require larger-scale computation. [Performed under contract with Office of Naval Research (Acoustics Programs).]

11:30

B9. Attenuation of Acoustic Waves by Submerged Viscoelastic Spherical Shells. George Workman (nonmember), *Lockheed Missiles and Space Company, Sunnyvale, California* and Sabih I. Hayek, *Department of Engineering Mechanics and Ordnance Research Laboratory, The Pennsylvania State University, University Park, Pennsylvania.*—A pulsating sphere is located inside a thick concentric viscoelastic spherical shell, which is surrounded by an infinite acoustic medium. The space between the sphere and the shell is filled with the same acoustic medium. A shaped beam of axisymmetric spherical harmonic wave, emitted from the sphere, is transmitted through the shell to the outside medium. The shell is analyzed by use of elastic wave potentials. The emitted acoustic waves are transmitted to the external medium by coupling to the shell through continuity and boundary conditions at the inner and outer surfaces of the shell. The investigation shows that the radiated farfield pressure can be attenuated by as much as 10% through the use of stiff polymers.

11:45

B10. Effect of Rain on Underwater Noise Level. Nicolaas Bom (nonmember), *SACLANT ASW Research Centre, La Spezia, Italy.*—The underwater noise due to precipitation has been measured in a small, shallow lake. The local wind speed, rain rate, atmospheric pressure, and noise level were recorded. It was found that the noise due to wind and the contribution from bottom boundary reflections over the period during which the data were recorded had a negligible effect. The data in the interval 300–9600 Hz have been analyzed in octave bands, and an estimate of the average noise level versus rain rate has been obtained. In comparison with the laboratory work done by Franz [J. Acoust. Soc. Amer. 31, 1080 (1959)] on splashes as a source of sound, our results show significantly higher noise levels and a difference in the shape of the noise-level-versus-frequency curve. However, the average rate of change in noise level with change in rain rate is of the same order of magnitude.

Tuesday, 19 November 1968 — Lewis Room, 9:30 a.m.

Session C. Musical Acoustics I: Brass Instruments Symposium

E. L. Kent, *Chairman*

Invited Papers (*30 minutes*)

9:30

C1. Human Factors in Wind-Instrument Performance. Arend Bouhuys (nonmember), *Yale University School of Medicine, New Haven, Connecticut.*—To the physiologist, wind-instrument performance is a prime example of a skill that requires precise coordination and control of the contractions of several groups of striated muscles. Respiratory muscles, together with elastic forces in lungs and chest wall, provide the required pressurized stream of air. Oral cavity and lip muscles provide adequate shape and tension of the lips for proper excitation of reeds. They also direct and shape the air-flow pattern in flutes. Lastly, forearm muscles control finger movements. The lip vibrations in brass players ocur at frequencies higher than those at which striated muscles can contract; these vibrations are passive, but muscle contraction largely determines the physical characteristics of the oscillating lips. Rapid and precisely quantified changes in muscle contractions are needed to alter this adjustment for production of tones of different pitch and amplitude. Coordination and control of striated muscle will be discussed, using the respiratory muscles as the main example. Relevant physiological knowledge will be reviewed; however, large gaps exist in the understanding of skilled movements and the learning processes involved in acquiring such skills.

10:00

C2. Mathematical Model of the Brass-Player's Embouchure. Robert W. Pyle, Jr., *Bolt Beranek and Newman Inc., Cambridge, Massachusetts 02138.*—A simple mathematical model of the self-oscillating system comprising the oral cavity, the lips, and the input impedance of an idealized brass instrument has been programmed for a digital computer. The lips are represented by a simple mechanical oscillator with amplitude-dependent damping, similar to the model of the vocal cords used by Flanagan and others in speech studies. The input impedance of the "instrument" is that of a horn whose resonances are precisely harmonically related. This formulation gives a set of coupled nonlinear integral-differential equations that can be solved numerically to give approximate values for the pressure in the oral cavity and in the mouthpiece cup, the volume velocity through the lip orifice, and the area of the lip orifice as a function of time. Although it would not be particularly meaningful to compare the computed waveforms in detail with experimental data, this simple model shows many of the characteristics of real brass instruments and should be useful for studying the effects of parameter changes.

10:30

C3. Trumpet Intonation Improvement with Multiple Helmholtz Resonator Terminations. W. T. Cardwell, Jr., *Chevron Research Co., La Habra, California 90631.*—The conventional trumpet mouthpiece has already been shown, theoretically and experimentally, to behave as a Helmholtz resonator termination of the trumpet air column, changing the apparent length of that column with frequency. Further theory indicates that for musically proper placement of the upper playing modes, a more nearly ideal termination would be a multiple Helmholtz resonator. Experiments confirm this.

11:00

C4. Effect of Dispersion and Scattering on the Startup of Brass Instrument Tones. A. H. Benade, *Case Western Reserve University, Cleveland, Ohio.*—A clean attack is favored if the round-trip time T_r for the initial sound from the lips sent down the bore and back is an integral multiple of the playing frequency period P_n. Consider a Bessel horn

TRUMPET INTONATION IMPROVEMENT WITH MULTIPLE HELMHOLTZ RESONATOR TERMINATIONS

W. T. Cardwell, Jr.

Text of an invited paper read to a Brass Instruments Symposium at the Cleveland Meeting of the Acoustical Society of America, in November, 1968.

INTRODUCTION

Today, I want to tell you about some work that is definitely in an unfinished state. However, if its promises inspire you, or its imperfections irritate you, perhaps some of you will be motivated to work on the subject and make up for my inadequacies.

The over-all subject is the tuning effect of the trumpet mouthpiece. You might say that in the paper given to the Society in 1966 we asked what the mouthpiece does. We found out that it has a great deal to do with the tuning of the upper playing modes, and we used our knowledge of how the mouthpiece cooperated with the bell of the trumpet to design and build an improved F-trumpet starting from scratch. Today, I want to tell you about some things that can be done with already existing trumpets, without changing anything but the terminations at their mouthpiece ends.

First, let us quickly review some parts of the 1966 paper, mainly to make sure we are all thinking in the same terms.

SLIDE 1 TP. DEFINITIONS

A trumpet is, by classical definition, an instrument having over half of its length untapered. If it tapers all the way, or most of the way, it is by classical definition not a trumpet, but a cornet.

Our present, particular concern is the mouthpiece end, which requires a relatively enlarged part to adapt to the lips. This part seems, intuitively, not only natural, but indeed unavoidable. The intuitively, unobvious requirement is the relatively small throat portion between the mouthpiece cup and the main tubing of the instrument.

We showed previously, both theoretically and experimentally, that the mouthpiece cup and throat together act as the cavity and orifice of a terminating Helmholtz resonator, and that they serve to tune the upper modes of the trumpet.

SLIDE 2 THE MP EFFECT

This slide shows the theoretical apparent-length-adding effect of a simple Helmholtz resonator. The dimensionless vertical coordinate is the apparent-length-addition divided by the resonant wave length. The dimensionless horizontal coordinate is frequency divided by the resonant frequency of the resonator.

The main point to notice is that at the resonant frequency of the resonator it adds an apparent length to the trumpet equal to one-quarter of the resonant wavelength. For example, if the resonant frequency is 800 Hz, the apparent length addition is about 11 centimeters, - a quite significant addition. This would be 8 per cent of the actual length of a conventional B flat trumpet.

At frequencies other than the resonant frequency, the apparent-length-addition depends upon the dimensionless constant K, the family parameter of the curves shown on the slide. K depends, as shown, on the relative dimensions of the resonator and tube to which it is attached. A large K connotes a large apparent-length-addition between the low frequencies and the resonant frequency of the mouthpiece.

Under some reasonable assumptions, it can be shown that the ideal K for a trumpet should be $\pi/2$. The apparent K of present commercial mouthpieces seems to be larger than this.

SLIDE 3 MAIN APPARATUS

This slide shows the main experimental apparatus used in this work:

A trumpet, or a part of a trumpet - sometimes only the mouthpiece itself - closed off at the lip plane of the mouthpiece by a condenser microphone - is subjected to ambient sound of constant level, the level being maintained by a monitor microphone and feedback loop. The response of the condenser microphone, in millivolts, is used as the vertical coordinate of the resonance curves made with this apparatus. Frequency read from the counter is used as the horizontal coordinate.

SLIDE 4 TYPICAL RESONANCE CURVES

This slide shows typical trumpet resonance curves obtained with the apparatus of the previous slide.

All of the abscissae run from zero to 1700 Hz. The ordinates are in millivolts.

The bottom curve represents a conventional B flat trumpet. The middle curve, an F-trumpet, and the top curve a high B flat piccolo trumpet.

The over-all object of all the work reported here is to move the shown resonance peaks horizontally into their musically-proper frequency positions.

SLIDE 5 F-TP INTONATION GRAPHS

This slide shows the result of designing a catenoidal bell to cooperate properly with a conventional mouthpiece to make a trumpet in high F.

The form of the data is one which has a least some appeal to trumpeters; it may require a little explanation for non-trumpeters. Music for trumpets, in several nominal keys, is written so that a note on the leger line below the musical staff represents the second mode of the trumpet, a note on the second proper line of the staff represents the third mode, and a note in the third space of the staff represents the fourth mode. The fourth mode is also usually, the tuning note. The other modes represented here are the fifth, the sixth and the eighth. (The seventh mode of the trumpet is not used in modern times. On even an ideal, natural trumpet it would be a third of a semitone below the nearest tone of the musical scale of even temperament.)

The horizontal coordinates of these graphs are in musical cents, or hundredths of a semitone. 17 cents is one per cent in frequency. Sharpness, or too high a frequency, is indicated by rightward displacement. Flatness, or too low a frequency, is indicated by leftward displacement from the central vertical line.

In each of the three tests represented here the tuning slide of the trumpet was adjusted until there was no detectable error in the fourth mode tuning note.

Trumpet J was an American F-trumpet of high reputation. Trumpet G a European F-trumpet of similarly high reputation. Trumpet H was the one designed with a catenoidal bell to cooperate properly with the conventional Bach 7E mouthpiece.

As you can see, the flat eighth mode shown by the commercial trumpets has been corrected. Also the sixth mode is so close to ideal intonation that it could be called entirely satisfactory for musical purposes.

Among the upper modes, which are the ones of importance on the little F-trumpet, only the fifth mode is significantly off. In a sense, even this is quite defensible. It is a result mainly of what we might call an error imposed on the natural musical scale, by definition, in the scale of even temperament. A 14 cents flatness would show that the instrument was, in that frequency region, behaving as an ideal, natural, trumpet.

Bringing up the fifth mode to standard modern frequency is, in a sense, doing something unnatural. However, that would have been the logical next step after the construction and testing of this F-trumpet. I did not go to that, because some of my friends were already seriously questioning my judgement in working on the F-trumpet at all. They pointed out that even if all the people in the world who played the F-trumpet became interested, - and that would be highly improbable - the entire group would still form a very small club. So I was persuaded to turn toward the B flat trumpet, the one most widely used in modern times.

The question became: How can we improve the intonation of the conventional B flat trumpet?

SLIDE 6 INTONATION GRAPHS
FOUR B flat TPS

This slide shows intonation graphs for ~~three~~ four modern B flat trumpet-mouthpiece combinations. It seems appropriate to emphasize that these are not selected bad examples. These are Cadillacs and Lincoln Continentals of the trumpet industry. All of these four graphs represent trumpet-mouthpiece combinations used by highly respected symphony trumpeters who are very particular about their instruments.

We are here concerned with the upper modes, beginning with the fourth mode, or tuning note. You will observe that there are some common tendencies: With the fourth mode tuning note set on pitch, the fifth mode is usually flat, as if the trumpet-mouthpiece combination were trying to be a natural trumpet, but with a vengeance, because the flatness never stops at a mere 14 cents. It is usually about twice that.

The peculiar actor is the sixth mode. Sometimes, as with trumpet-mouthpiece combination A, the sixth mode falls smoothly into a monotonic curve going toward the eighth mode, which is usually quite flat - about a quarter tone. Oftener however the sixth mode jumps back toward proper pitch, and sometimes, as in the case of trumpet-mouthpiece combination C, actually makes it.

Trumpeters compensate for these instrumental peculiarities, not only with lip adjustments, but also with so-called false fingerings, using their valves. It is very common for a meticulous trumpet player to press down the first and second valves when playing his written E, thereby using the sixth vibrational mode of a longer air column, rather than the fifth mode of his so-called open horn.

What is the explanation of these common intonation errors? We may immediately suspect mouthpiece action because we have already found out that the bell shape, and more particularly, the bell-stem shape affects mainly the intonation of the lower modes. In the higher frequency range the bell is relatively inactive intonationally. The mouthpiece produces the frequency stretching in the higher frequency range.

SLIDE 7 THE MP EFFECT
REPEAT OF 2

Here we see again the theoretical apparent-length-adding effect of a terminating Helmholtz resonator. We see that if we are getting excessive musical flattening, which means excessive apparent-length-adding effect, in the active range of our mouthpiece, there are at least two things that might be wrong. We might be too high up on a curve of given K, that is, too near the resonant frequency, or the K itself might be too large. So we might think about raising the resonant frequency, or lowering the value of the dimensionless constant K.

These are good clues to a solution, but if we think about the entire problem somewhat more deeply, we can see still other, more fundamental, possibilities.

SLIDE 8 WAVE IMPEDANCE DIAGRAM

This slide represents schematically, the wave impedance as a function of distance, in an air column closed at the left end. The most leftward quarter-wave has an infinite capacitive impedance at its left, and a zero impedance at its right. We know that as we raise the frequency, the whole diagram will seem to compress toward the left.

To visualize the action of a mouthpiece as a terminating resonator we may put our attention on a fixed X - location that is initially in the leftward quarter-wave and imagine that a variable impedance device is placed there, substituting for the leftward end of the tube. As the frequency rises, and the impedance of the device rises from a negative, capacitive value, the wave will seem to move leftward into that device, the whole diagram may compress toward the left faster than it would have compressed if the tube had had a simple closure at the left end, and the effect will be as if the tube were increasing in length with increasing frequency. This is just the qualitative explanation of the mouthpiece effect.

As mentioned before, at the resonant frequency of the terminating resonator, when its impedance is zero, it seems to add a quarter of the resonant wavelength.

Now comes the most important point for our present purposes. As the frequency increases above resonance, the impedance of a simple Helmholtz resonator continues to increase monotonically toward infinite inductive impedance. The apparent-length-addition can never be more than another quarter wave, and it is a quarter-wave of ever decreasing length, so as shown on the previous mouthpiece effect diagram, the apparent-length-addition after resonance actually declines. A simple Helmholtz resonator actually starts to subtract some of the apparent-length it has added, sometime after it has passed resonance. This is not what we want.

We would really like to have a terminator that kept on adding apparent-length monotonically, in accordance with a theoretical relationship which says that if the closed-open trumpet system is to have musical-type resonances in a complete harmonic series its apparent length must increase monotonically with frequency, along a hyperbolic curve. We want the impedance diagram to keep contracting into our terminator. We see that it would do this if the impedance of our terminator did not merely rise monotonically toward inductive infinity, but rather rose to inductive infinity, jumped down to capacitive infinity, rose again through zero toward another inductive infinity, and so on.

So, perhaps what we need is a terminator with a first resonance followed by an antiresonance, followed by a second resonance, and so on.

If we pursue this quantitatively for our particular case, it turns out that, ideally, we want a device that has an antiresonance at three-halves the frequency of its first resonance, a second resonance at twice the frequency of the first resonance, and so on.

SLIDE 9 DOUBLE RESONATORS

One possible form of a terminator that immediately suggests itself is a multiple Helmholtz resonator, a set of orifices and cavities in tandem. A start in this direction is a simple double resonator.

This slide shows the electric analog double resonator, and two versions of the acoustic configuration of two orifices and two cavities in tandem. The rounded-off configuration we know from other considerations, would be more appropriate in our case of interest. The slide also shows the kind of impedance diagram we expect from such a configuration. The acoustic impedance, looking leftward into such a device, should show a first resonance, an antiresonance, and then a second resonance.

Specifying the values of the two resonances we want, and the one antiresonance, is not quite enough to enable us to compute even the basic four parameters of a physical double resonator: Two capacitances and two inertances. We need at least one more specified quantity. In our case, the natural quantity turns out to be the apparent length that the configuration will add at low frequencies, which is very nearly proportional to the total internal volume of the configuration. If this fourth quantity is specified we can then calculate two capacitance values and two inertance values.

This simple lumped-constant approach gives a good start. However it is just a start. It is perhaps almost intuitively evident that at least two more numbers need to be specified, because each inertance needs two numbers. The inertance value merely fixes the ratio of the orifice length to the orifice cross-sectional area, so it does not fix the shape of the inertance.

To make useful design calculations it seems to be necessary to complicate the theory at least to the extent of taking into account phase changes, and therefore, wave impedance changes, in the orifices.

After we have designed and built a double resonator, and before we consider putting it on the end of a trumpet, we need some way to check our design by measuring at least its first resonance, and the succeeding antiresonance.

SLIDE 10 THE SMALL RESONATOR TESTER

This slide illustrates a small resonator tester. It might be described merely as a reactive pressure divider. Its electric analog is shown at the left.

The upper inertance and capacitor are chosen so that the frequency region of interest is well below their resonance. The inserted double resonator acts almost as a short to ground at its resonance and acts almost as an inert solid plug at its first antiresonance. A typical response curve from the condenser microphone, as a function of frequency, appears as indicated in the lower part of the slide. The valley is approximately at the resonant frequency, and the succeeding peak is approximately at the antiresonant frequency of the small double resonator.

SLIDE 11 THE BACH 7C MP AND TWO DOUBLE RESONATORS

This slide shows the internal profile of the Bach 7C mouthpiece, a commercial model that is generally familiar among trumpeters.

Also shown are the internal profiles of two double resonators made in this work. The labeling numbers, in case you are curious, merely signify that the center one is the Kth (or eleventh example) made in August 1968, and the lower one is the Kth example made in September 1968. All three profiles are drawn to the same scale.

Comparative results from these three represented terminations on a B flat trumpet are shown in the next and final slide.

SLIDE 12 INTONATION WITH BACH 7C, 868K AND 968K

This slide shows intonation results using the previously represented terminators on a B flat trumpet, my own playing trumpet, a B flat Calicchio. The results are not as spectacular as they might have been if I had started with one of the trumpet-mouthpiece combinations previously represented, because as you see in the upper left diagram, the Calicchio plus the Bach 7C mouthpiece is already in untypically good intonation. However, it does show the typical general characteristics, a flat fifth mode, then an on-pitch sixth mode, and finally, a flat eighth mode.

The terminator 868K is interesting not because it corrects the errors (although it does substantially correct the fifth mode.)

It is interesting because it puts the modes in a relatively smooth, monotonic line. But the eighth mode is even flatter than it was with the commercial mouthpiece.

Terminator 968K is most interesting. As you see, with it, the fifth mode is very close to correct and the sixth and eighth modes are actually overcorrected, but not very far. This trumpet-terminator combination is in better intonation than any other that I have tested.

This then is the principal result I wanted to show you.

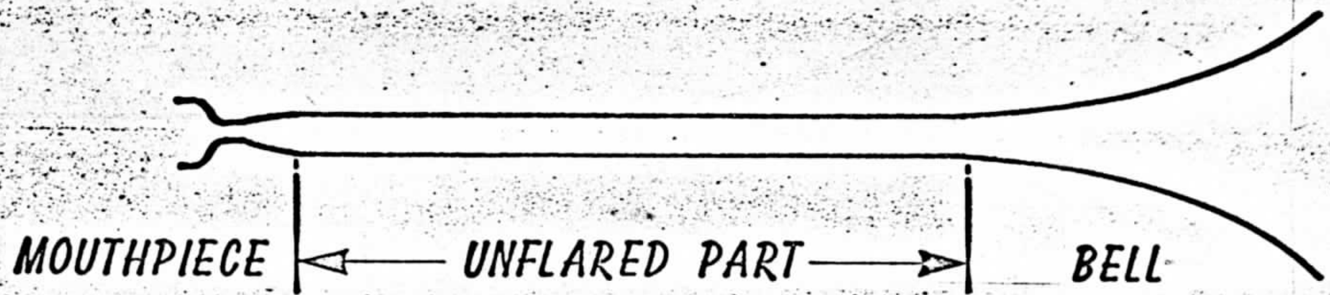
I had hoped to be able to give you a summary theoretical explanation of all the experimental points shown on this last slide, in terms of the measured resonances and antiresonances of terminators 868K and 968K. (Parenthetically, for 868K the first resonance was at 766, the antiresonance at 1014 Hz. For 968K, the values were 880 and 1190 respectively.)

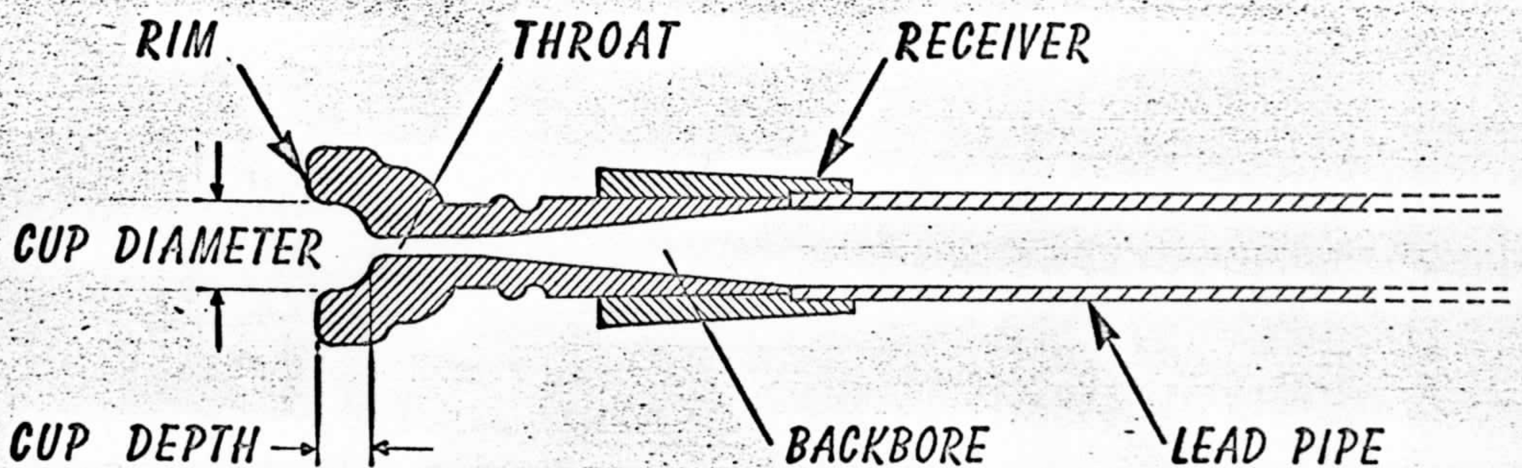
Regrettably, I have not yet been able to formulate a theoretical summary that even satisfies myself. The difficulty has to do with the generalization of the dimensionless constant K, which was so easily defined for the single Helmholtz resonator. I hope you will be temporarily satisfied with only the theory that led me to these experimental results, and with the results themselves.

I should like now to conclude with the statement that -

We can selectively tune the playing modes of existing trumpets by means of special mouthpieces.

In the future, I believe that with the aid of a little better design theory, and somewhat more definitive testing apparatus than was used in the work reported here, we can have trumpet-mouthpiece combinations, in any key, that have intonation within a very few cents of the ideal in all the upper playing modes.





SLIDE 1 of '68

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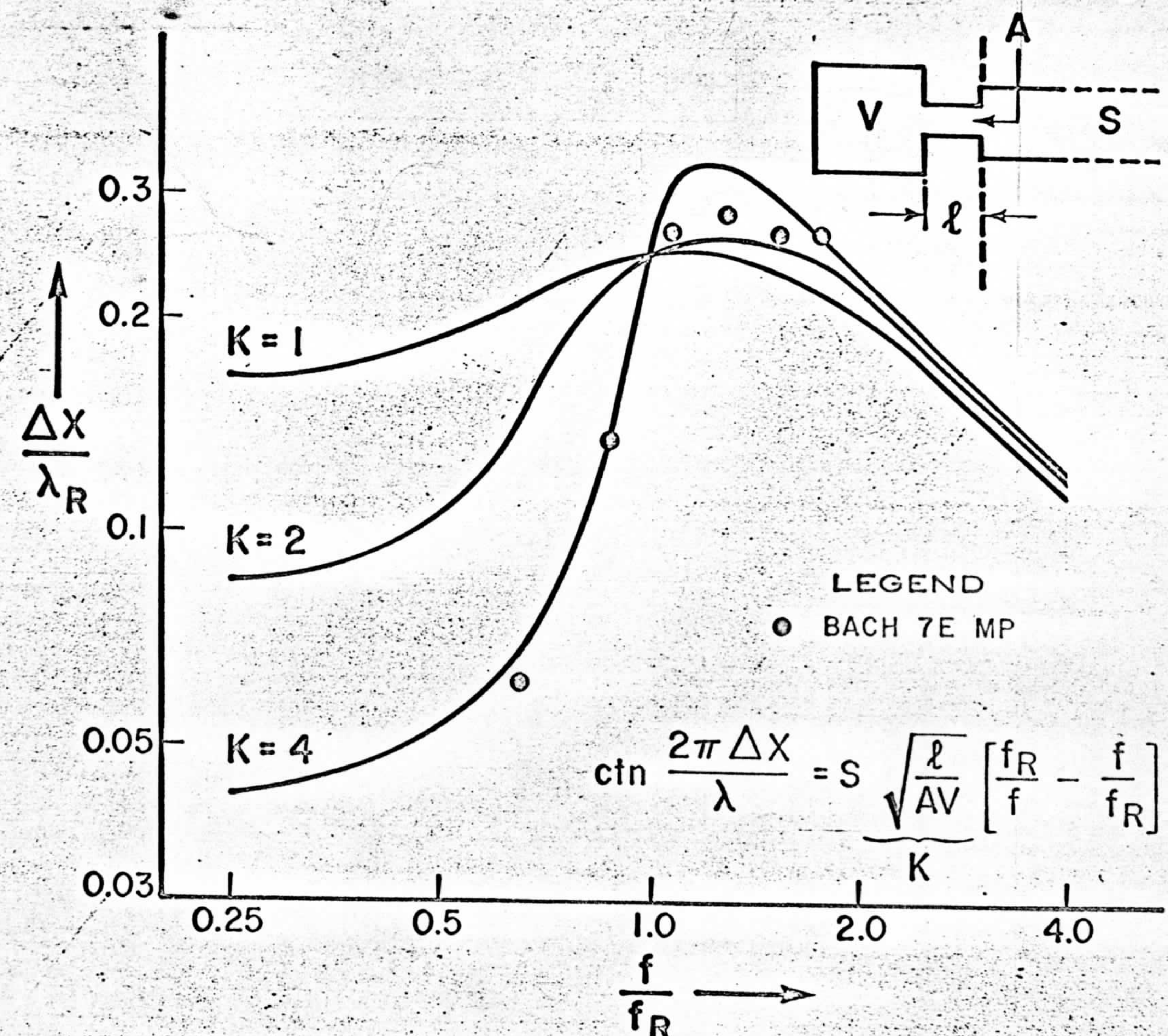
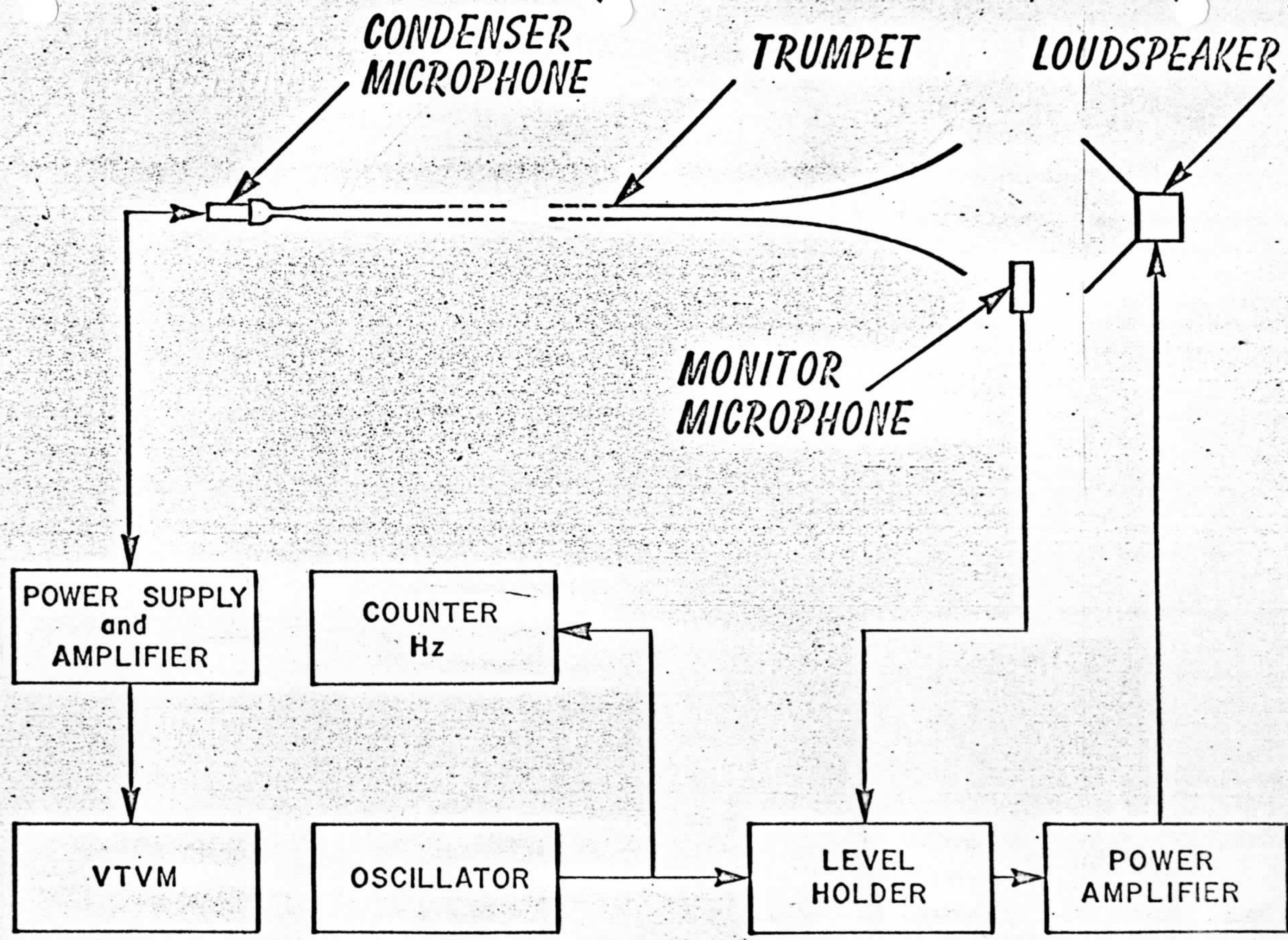


A
V
S
ℓ
0.3
0.2
0.1
0.05
0.03
ΔX / λR
K = 1
K = 2
K = 4
LEGEND
BACH 7E MP
ctn 2πΔX/λ = S √(ℓ/AV) [fR/f − f/fR]
K
0.25
0.5
1.0
2.0
4.0
f / fR

SLIDE 2 of '68



SLIDE 3 d'68

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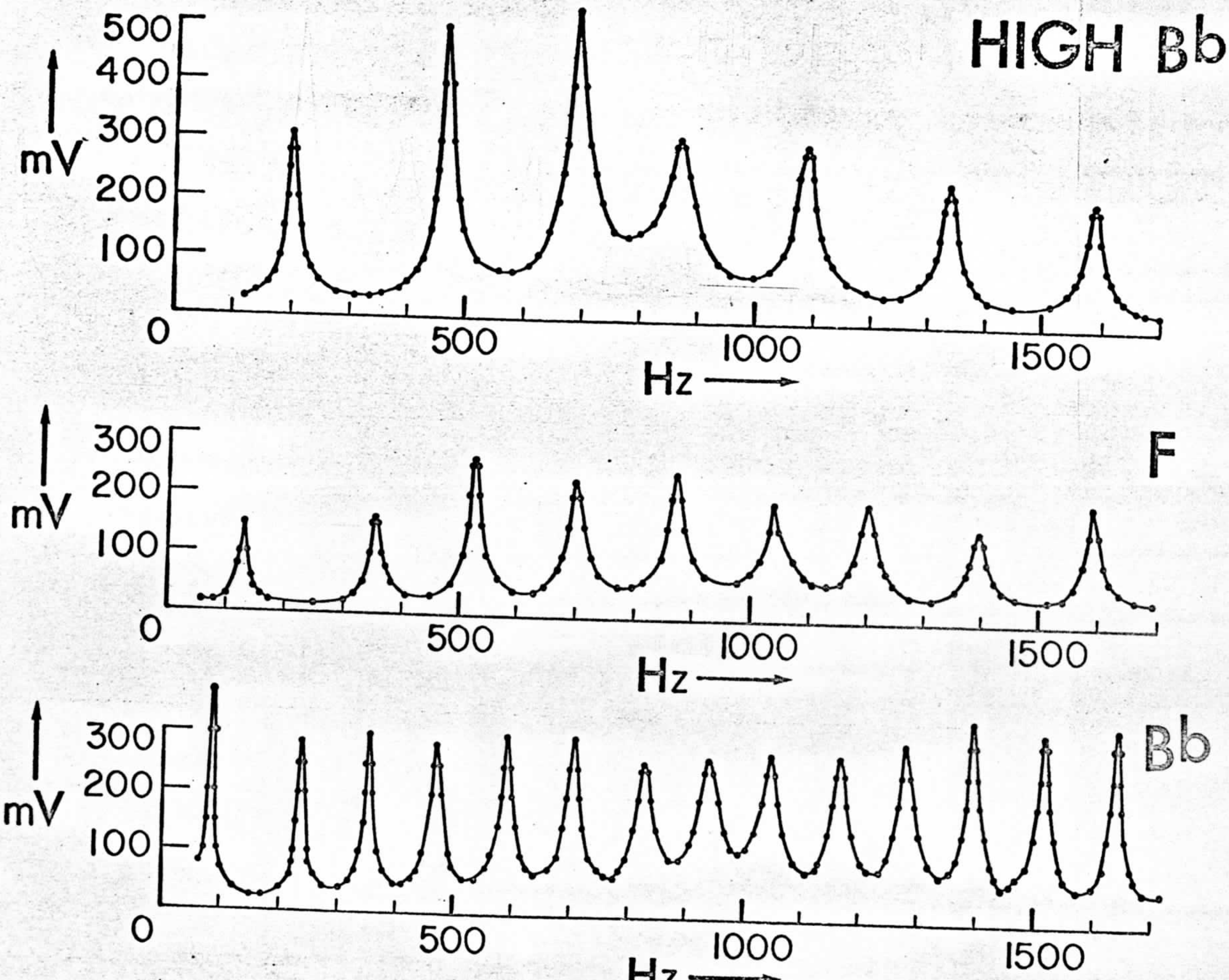
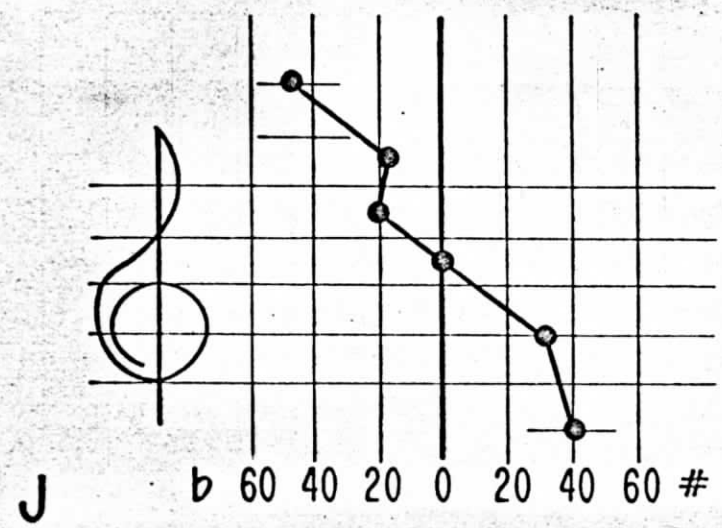
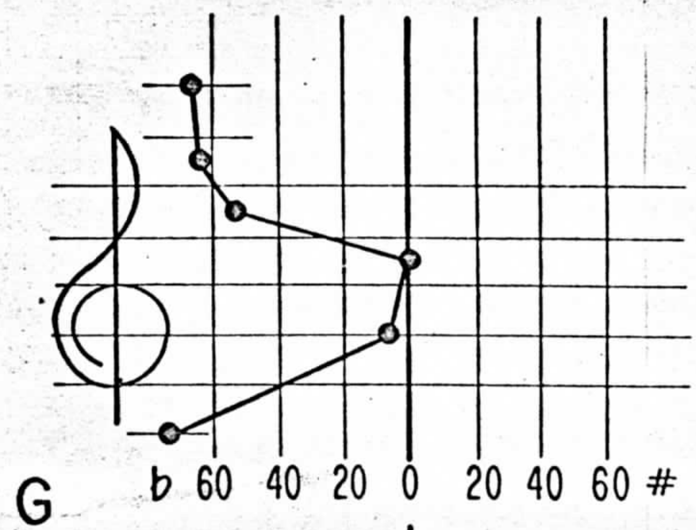
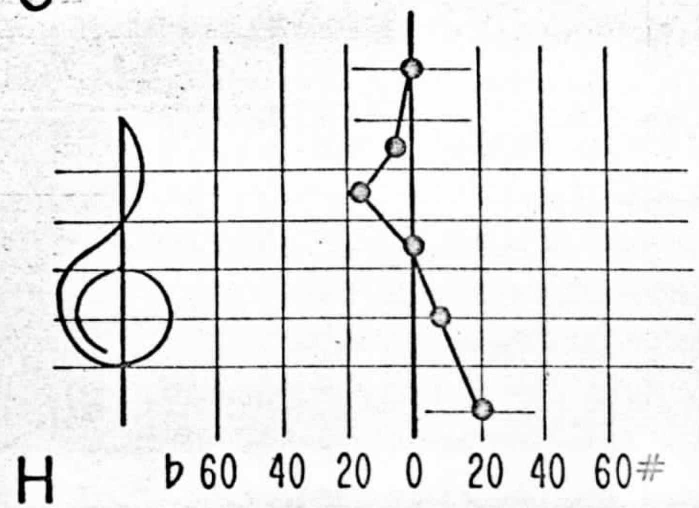


SLIDE 4 of '68

FIG. 3







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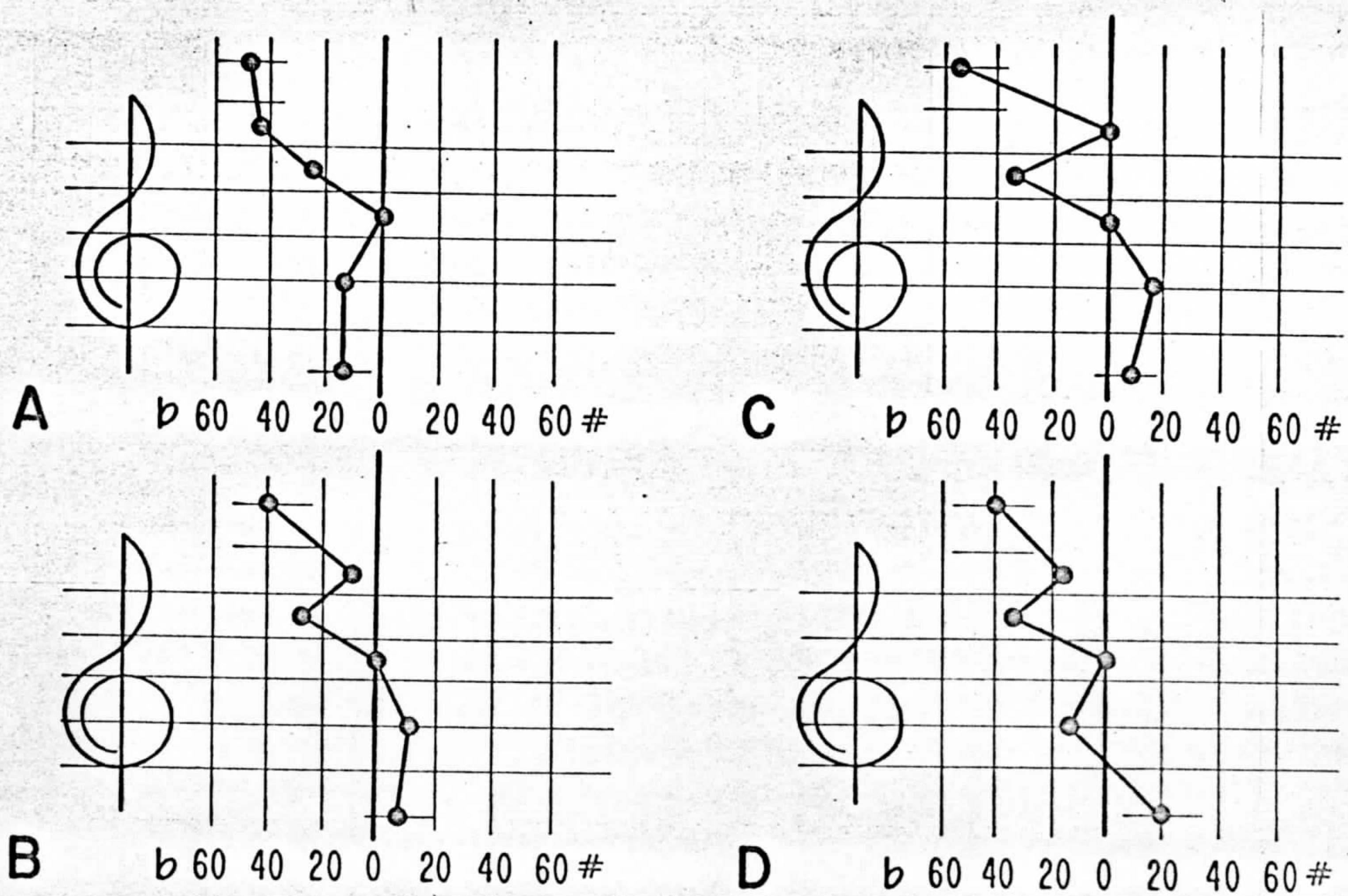

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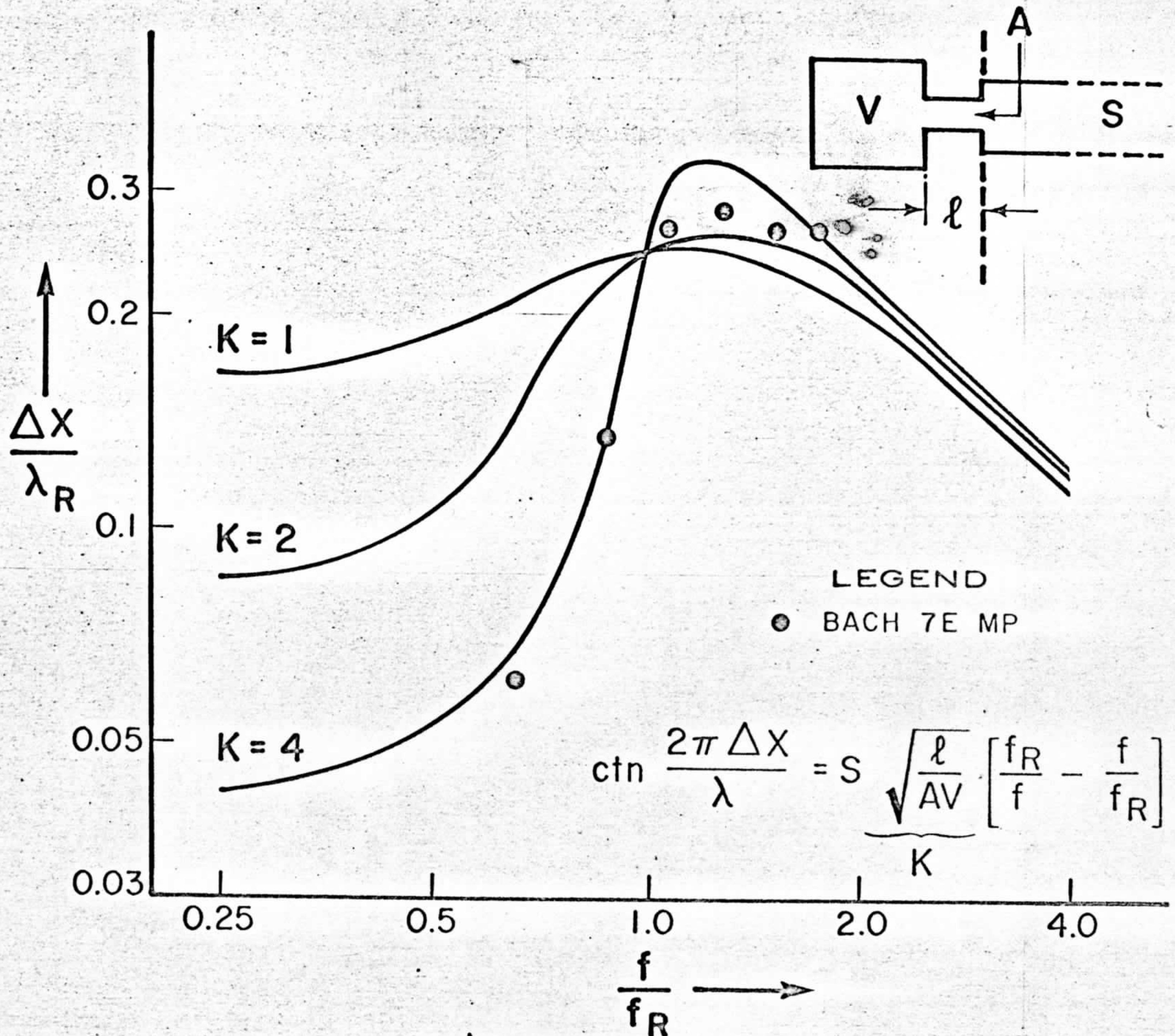

SLIDE 7 of '68 PAPER. (REPEAT OF 2)

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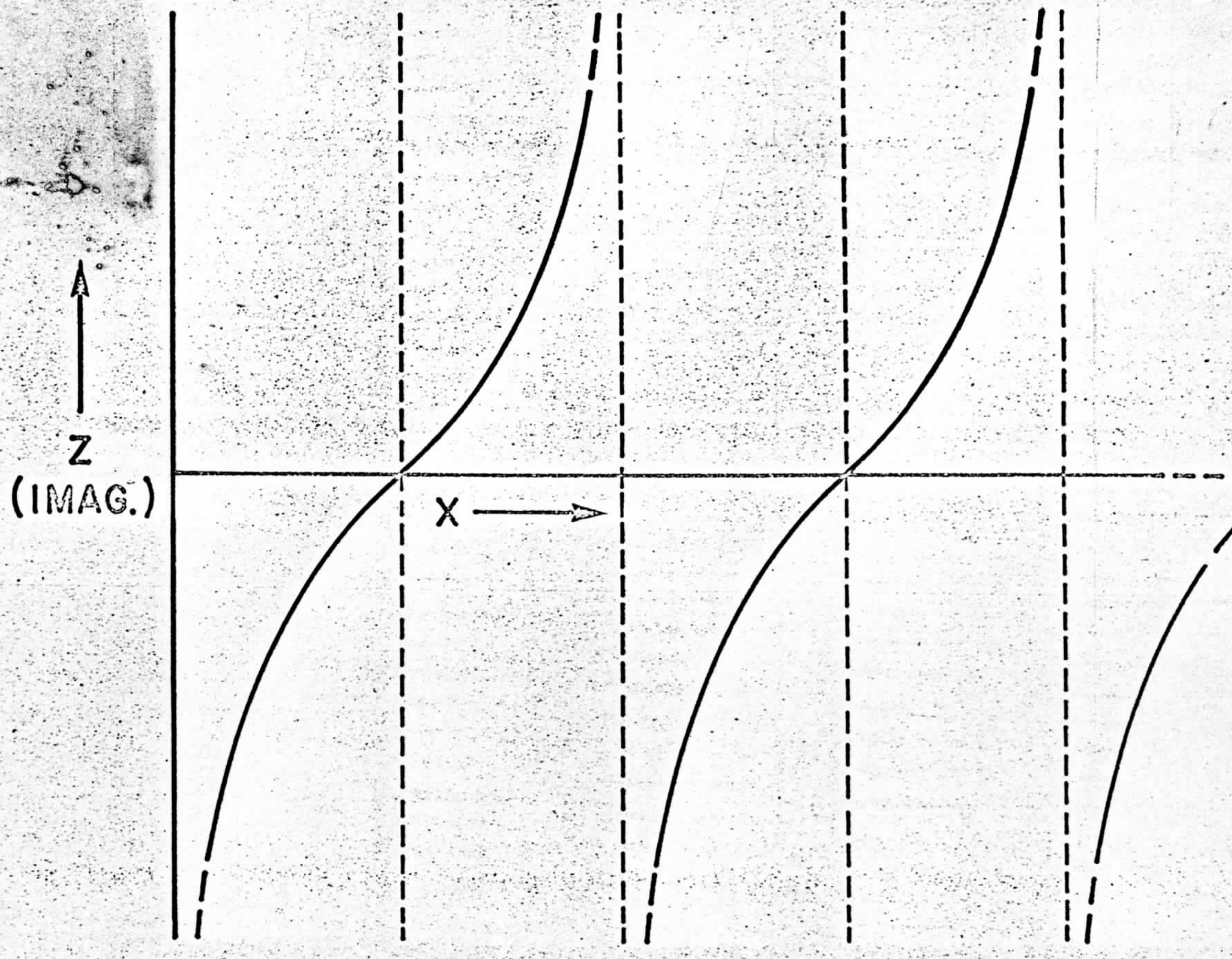

SLIDE 8 of '68 #7 of '66

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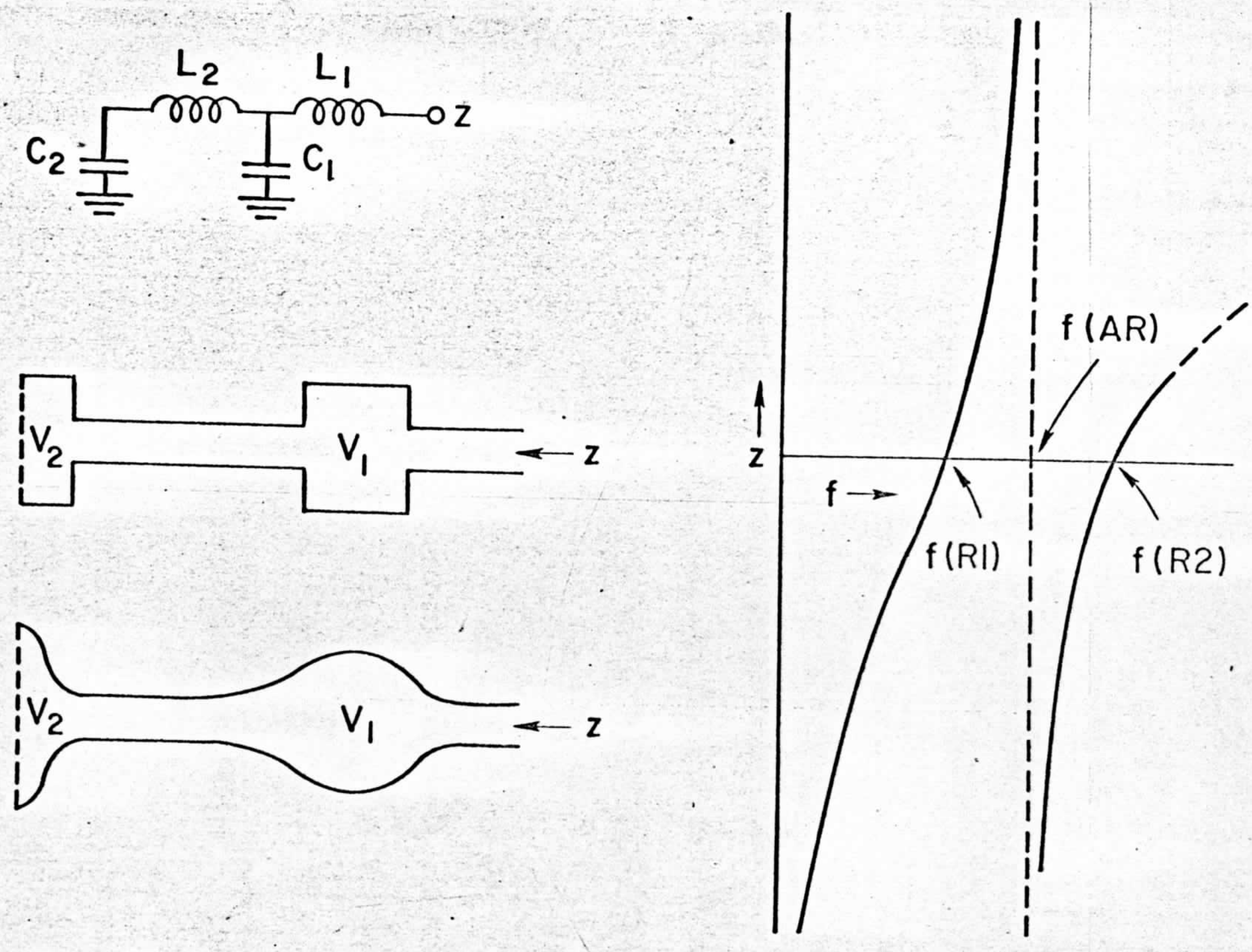

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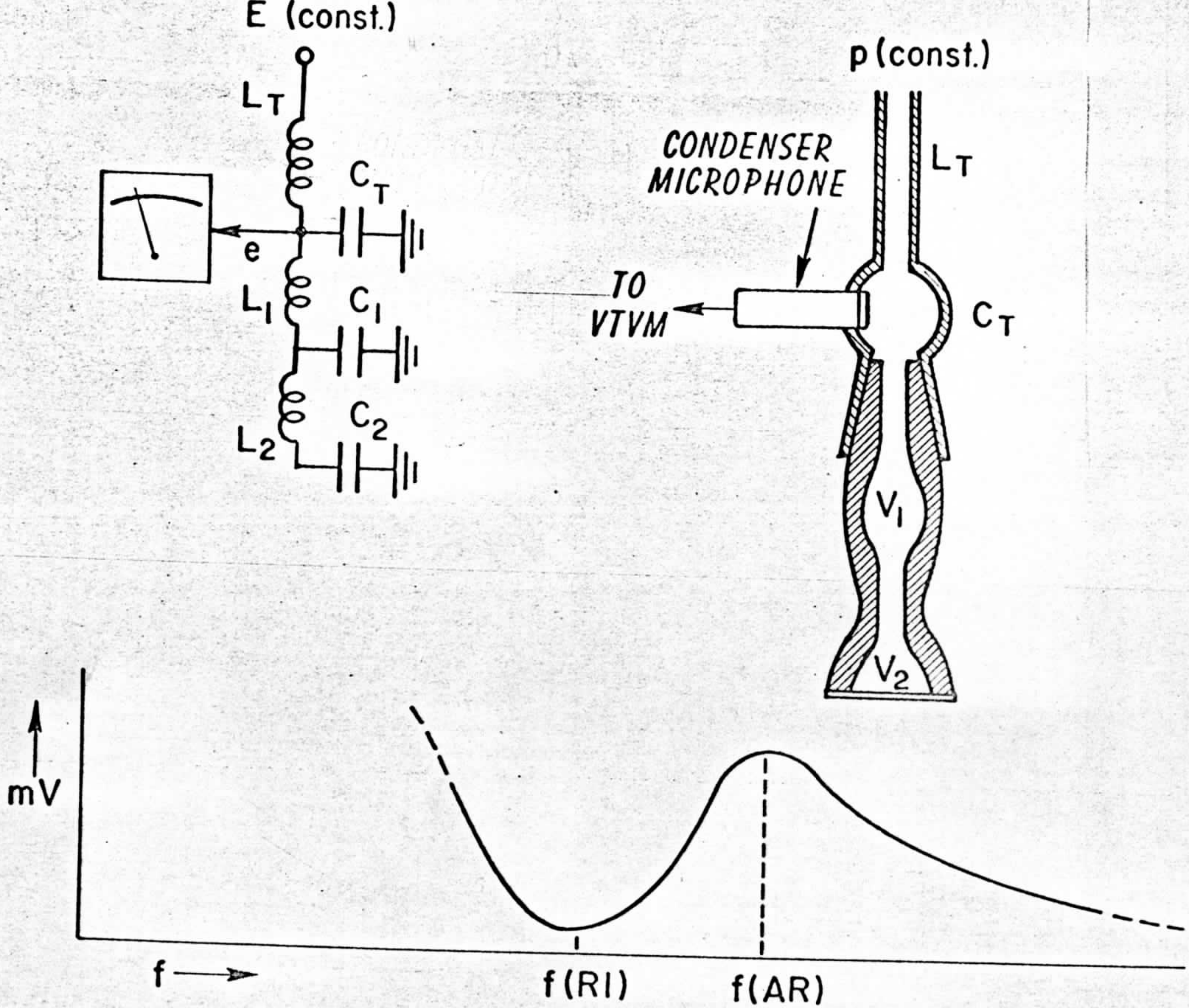

SLIDE 10 of '60

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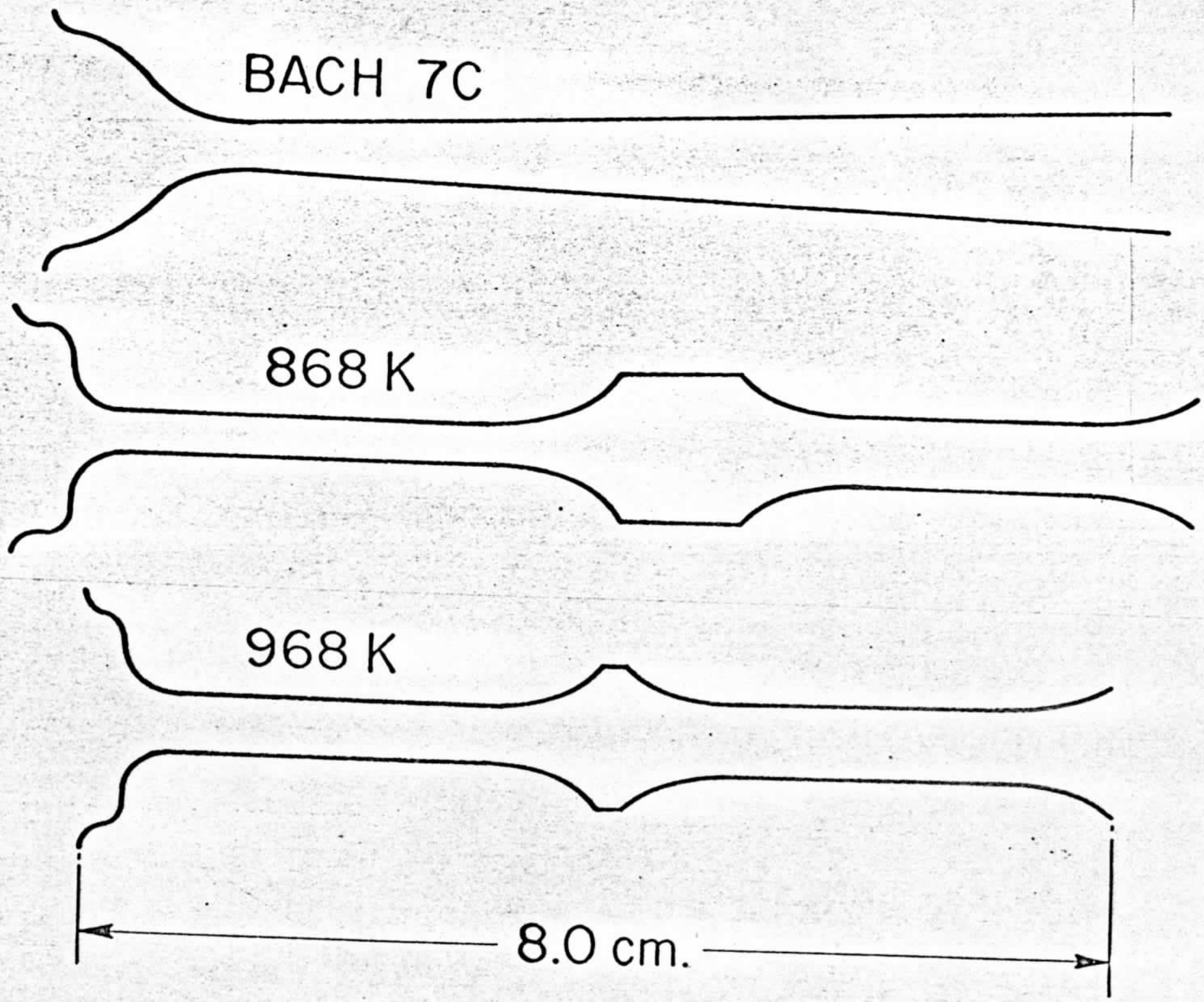

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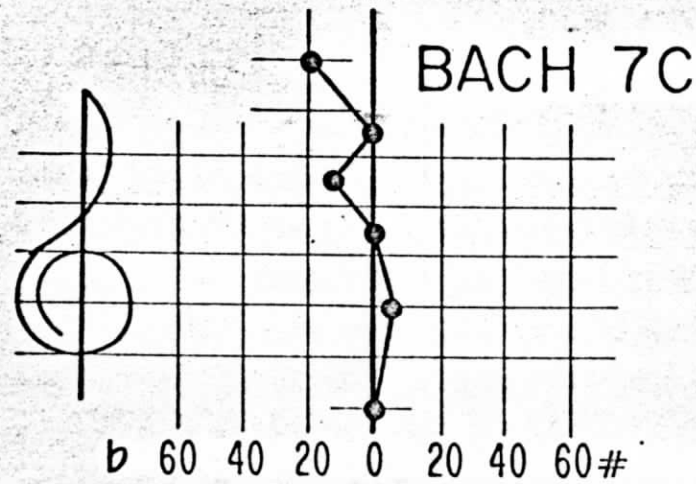

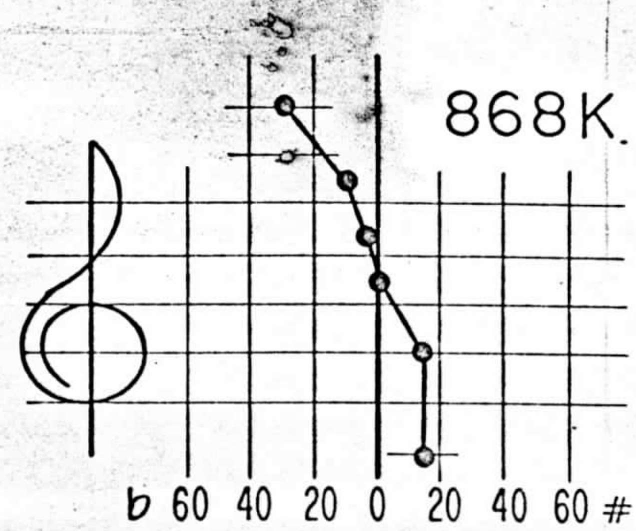

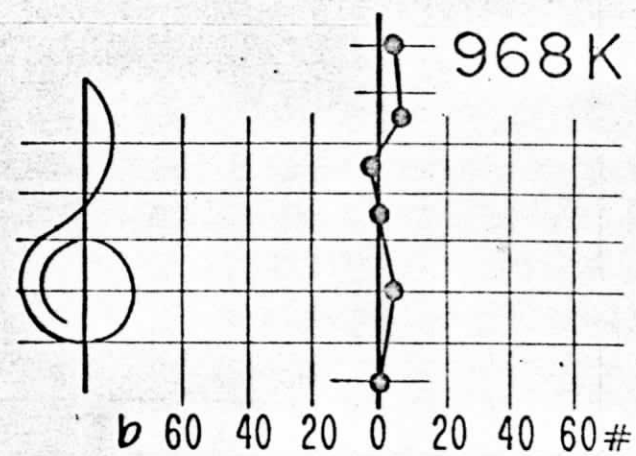

SLIDE 12 of '68

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