saxophone, bassoon.......

A First View Of The Oscillator

THE FEEDBACK LOOP



Controlled air flow enters air colum thru the reed aperture.

FLOW = A·(p−P)

Controller nonlinearity → flow has spectral components at all harmonics of oscillatory repet. rate

If air column modes ≈ match frequencies of these harmonics Osc. FAVORED

Nonlinearity of controller transfers energy between harmonics by heterodyne action.

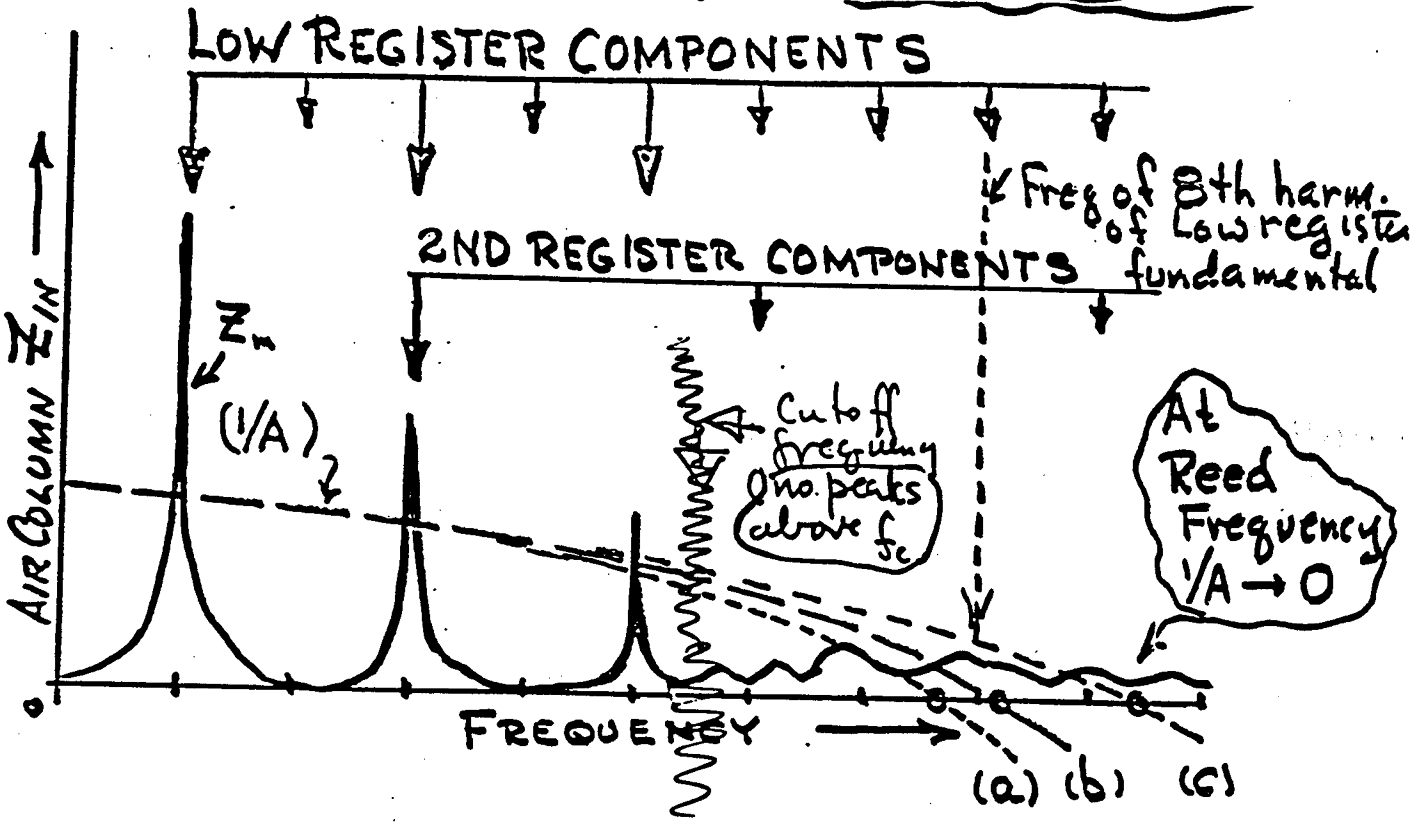
⇒ **REGIME OF OSCILLATION**

ENERGY PRODUCTION AT FREQUENCIES

⟹ [Z] · [A] > 1

Air column impedance (Z) — Reed transconductance (A)

SAY IT AGAIN SAM! Z > 1/A



So: Curve (a) has f_r too low to feed 8th harm. Low Reg.
⟹ (b) " " JUST RIGHT " " " "
(c) " " too high
However feeding #8 is only slightly useful.

THIS IS IMPORTANT.

HOWEVER: 2ND REGISTER HAS NO HELPERS"
unless f_r is right for 3rd harmonic
Curve (C) has f_r slightly too high....
SLACKEN EMBOUCHURE TO LOWER IT!

<u>WHAT THEN ARE WE TRYING TO DO?</u>

(1) Align 1st & 2nd resonance peaks for good cooperation while playing the low register

MUST DO THIS UNDER PLAYING CONDITIONS OF REED, HUMIDITY, TEMPERATURE...

(2) Choose register hole proportions such that the <u>pulling-up</u> of pitch at the ends of the 2nd register scale by the register hole

JUST OFFSETS

The <u>pulling-down</u> of pitch associated with embouchure slackening that is required to get reed resonance cooperation just right.

(3) Get a bell whose input impedance behavior (as seen by the clarinet) and radiation behavior (as heard by the listener) are accurate surrogates of a tone hole lattice

This is a quasi-return to The 1820's!

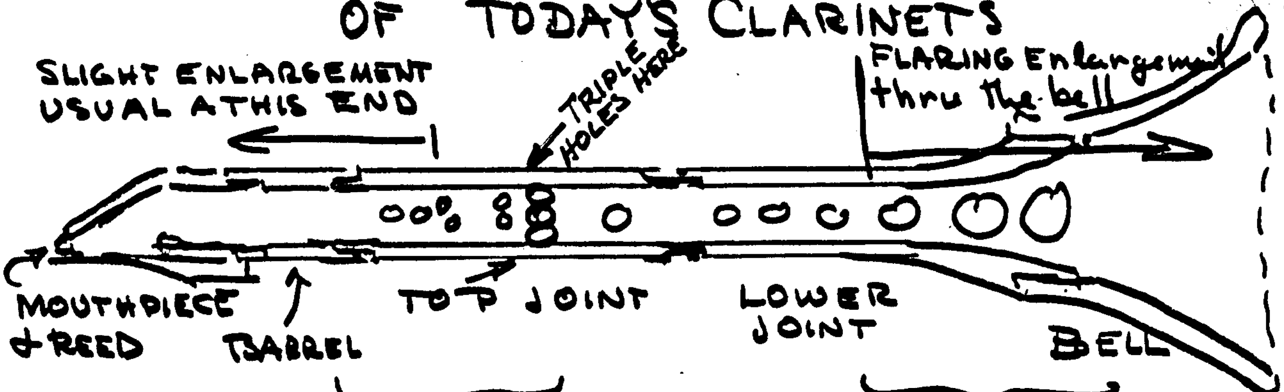
Benade Feb 1983

WHAT ARE WE TRYING TO DO? (CONTINUED)

(4) REDUCE SECOND-ORDER (But Large)
Convection-term effects
Turbulence effects
AND EVANESCENT-MODE COUPLING
BETWEEN SUCH EFFECTS
THAT MAKE THEM ACT MUCH WORSE

This is one of the places where we recognize via HINDSIGHT that the 1820's were trying to tell us something! [Not conscious in the maker's minds but later changes were criticized at the time for reasons now clearer]

TAKE A QUICK LOOK AT BASIC STRUCTURE OF TODAY'S CLARINETS



Small holes, close together
Wall thickness ≈ hole diameter

Large holes far apart
Wall thickness << hole diameter

TAKE IT STEP BY STEP

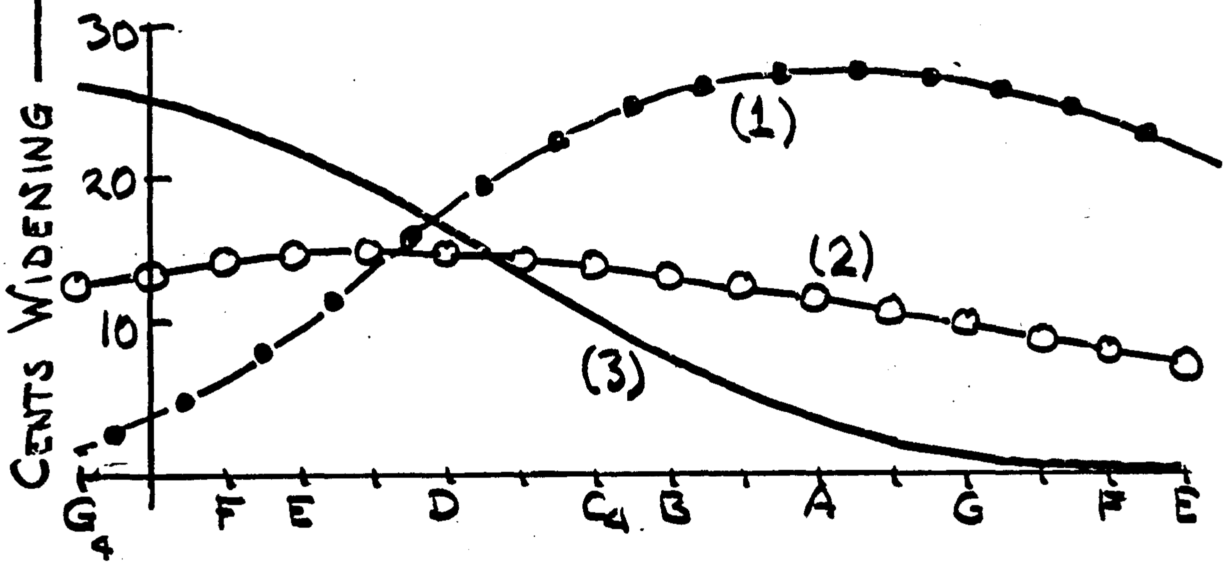
Benade Feb 1985

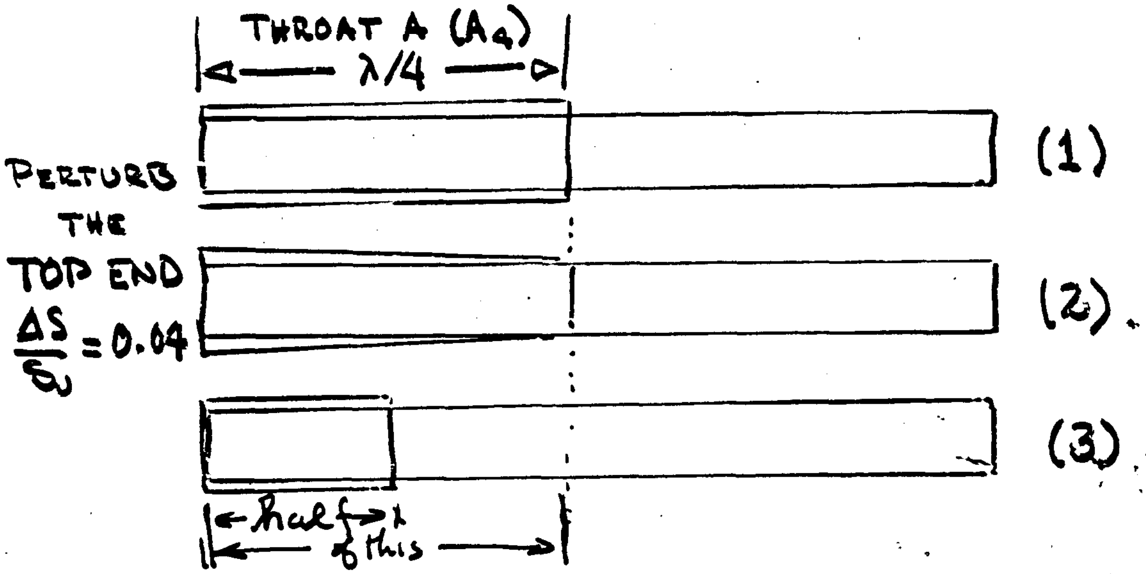
ITEM 1: ALIGNMENT OF MODE 1, MODE 2 FREQUENCIES

ONCE THE ALIGNMENT ERRORS ARE KNOWN
⇒ WE CAN MAKE MAJOR CORRECTIONS.

USEFUL BORE-PERTURBATIONS

AND THEIR EFFECT ON THE ALIGNMENT





NOTE: CLARINET BORE DIAM ≅ 15 mm

$\frac{\Delta S}{S_0} = .04 \longrightarrow \frac{\Delta\,\text{diam}}{\text{diam}} = .02 \longrightarrow \Delta\,\text{diam} = 0.3\,\text{mm} \cong .012\ \text{inch}$

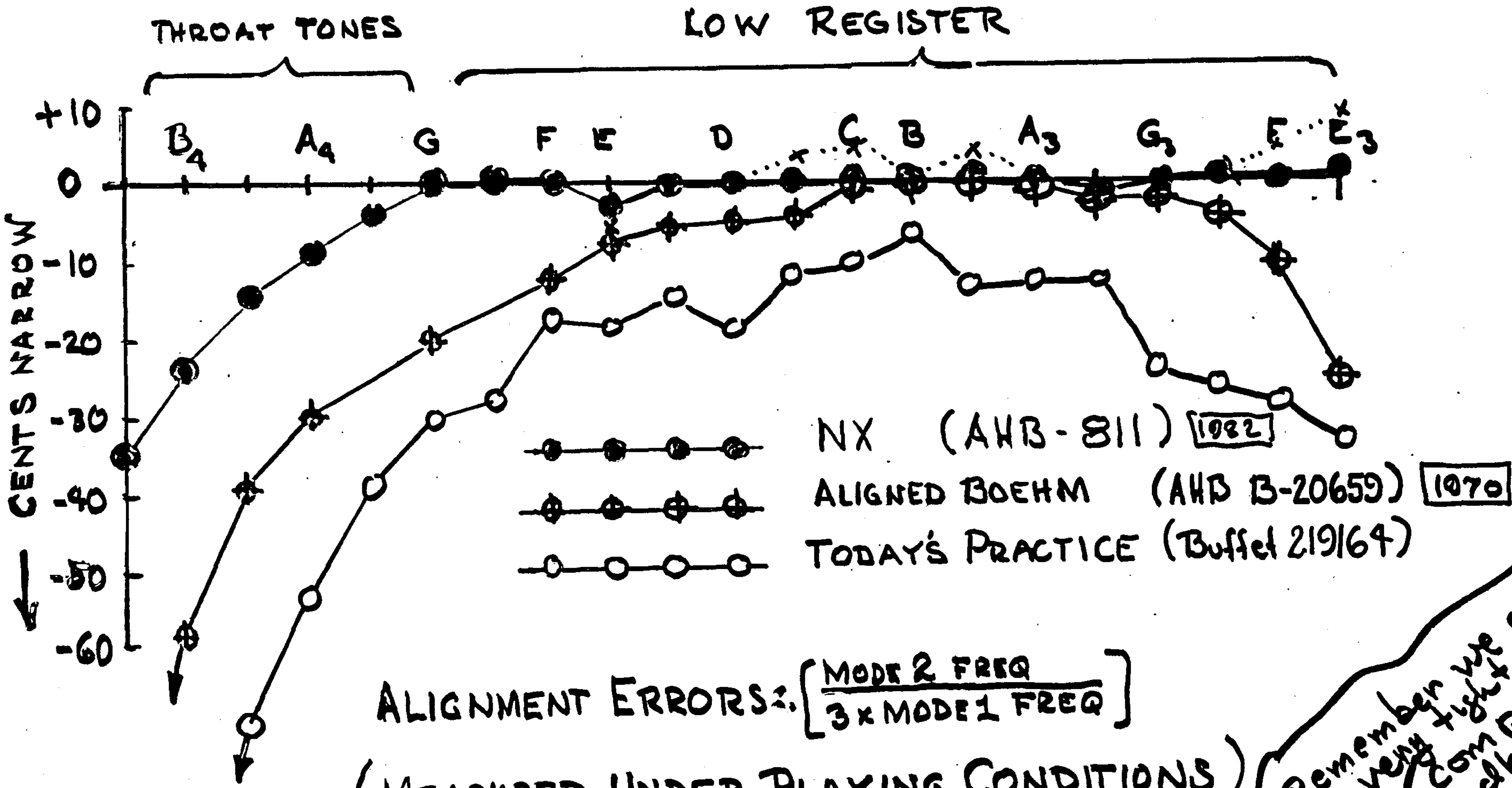
λ/4 AT CLARINET A_4 ≅ 220 mm

IN THE REAL WORLD, This counts as a big change

AHB Feb 1983

(8)

Results of Item 1 in our list: Alignment of Mode 1, 2 Frequencies



Alignment errors: $\left[\frac{\text{Mode 2 freq}}{3 \times \text{Mode 1 freq}}\right]$

(Measured Under Playing Conditions) (Essential)

Remember we are in a very tight multi component feedback loop!

Remark: { Over 15¢ misalignment ⊕ or ⊖ distinctly spoils response.
Within 5¢ misalignment essentially perfect
5¢ is detectable in careful work ($\frac{1}{330}$ is error, Q ≅ 20!) }

AHB 4 Feb 1983

ITEM 2. PLAY-OFF OF REGISTER HOLE VS EMBOUCHURE SLACK

REGISTER HOLE PULLS MODE 2 FREQUENCY UP SOMEWHAT!

SLACKENING OF EMBOUCHURE AT ENDS OF SCALE CAN COMPENSATE .. AT THE SAME TIME PUTS REED'S RESONANCE IN ALIGNMENT.... GOOD TONE

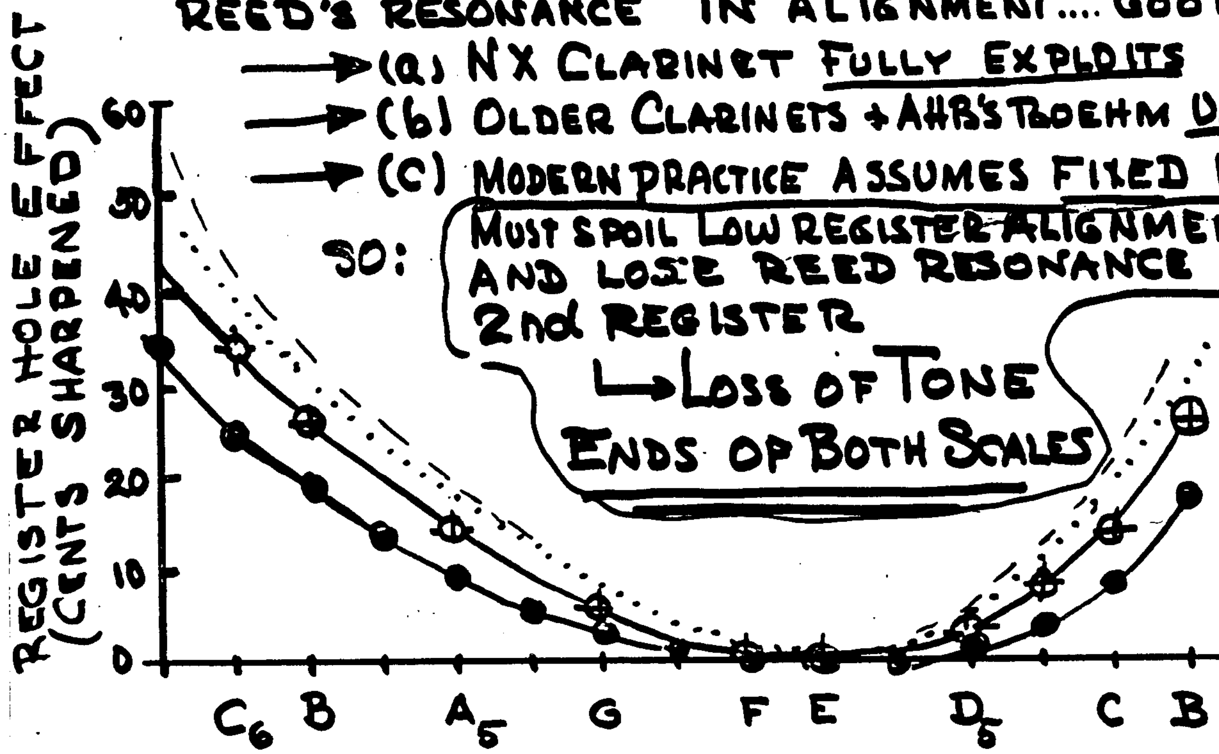
→ (a) NX CLARINET FULLY EXPLOITS THIS

→ (b) OLDER CLARINETS + AHB'S BOEHM USE IT.

→ (c) MODERN PRACTICE ASSUMES FIXED EMB!

SO: MUST SPOIL LOW REGISTER ALIGNMENT AND LOSE REED RESONANCE IN 2nd REGISTER

↳ LOSS OF TONE ENDS OF BOTH SCALES



2nd REGISTER SCALE

—●—●—●— NX (AHB 811)

—⊕—⊕—⊕— { ALIGNED BOEHM (AHB. B20659) / TODAYS PRACTICE (Buffet 219164) }

. . . . 1920's SELMER (2188)

— — — — — — GERMAN STYLE CLARINETS

(a) FULL EXPLOITATION OF REED RESONANCE IN 2nd REGISTER DICTATES REGISTER HOLE SIZE

(b) TO DO THUS REQUIRES SEPARATION OF

Not a new idea → { REGISTER HOLE FUNCTION FROM $B_4\flat$ TONE HOLE FUNCTION } ← NEEDS FAILSAFE MECHANISM

But the maximum exploitation is new

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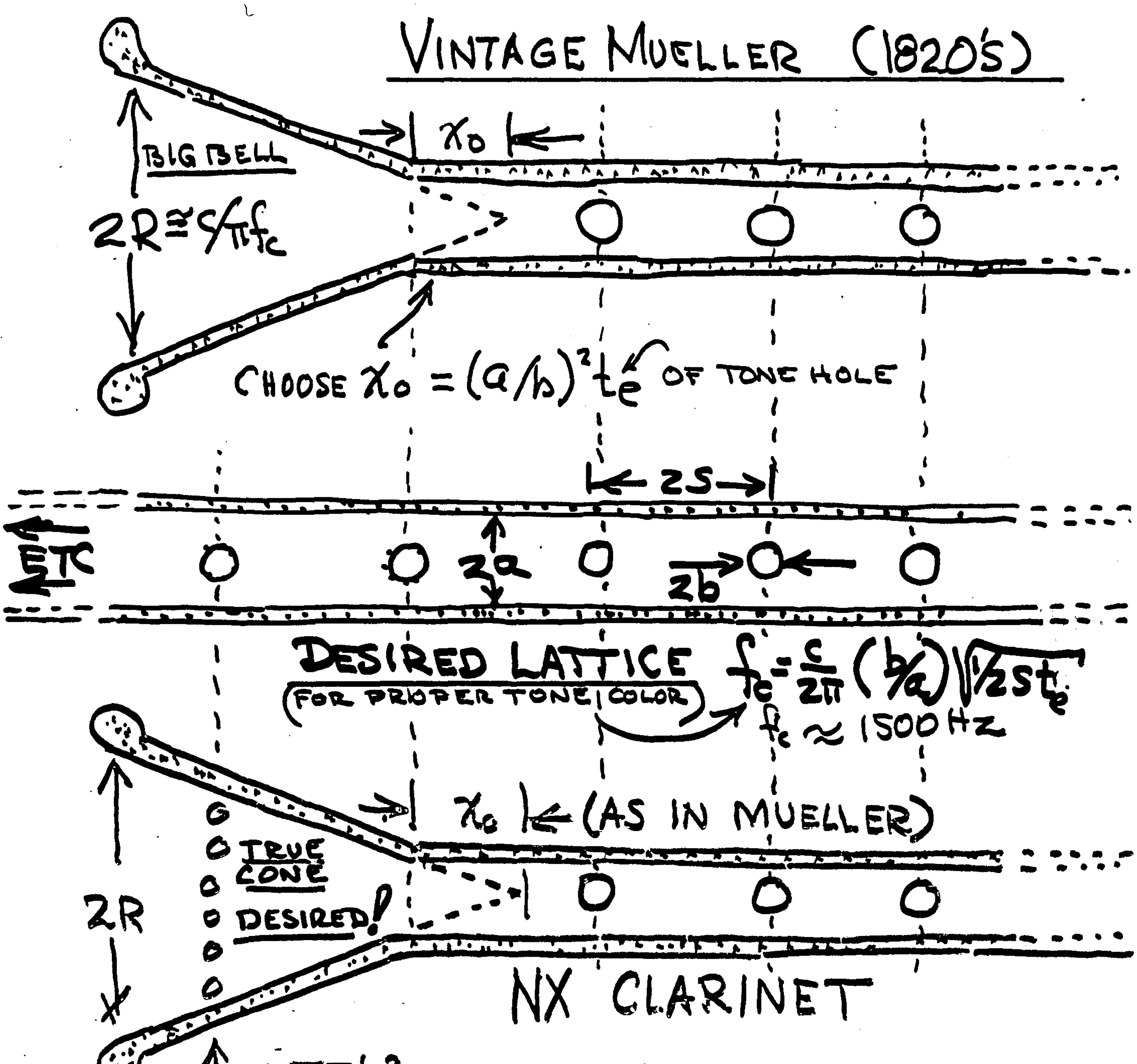
ITEM 3 OF THE LIST
THE BELL IS A SURROGATE TONE HOLE LATTICE



$$\left(\frac{\Sigma \pi b_i^2}{\text{CONE AREA}}\right) \cong \left(\frac{\pi b^2}{\pi a^2}\right) \text{ OF LATTICE HOLES}$$

VISCOUS LOSS ↗ + RADIATION
HELPS RADIATION LOSS
FROM BELL END

FOR THE CONE ITSELF

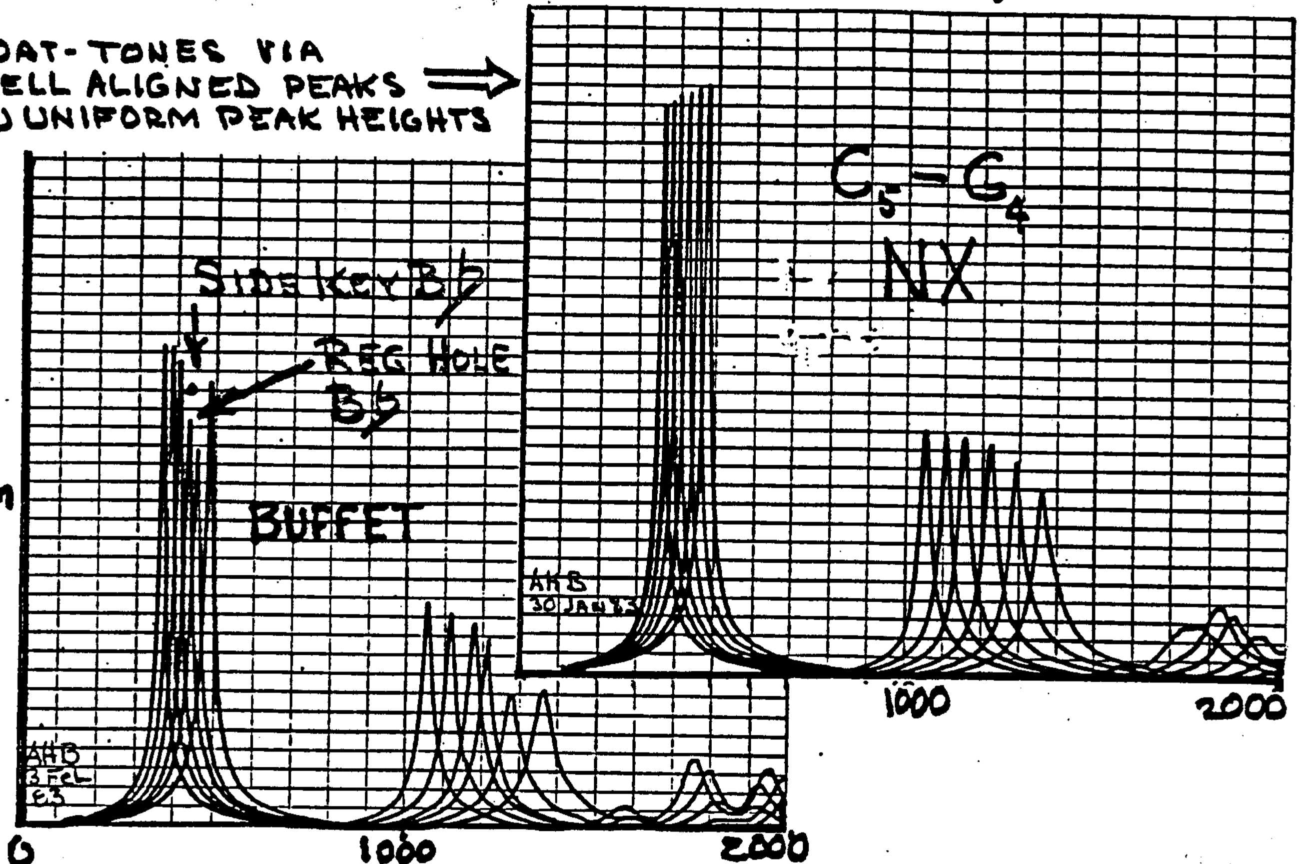
$$Z_{in} = \frac{\left[j\left(\frac{\rho c}{\pi a^2}\right)\tan kL\right]\left[j\frac{\rho c}{\pi a^2}k X_0\right]}{\left[j\frac{\rho c}{\pi a^2}\tan kL\right] + \left[j\frac{\rho c}{\pi a^2}k X_0\right]}$$

HERE IS THE CLUE!

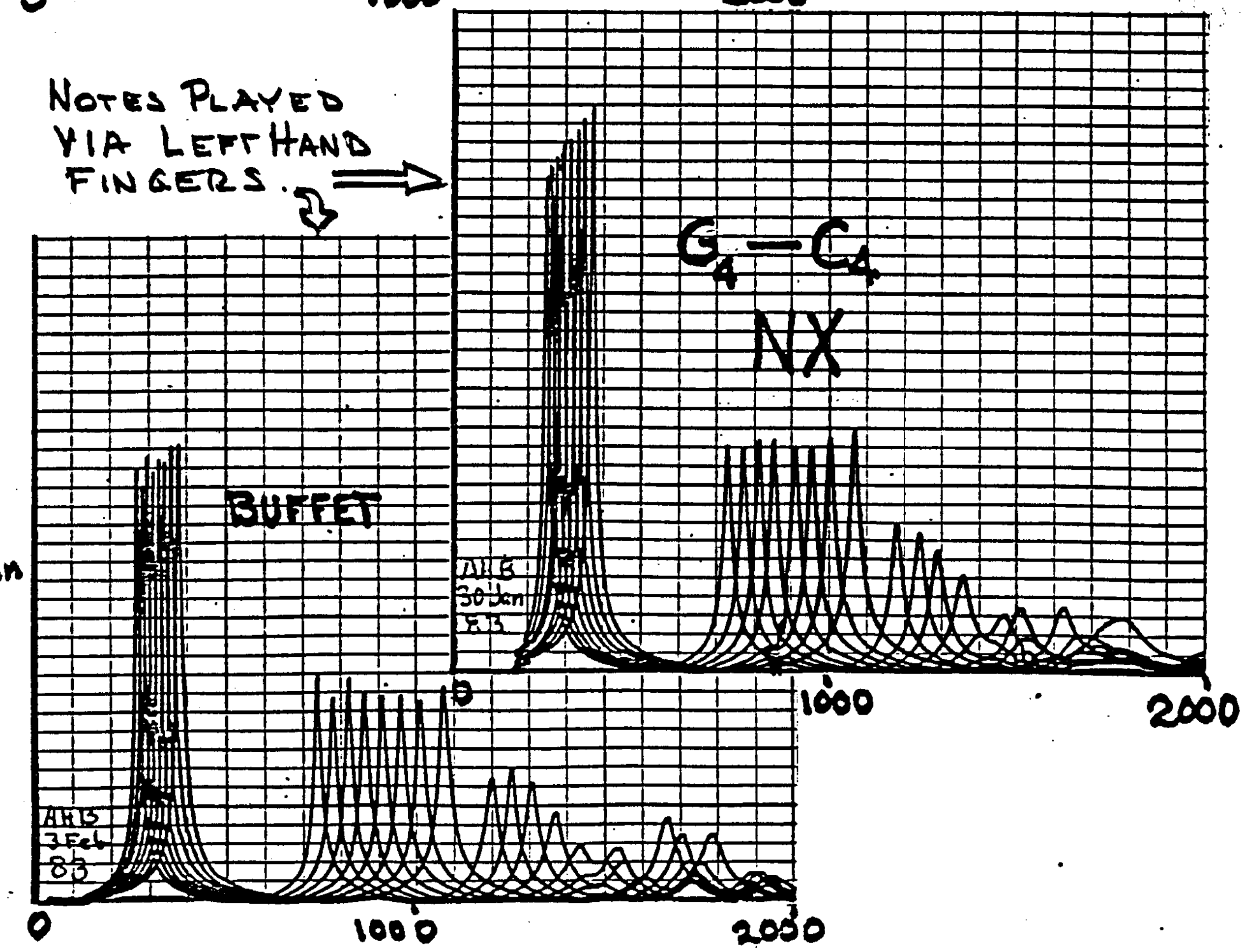
AHB Feb '83

ACOUSTICAL REGULARITY IS A VIRTUE!

THROAT-TONES VIA
~ WELL ALIGNED PEAKS
ALSO UNIFORM PEAK HEIGHTS ⟹



NOTES PLAYED
VIA LEFT HAND
FINGERS. ⟹



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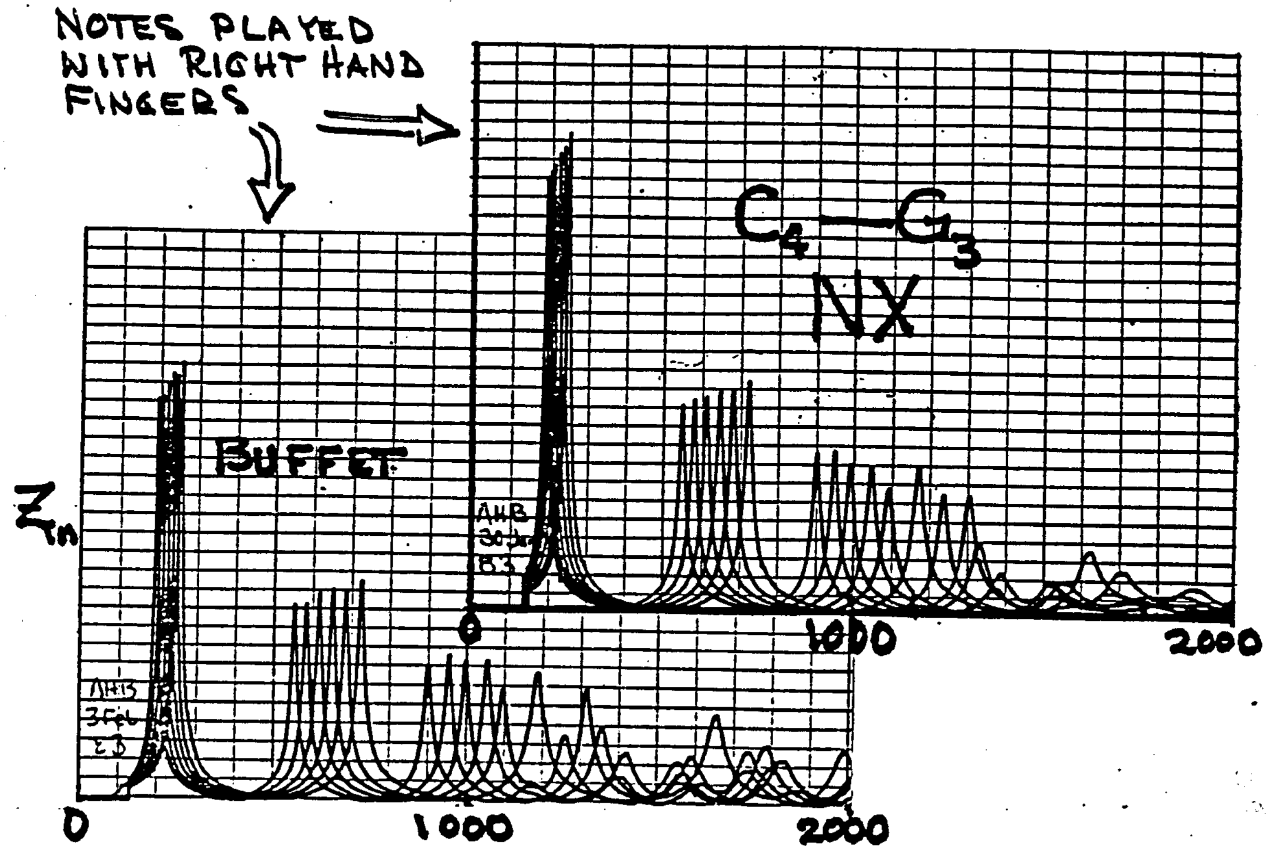
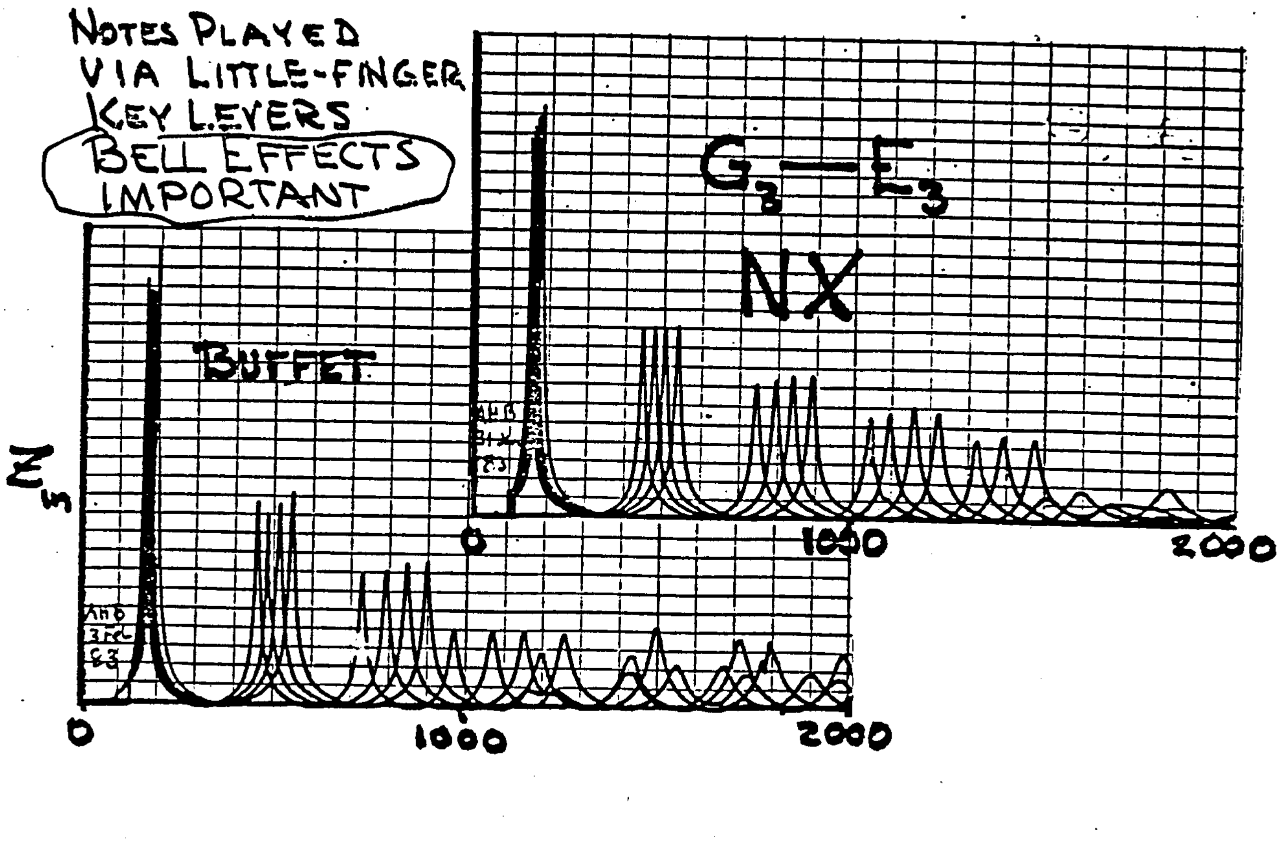
BEHAVIOR AT LOWEND OF THE SCALE,
WHERE THE BELL PLAYS A ROLE





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ITEM 4 OF OUR LIST (Turbulence and Interactions.)

2ND ORDER WAVE EQUATION

$$(1/c^2)\frac{\partial^2}{\partial t^2}p_2 = \nabla^2 p_2 + (\rho/B^2)(\gamma+1)\frac{1}{2}\frac{\partial^2}{\partial t^2}p_1^2 + \sum_{\mu,\nu}\frac{\partial^2}{\partial x_\mu \partial x_\nu}(\rho v_{1\nu} v_{1\mu})$$

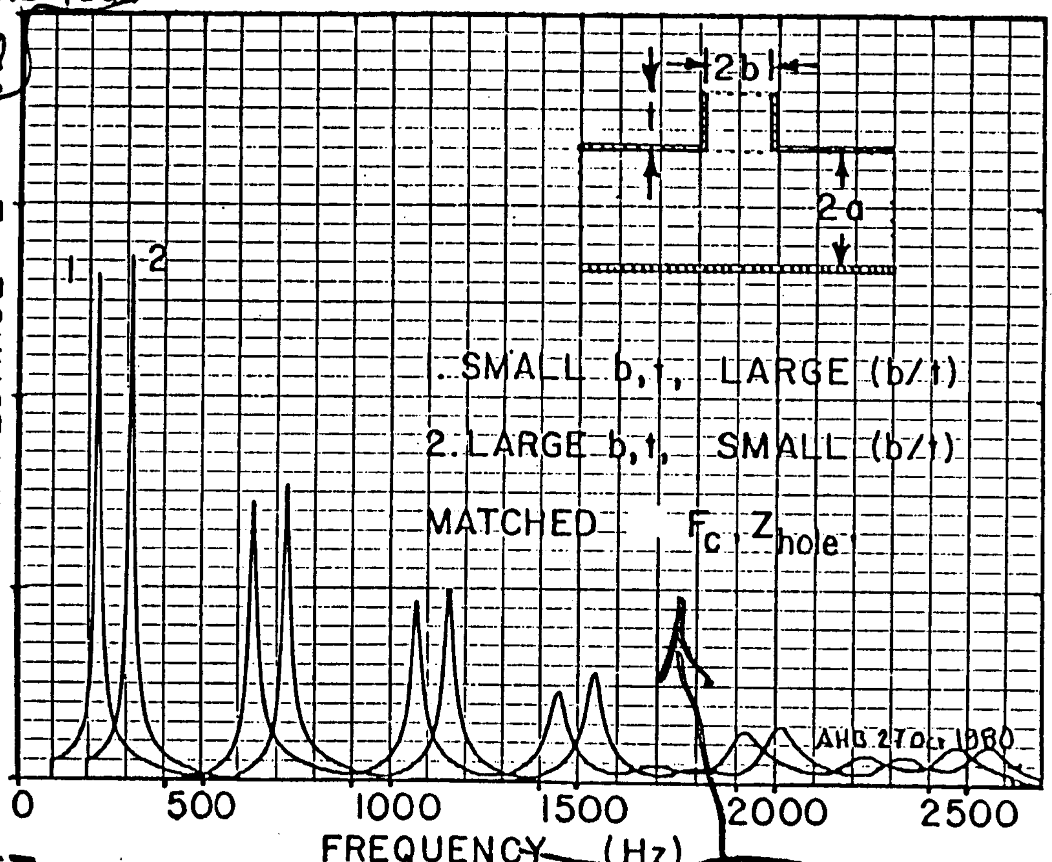
→ THIS "LIGHTHILL TERM" "CONVECTIVE TERM" OR "COMPLICATED-FLOW TERM" **IS THE VILLAIN!** Varies as $(p_1^2/\omega)\times(1/\delta^2)$

ANYTHING THAT MAKES FOR COMPLICATED FLOW MAKES THIS TERM BIG → $p_2/p_1 \cong \frac{1}{2}$!!

TRANSFERS ENERGY AROUND THE SPECTRUM IN BAD WAYS

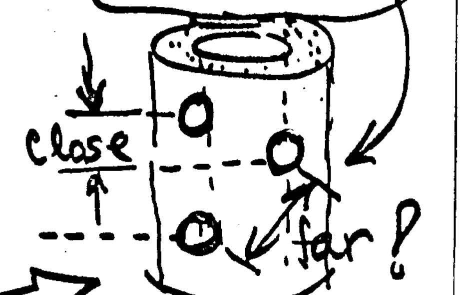
ALSO MORE WAYS FOR VISCOUS LOSS

NOT TO SPEAK OF TURBULENCE LOSSES.



Far-apart tone holes keep their flow effects from interacting

If holes must be close axially $2s < 2a$ ZIG-ZAG THEM!

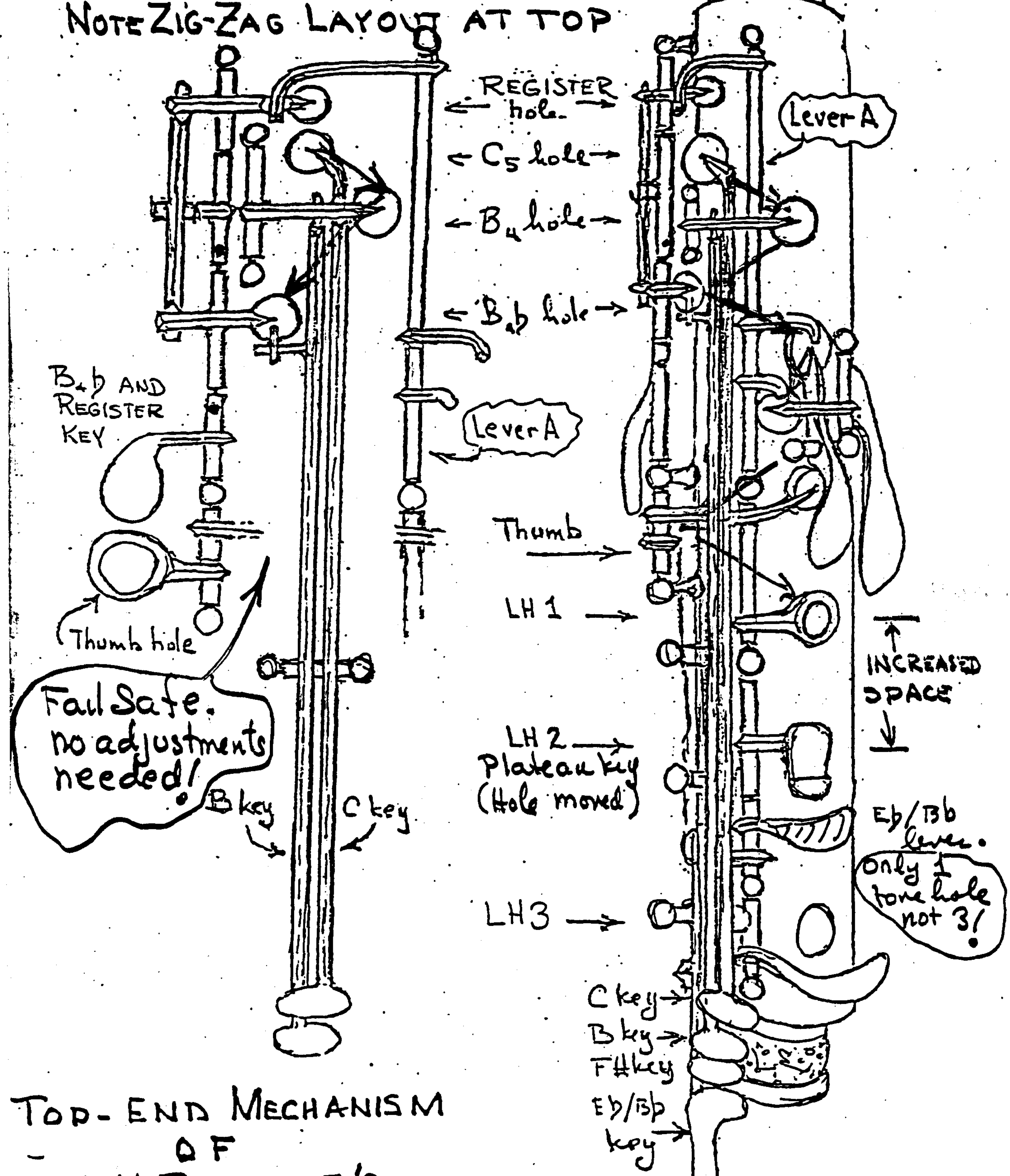


A USEFUL FACT

IN A DUCT, COMPLEXITIES DON'T SPREAD MORE THAN ABOUT 1 DIAMETER ⟹

Tall tone hole chimneys $t/2b \gtrsim 1$ keep entrance/exit complexities apart.

MODIFICATIONS TO THE MECHANISM



TOP-END MECHANISM
OF
A H BENADE'S
NX CLARINET

(14)

AHR FEB 1982

AHR 23 Jan 1983

PROPERTIES OF A GOOD INSTRUMENT

(1) Full steady tone . . .
(suitable spectrum, small FM/AM noise)

(2) Clean start and stop
(controllable articulation .. dependable

(3) Wide dynamic range.
(stable and controllable)

(4) { Pitch flexibility without loss of tone
Tonal flexibility without loss of pitch

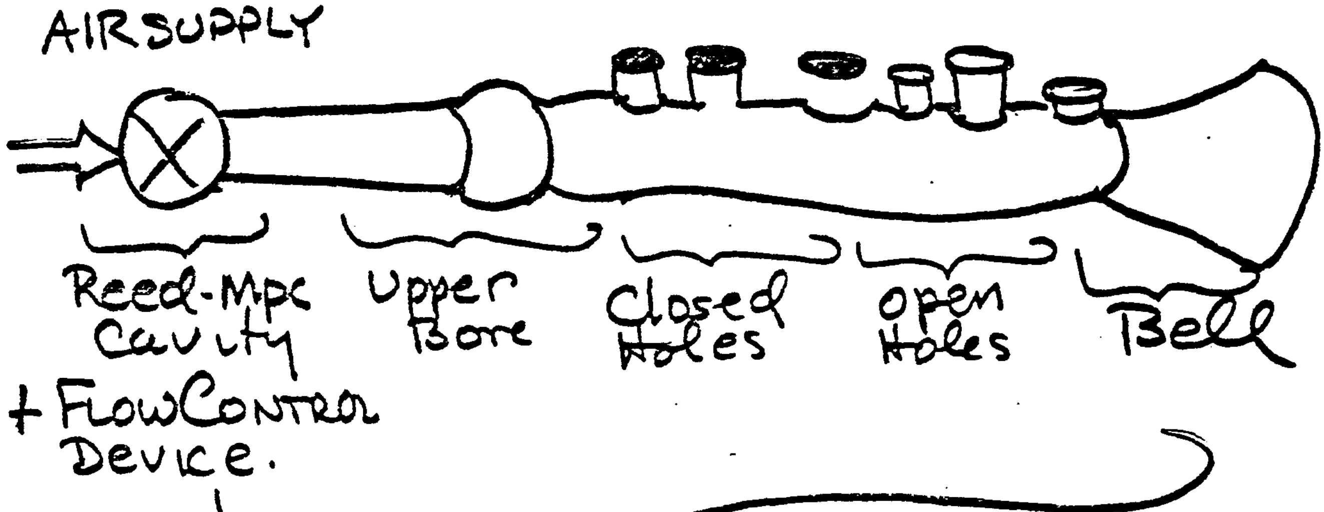
(5) Large muscular efforts control small musical changes, but with preservation of (2), (3) and (4)

↑ { Permits fine control
Protects from small glitches

It **Wants** to do your bidding!

[OBERLIN TALK]

WHAT IS A WOODWIND?



The Air Column Has Its Own Set of Natural Frequencies of "Sloshing".

The Sloshes individually could open and shut the reed and so keep themselves running.

If the aircolumn shape is <u>Right</u> The different sloshes can "gang up on the reed — <u>THIS IS GOOD</u>!

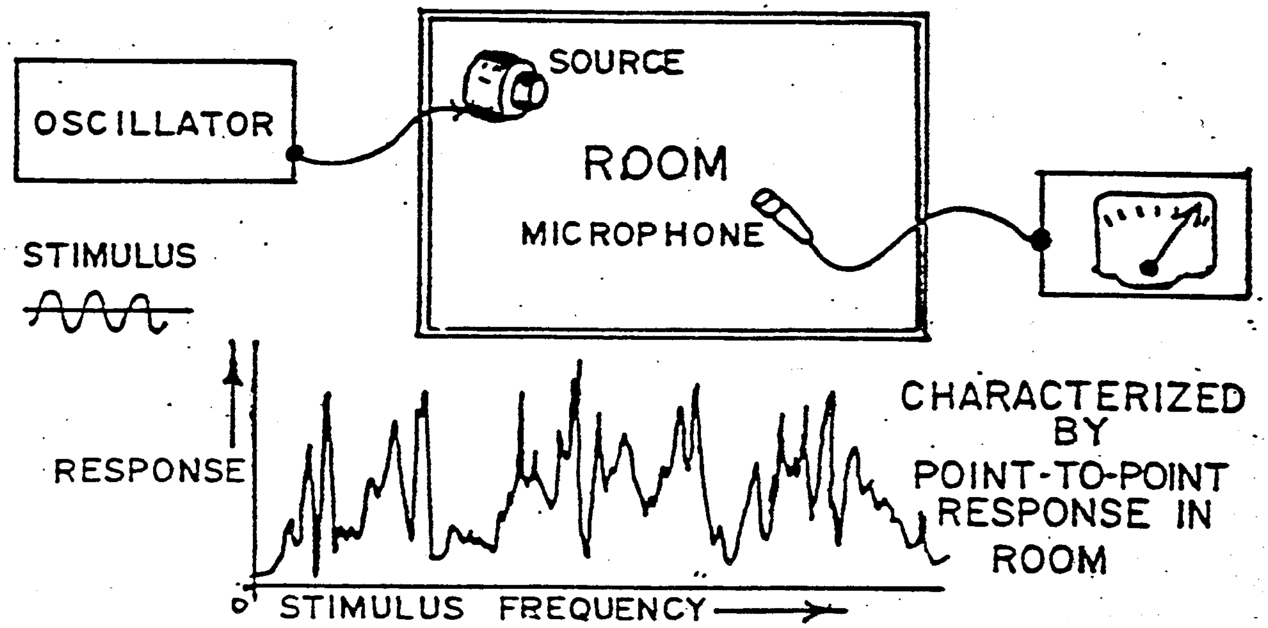
Why??

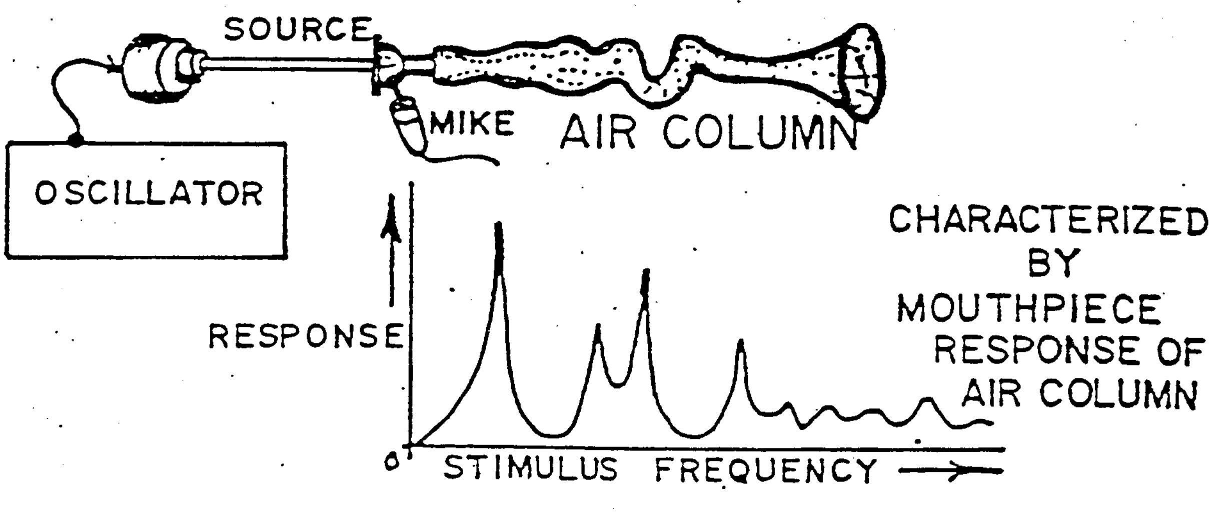
"Willing, steady, controllable, clear tone all the musical virtues

[OBERLIN TALK]

Benade

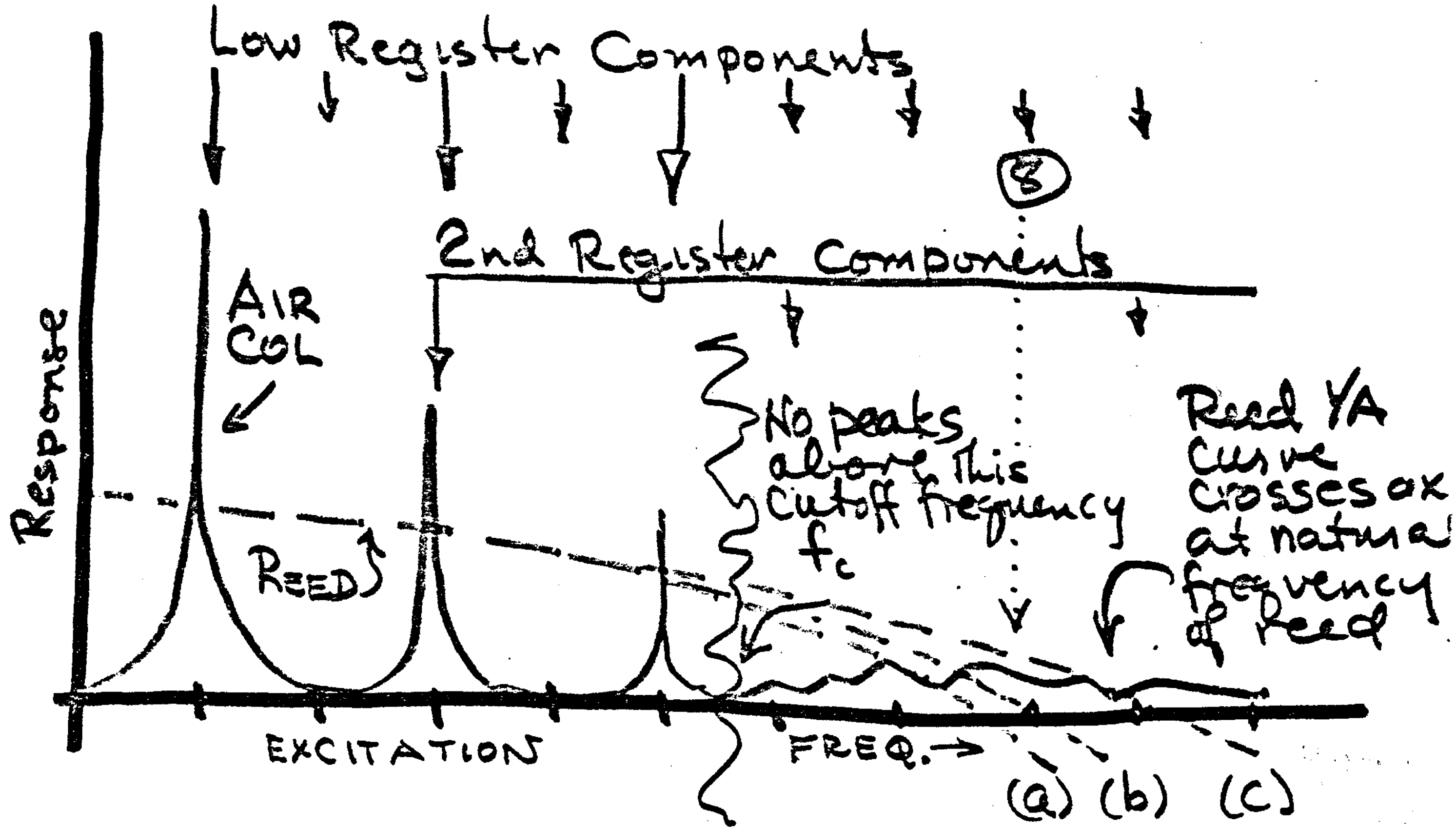
HOW TO USEFULLY CHARACTERIZE AN AIR COLUMN





ONE CAN LEARN TO "READ OFF" THE DYNAMICAL AND MUSICAL FEATURES

[OBERLIN TALK]



So: Curve (a) has f_r too low to feed 8th harm. Low R
⟹ (b) " " JUST RIGHT " " " "
(c) " " too high " " " "

This is important

HOWEVER: 2ND REGISTER HAS NO "HELPERS"
unless f_r is right for 3rd harmonic
Curve (c) has f_r slightly too high.
SLACKEN EMBOUCHURE TO LOWER IT!

There is yet another player's resource — there are resonances in the windway from lungs to mouth — they can be put to good use —

[OBERLIN TALK]

WHAT THEN ARE WE TRYING TO DO IN THE NEW CLARINET?

(1) Alighn 1st and 2nd resonance peaks for good cooperation in the low playing register.

(2) Chose register hole proportions such that the pulling-up of pitch at the ends of the 2nd register scale by the register hole

JUST OFFSETS

The pulling down of pitch associated with embouchure slackening that gets reed resonance. Cooperation just right

(3) Get a bell whose acoustical "appearance" (as seen by the clarinet) and radiation behavior (as heard by the listener)

ARE ACCURATE SURROGATES OF A TONE HOLE LATTICE

This is a Quasi-Return to the 1810's!

⑤

[OBERLIN TALK]

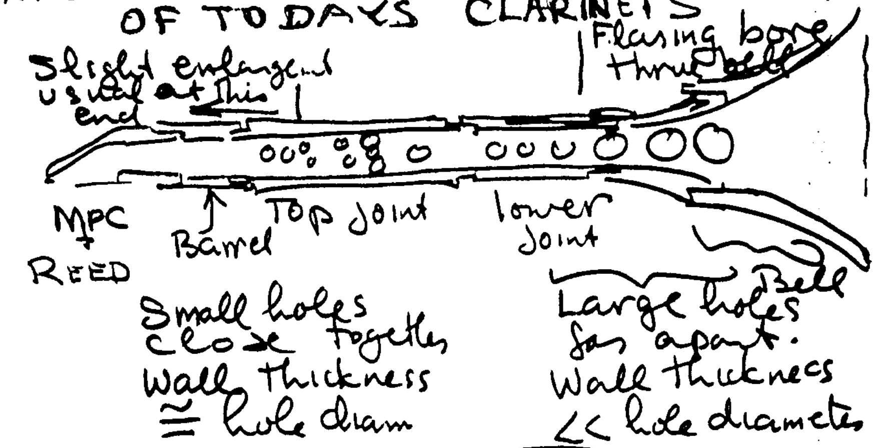
WHAT ARE WE TRYING TO DO? (cont)

(4) Reduce "Complicated flow" effects at the tone holes (Formally pointed out by DH Keefe. Studied R B Richards.

This is one of the places where we recognize via {FORSIGHT / HINDSIGHT} that the 1800's instruments were trying to tell us something.

Not clear in old makers minds, but later changes were criticized for reasons that are now clear.

TAKE A QUICK LOOK AT BASIC STRUCTURE OF TODAY'S CLARINETS



TAKE IT STEP BY STEP

⑥