SLIT HEIGHT AND BLOWING PRESSURE AS PARAMETERS CONDITIONING THE FUNCTION OF THE CLARINET AS A QUASI-QUARTER-WAVE RESONATOR[1]

Niels Bak

Abstract: Using mechanical blowing applied both to a conventional clarinet and to experimental devices with the same reed excitation mechanism, the author has investigated the relationships referred to as "clarinet embouchure". The results confirm John Backus' statement that "Apparently, the intonation characteristics of the clarinet (and, perhaps, the other woodwinds) depend on more than just the geometry of the instrument" (Backus 1964, p. 2014).

1. Purpose of the investigation

The primary purpose of this author's research project dealing with the clarinet has been to throw light on those properties of tone production which are influenced by the player's blowing technique - his embouchure. The present paper deals with but a single aspect of this complex of problems, viz. the question why the clarinet has resonant properties typical of a tube closed at one end, even in such, frequently occurring, cases where by witness there is only a transient closure or no closure at all in the vibratory cycle of the reed during tone procution. It is the aim of the present paper to contribute to an explanation of this crux.

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[1] I am indebted to professor Eli Fischer-Jørgensen for her encouragement and her kind permission to use the facilities of the Institute of Phonetics. My thanks are extended to the staff of the Laboratory, and to my two excellent assistants, Ole Birk Wulff, M.Sc., and Jan Nicolas Fredholm, M.Sc., for their enthusiasm and diligence in contributing to complete the various tasks within this project. Moreover, I wish to thank Dr. Johan Sundberg of the Speech Transmission Laboratory, Royal Institute of Technology, Stockholm, for fruitful and inspiring discussions. I am particularly indebted to Professor Jørgen Rischel, now at the Institute of Linguistics, University of Copenhagen, for his advice and extensive help in bringing the text of this report into its present shape.

2. Presentation of the basic clarinet

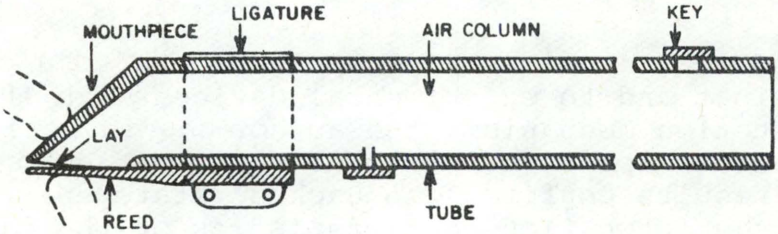

Figure 1

The primary components of the clarinet, viz. the excitation mechanism and the resonator tube. (From Backus 1969, p. 189.)

In a somewhat simplified exposition the clarinet may be described as a woodwind instrument consisting of two parts:
(i) the resonator, i.e. the (quasi-)cylindrical tube whose acoustic length can be varied by the fingering.
(ii) the excitation mechanism, i.e. the mouthpiece with reed, which is attached to the "upper" end of the tube and functions as a valve-like regulator of the stream of exhaled air forced into the instrument by the player. The outermost part of the reed, which is thin and elastic, performs oscillatory movements up and down during tone production and thus varies the slit height at the tip of the mouthpiece. This action of the reed is a crucial factor in the excitation and maintenance of vibrations of air in the tube.

Although those acoustic properties of the clarinet which are associated with the geometry of the tube are quite well understood, there are still many unsettled questions concerning the excitation mechanism. The research project of which some results are presented in this paper is intended to counteract this bias in the research. It focuses primarily on acoustic properties which - although they are inseparable from the functioning of the instrument as a totality - are specifically associated with the mouthpiece and with the blowing technique used in clarinet playing.

3. Aims and purposes of recent research on the acoustics of wind instruments, and the need for research of a complementary kind

During the last couple of decades improvements in measuring techniques have made it possible to gather highly reliable data on the acoustic behaviour of wind instruments, and thanks to a research activity of high quality, significant advances have been made towards an understanding and description of the functioning of these instruments.[1]

The following passage from Nederveen (1969) will serve to illustrate what kinds of issues have been predominant in previous research (according to the literature accessible to me): "The aim of the investigations was to find a method for calculating the right position and size of the holes of a woodwind instrument. This can be useful for designing a new instrument or changing an existing one." Research with this expressed goal may first and foremost be useful to the professional musician as a performer, since he may expect new insights to assist the manufacturer in designing instruments for easy intonation and with the timbre desired by the expert player. It is different for the clarinet teacher, however. Among his tasks is the very essential one of guiding his pupils in their struggle to establish the embouchure,[2] which is so crucial in clarinet playing. The scholarly literature referred to above hardly offers much information that will assist him in accomplishing this.

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1) Henri Bouasse's works, which appeared some decades earlier, were a valuable source of inspiration (Bouasse 1929; 1930). One of the landmarks of this research is A.H. Benade (cf. Benade 1959; 1960; and also his book, Horns, Strings and Harmony, Anchor, Garden City, N.Y., 1960, which is intended as a textbook for the common reader). In more recent years, John Backus and C.J. Nederveen have likewise contributed significantly along much the same lines as Benade. A thorough and lucid survey of the major advances due to the research of the last few decades is available in Benade's book from 1976.

2) The term embouchure is here used in the wide sense associated with it in Webster's Dictionary: "(...) the mouthpiece of a wind instrument; also, the fitting of the lips and tongue to the mouthpiece in playing a wind instrument".

The organization of the present project reflects the author's opinion that conditions are favourable now for attempts to arrive at a better understanding of the rôle of the embouchure as a component of clarinet playing. The possibility of arriving at results which may be applicable in a pedagogical framework was an essential driving force.

The approach chosen for this purpose consists in a continuation and further development of the kind of experimental work that is represented so instructively in Backus' pioneer work (Backus 1961, p. 806-809, and 1963, p. 305-313) with the goal of making it possible to throw light on various aspects of the acoustics of the clarinet which still await elucidation.

Since the investigation dealt with in this paper is specifically directed towards the excitation mechanism, it seems useful to start by presenting the following list of symbols to be employed in the remainder of the paper.

H_I: the constant slit height (i.e. the height of the slit between the reed and the lay at the tip of the mouthpiece) with no load on the reed,

H_{II}: the constant slit height if the reed is loaded by lip pressure only,

H_{III}: the constant slit height just before the reed begins to oscillate,

P: the excess air pressure on the outer side of the reed compared to a mean value of air pressure inside the mouthpiece during excitation (this corresponds to "blowing pressure" or "mouth pressure" in the case of natural blowing),

P_{thr}: the lower threshold for excitation of tone at a given embouchure.

4. Experimental setup

The basic components of the experimental setup is shown in fig. 2a. In a number of cases it proved advantageous to produce

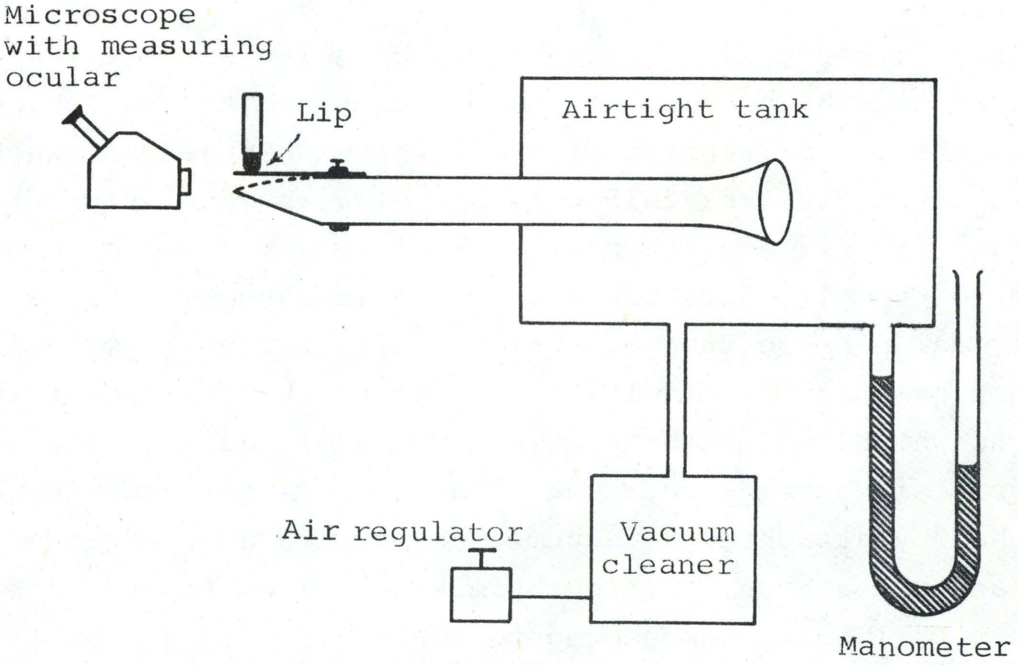

Figure 2a

Simplified presentation of the experimental setup used for a detailed investigation of the excitation mechanism.

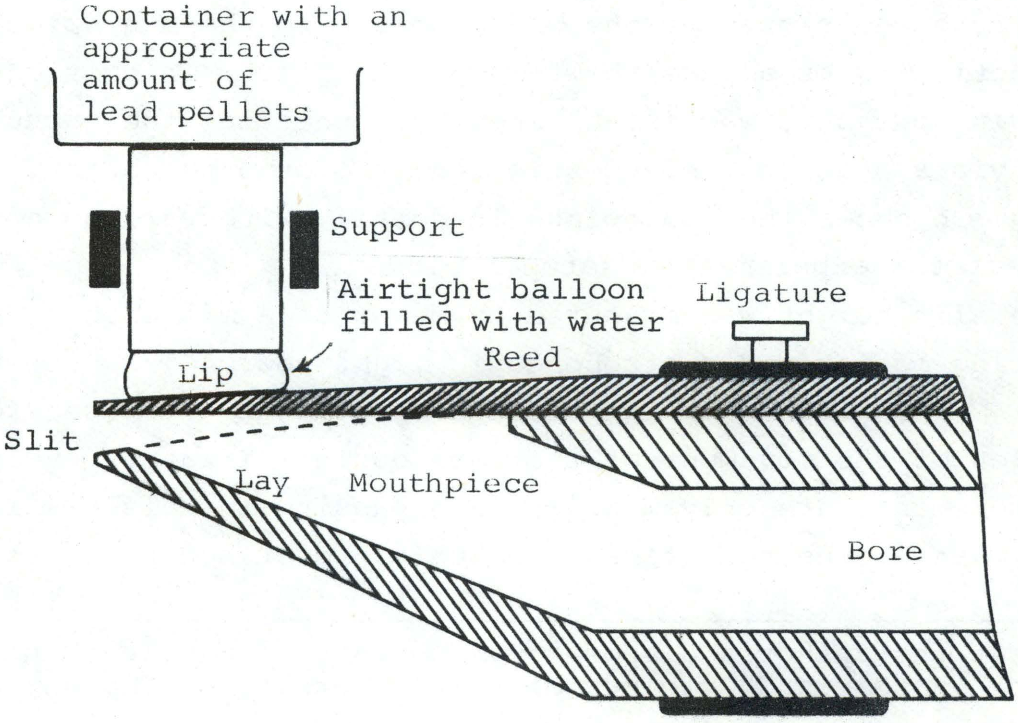

Figure 2b

An enlarged section of fig. 2a, presenting the embouchure end of the clarinet in more detail.

the desired pressure difference by establishing a "negative pressure" in the mouthpiece and resonator, compared to the ambient pressure (the latter representing the "blowing pressure" in this case). A tank (size 78x32x15 cm), whose walls consisted of a rigid framework of metal threads covered by a plastic bag, was attached to the clarinet bore - or (in some experimental series) a cylindrical plastic tube of an inner diameter of 17 mm - in such a way that only approximately one fourth of the instrument (viz. the end to which the mouthpiece was attached) was situated in the atmospheric air outside the tank. The "negative" pressure was established by attaching a vacuum cleaner with an air regulator to the tank via a hose. Various admission pipes for registration purposes were likewise connected to the cavity inside the tank. When using pressure above the atmosphere instead of "negative" pressure, the bag functioning as a tank for the air supply was fitted around the mouthpiece leaving the other, open end of the resonator free (in this case, the plastic bag was placed inside the metal framework for obvious reasons).

In one specific experiment (see fig. 8) the above mentioned plastic tube was closed at the end opposite to the mouthpiece, thus functioning as a quasi-half-wave resonator. In this case, the blowing pressure was established by connecting the vacuum cleaner via a hose to the acoustic center of the resonator.

Fig. 2b shows the mouthpiece in detail, with various components of the experimental setup included.

The slit height was measured by means of a microscope[1] with a measuring ocular and a stroboscopic light source[2], as shown in fig. 2a.[3] The flashes of the stroboscopic light were used for registration of the movement of the reed during vibratory cycles (these movements are only mentioned in passing in this preliminary report), but at the same time a number of reference points for the

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1) Put at the author's disposal by courtesy of the Institute of Plant Anatomy and Cytology of the University of Copenhagen.

2) Put at the author's disposal by courtesy of the Audiologopedics Research Group at the University of Copenhagen.

3) The actual setup included a considerable amount of instrumentation and acoustic shielding not shown in the schematic drawings. (An essential part of this extra outfit was required for the recording of data which are not included in the present paper.)

movements of the reed were established.[1] These included the position of the edge of the reed when there is no load (in terms of air pressure or mechanical pressure) on the reed (H_I); further, the position of the reed loaded with lip pressure but without any difference in air pressure between the outer side of the reed and the cavity inside the mouthpiece (H_{II}); and, finally, the position of the reed when lip pressure is applied and there is, furthermore, a difference of air pressure that is just below the value making the reed begin to oscillate (H_{III}).

Almost all the experiments were made employing a geometry of the tube corresponding to the excitation of tones in the low register,[2] viz. D_3, A_3 and D_4.

The measurements testify to the existence of the following tendencies, which as such are generally accepted: rising pressure (in the case of alternating pressure) inside the mouthpiece contributes to a tendency toward greater reed aperture, and falling pressure contributes to a tendency toward closing of the aperture. However, the results yield a picture of the functioning of the embouchure which deviates on some points from the traditional view. For example, it has been known for a long time that there is no complete closure when notes are played piano, but authorities have been convinced that in mezzoforte, and under any circumstances in forte, there is an interval of complete closure which may last for as much as half of the duration of a complete cycle. This is not confirmed by my measurements, and other such details might be mentioned.

It should be noted in this context that the basic parameters - which fortunately are easily checked - such as P, P_{thr}, and the possibilities of varying the sounding frequency and the spectral composition of the tone, are in good agreement with measurements

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1) The use of stroboscopic light was not essential for measuring these positions, since the reed was stationary in each position. However, the measurements were made in connection with measurements serving to determine the movement of the reed, and hence the stroboscopic light was used throughout.

2) The choice of these particular notes was primarily due to the fact that the literature accessible to me fails to give detailed information on the conditions with respect to the embouchure for intonation in the deep register (see, e.g., Backus 1963, p. 311).

made by others. Impressionistically, the timbre of the tone was adequate, disregarding the necessarily artificial character of a completely stationary tone deprived of transient phenomena (cf. Backus 1969, p. 193, and Coltman 1973, p. 418 on the character of mechanically blown tones).

Analyses of the spectrum of the tones produced by mechanical blowing show that the spectral composition can be varied apparently over the total range of variation possible with natural blowing, by manipulation of the parameters referred to above.

Thus it can be concluded that the artificial embouchure used in this investigation was sufficiently good.

5. Presentation of some experimental data with interpretation[1]

5.1 Threshold blowing pressure

One way of approaching the many phenomena associated with the embouchure is to gather experimental data on parameters which influence P_{thr}, i.e. the minimum blowing pressure necessary for the starting transient of the clarinet tone to appear (provided that certain other conditions are met). Diagrams figs. 3a, 3b, and 3c exemplify this approach by presenting data from a pilot experiment.

A setup of the type shown in fig. 2a above was used. In this case the resonator was the above mentioned cylindrical plastic tube adjusted for intonation of the note A_3. The clarinet reed was made of cane and of medium stiffness. During the experiments no moisture was applied to the reed (with the exception of a single experimental

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1) In this project a new type of pick-up: the flow-meter, was introduced and, furthermore, the number of parameters to be studied was augmented by the addition of lip function, which does not appear in analogous fashion as a parameter in previous research. These novel features of the experimental approach entail a widening of scope of the research. As might be expected under such circumstances, part of this research must be characterized as pilot experiments. For this same reason, some of the results must be tentative, since further research may reveal relations and show the operation of factors which cannot be grasped at present. These reservations, however, apply specifically to results which are not included in the present paper. The relationships reported on in this paper can be interpreted with certainty.

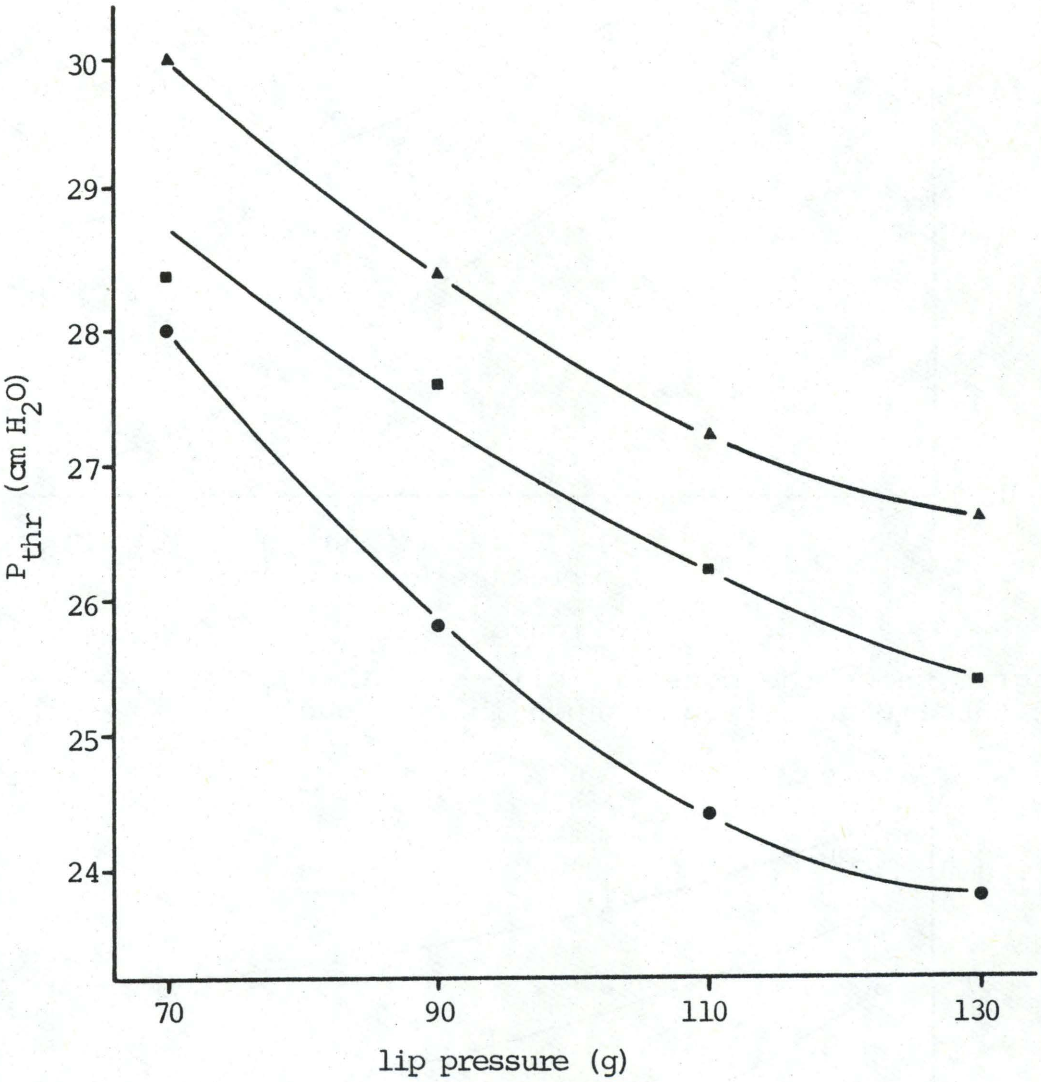

Figure 3a

Curves showing threshold blowing pressure versus lip pressure. The three curves represent different lip positions. In the case of the lowest curve the artificial lip was placed so as to leave the tip of the reed free, the area not covered by the lip extending 1 mm inwards from the edge; in the case of the next curve, this free area extended 2 mm inwards; in the case of the uppermost curve, it extended 3 mm inwards.

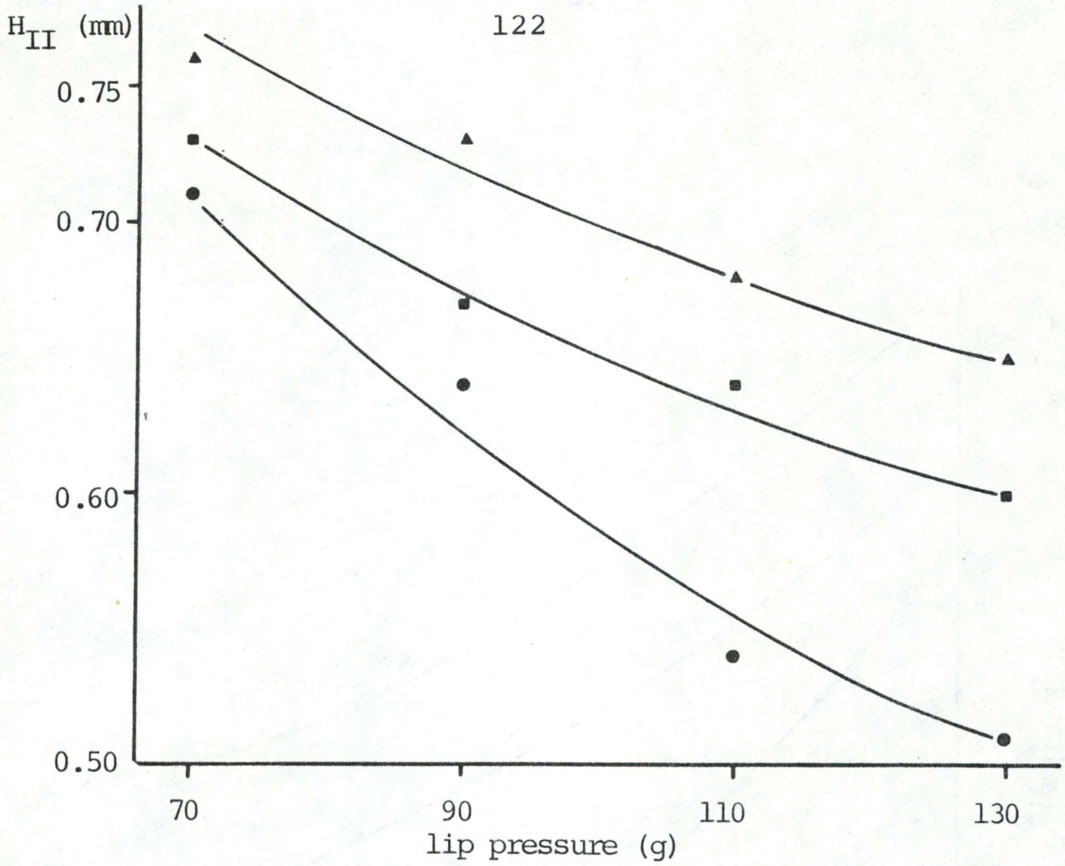

Figure 3b

The diagram shows the constant slit height (H_{II}) in mm as a function of the lip adjustments shown in fig. 3a.

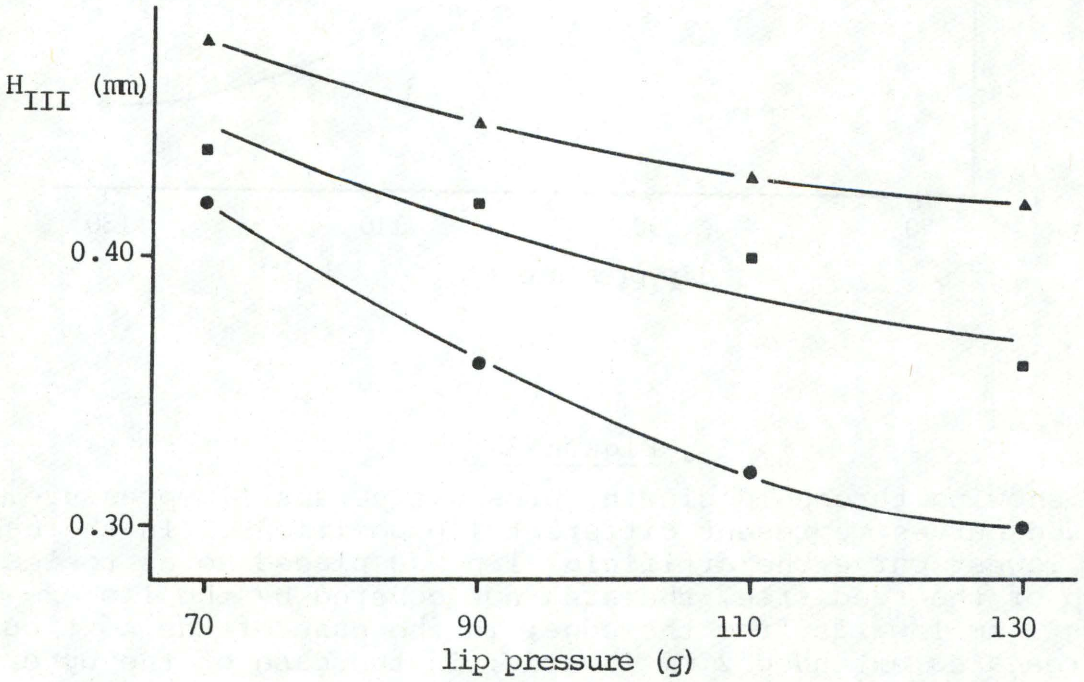

Figure 3c

This diagram shows the size of H_{III} in mm, i.e. the slit height measured just before the blowing pressure, which was gradually increased, reached the value $P = P_{thr}$ (the level at which periodical oscillations of the reed will begin). H_{III} is depicted as a function of the lip adjustments shown in fig. 3a.

series not accounted for in this report). Thus the moistness of the reed was conditioned by the natural humidity of the surrounding air only. This solution was chosen in order to keep the elasticity and the weight of the reed as constant as possible during measurements.

The diagram fig. 3a exemplifies how the parameters lip position and lip pressure influence the value of P_{thr}. It is seen that there is a trading relationship among these parameters: with a given lip position (measured as a displacement from the extreme position at the tip of the reed) and a given lip pressure, a certain blowing pressure is required to just excite a tone, viz. the P_{thr}; the further the lip is moved inwards, and the lesser lip pressure one employs, the higher is the value of P_{thr}, and vice versa.

On closer inspection several factors conditioning this trading relation can be singled out. One obvious cause is that if the lip position and the lip pressure are such that the slit height is reduced only very slightly, a much higher static pressure difference, P, between the outer side and the inner side of the reed is required in order to force the reed inwards toward the lay. Hence, under such conditions of lip position and lip pressure, P_{thr} is correspondingly higher. However, this interpretation is an oversimplification of the causal relations.[1] This is because any change in either P or the slit height, H, has a multiple influence on the entire sound generating mechanism (with reed and resonator as integral parts). Because of this complexity it is useful to sort out as a separate intermediate step a series of experiments serving to establish the influences of variations in H and in P on the entire oscillatory system.

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1) To exemplify the relationships, it may be pointed out that H_{II} assumes practically the same value, according to figs. 3b and 3c, under the following three conditions: (i) Lip position A + 1 mm, lip pressure 90 g; (ii) Lip position A + 2 mm, lip pressure 110 g; (iii) Lip position A + 3 mm, lip pressure 130 g. However, the size of H_{III} is different, viz. 0.36 mm, 0.40 mm and 0.42 mm, respectively, see fig. 3c. - It may be added that the performance of the reed as a variable valve is highly dependent upon the size of H_{III}.

5.2 The dependence of resonance conditions on slit height[1]

In most of the series of experiments dealt with in this paper a test instrument, Buffet-Lyre S 1, model no. F 152064, was employed.[2] As mentioned already, the clarinet bore was replaced by a cylindrical tube (of an inner diameter of 17 mm) in some of the series. The mouthpiece was a Vandoren 5 R V.

As shown in the schematic drawings of the experimental setup for resonance measurements (figs. 4 and 5), the resonator was excited by an external sound source, viz. a Philips loudspeaker, type RH 541 MFB. Measurements were made in an anechoic chamber.

The resonance conditions were analyzed by a sweep-tone technique. The analyzer, B&K, type 2010,[3] was manually operated. By using this approach under otherwise favourable conditions, the author succeeded in acquiring more precise information than previous investigations did about the values of the resonant frequencies.

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[1] In the following the frequency measurements are converted into values of frequency deviation, viz. the deviation of a resonant frequency from the frequency of the corresponding component in the complex tone in question. (100 cents = 1 tempered semitone.) The deviations of the resonant frequencies of a half-wave resonator can be calculated by means of this formula:

$$\text{deviation} = \log \frac{f_{\text{res n}}}{n \times f_{\text{blow}}} \times (1200/\log 2) \text{ cents}$$

With reference to a quarter-wave resonator, the formula is like this:

$$\text{deviation} = \log \frac{f_{\text{res n}}}{(2n-1) f_{\text{blow}}} \times (1200/\log 2) \text{ cents}$$

where $f_{\text{res n}}$ is the n'th resonant frequency, and f_{blow} is the blowing frequency of the tone in question.

This paper deals with measurements made with the test instrument adjusted for the notes D_3 and A_3. In the calculation of frequency deviations it is assumed that the blowing frequencies of the tones in question are 146.7 Hz and 220 Hz, respectively.

[2] The test instrument was placed at the author's disposal by courtesy of Marno Sørensen Instrument Dealers, Copenhagen. The staff of this firm kindly assisted the author in modifying the clarinet by closing the radial holes (which are otherwise available for changing the acoustic length of the clarinet by means of the fingering) and in other ways.

[3] Put at the author's disposal by courtesy of the Acoustics Laboratory of the Danish Technical University and Brüel & Kjær, Nærum.

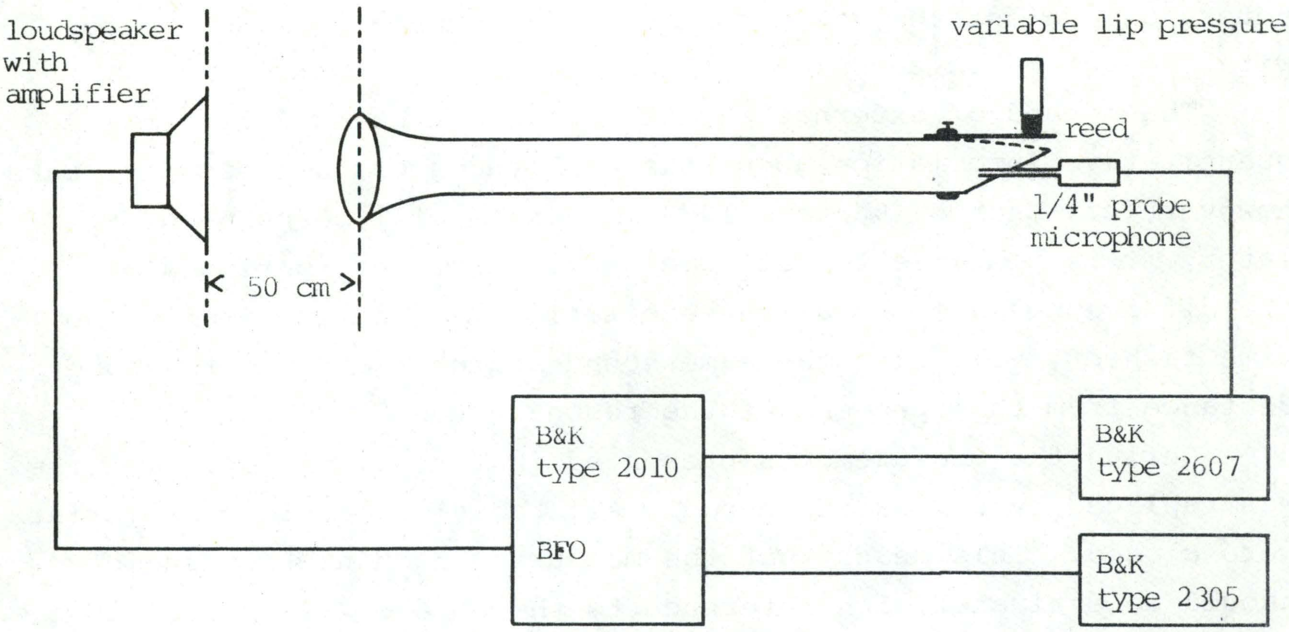

Figure 4

Schematic drawing of the experimental setup employed in measurements of the resonant frequencies of the resonator with external excitation.

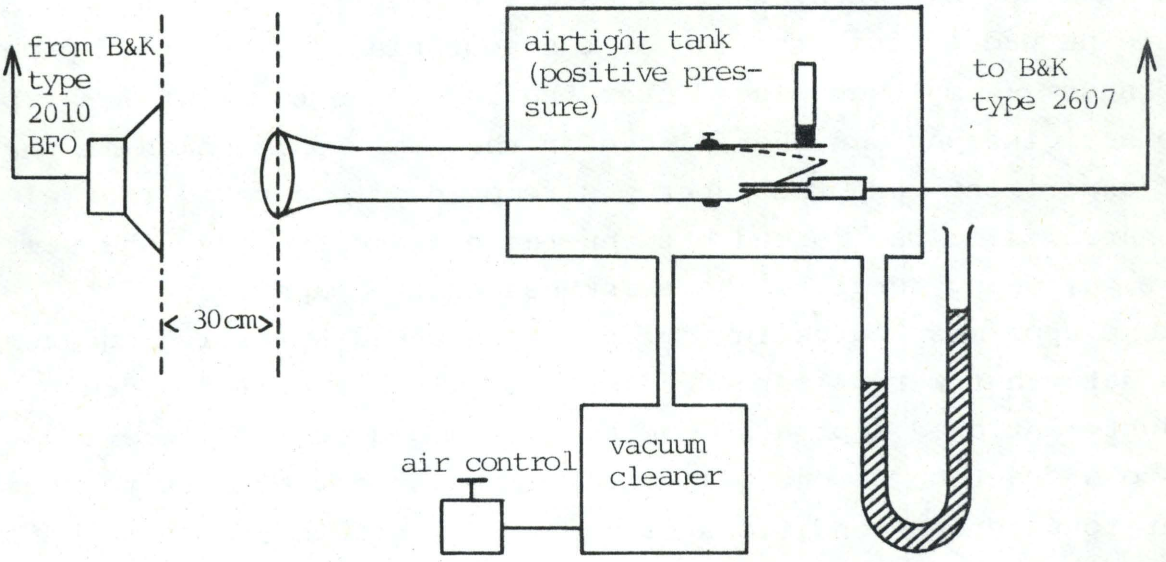

Figure 5

Schematic drawing of the setup employed in measurements of resonant frequencies (cf. the setup in fig. 4) with P added as a variable. In this case a "positive" pressure was established in the tank which included the upper end of the clarinet. Note that in the case of resonance measurements P did not represent a "blowing pressure" in the traditional sense, since the slit height was kept constant for such measurements.

(In return, the measurements had to be confined to relatively few notes, as against the greater number of frequencies investigated with the automatic technique of Backus.)

The method of external excitation cannot be used to obtain quantitative information about the amplitudes of the resonant peaks, however (cf. Backus 1968 and 1974). But as will be pointed out later, it is possible to get some qualitative information about the differences as long as the excitation is made in exactly the same fashion, viz. with the same sound source placed at the same distance from the open end of the resonant tube.

During the measurements presented in fig. 6, the clarinet reed was replaced by a plasticine pad. All radial holes in the clarinet were closed. This means that the measured resonant frequencies should be evaluated with reference to the note D_3 (fundamental frequency 146.7 Hz).

The lowest curve in fig. 6 (represented by a filled circle) shows the resonant frequency under conditions of total closure at the embouchure end of the clarinet, the plasticine pad forming an airtight closure with the lay.

The next lowest curve in fig. 6 (represented by filled triangles) shows data that were recorded after the conditions at the embouchure end had been modified as follows: before placing the plasticine pad against the lay of the mouthpiece, a sheet of paper (thickness 60 my) was placed over the lay so as to cover its tip. The plasticine pad was then placed in the same position as in the first experiment, and the paper was removed with care so that a very narrow slit was formed between the pad and the lay, the slit height, H, being equal to the thickness of the paper.

The uppermost curve in fig. 6 (represented by filled squares) shows data that were recorded after the slit height (adjusted by the just mentioned approach) had been enlarged from the previous size to a fraction of one millimeter, H being now similar to average height found under conditions of mechanical blowing, according to the author's estimate.

In fig. 6 the two uppermost curves have been cut off (for considerations of space), so that the plots of the frequency deviation of the first harmonic are missing. The values were as follows: for the smaller value of H (the data plotted with filled

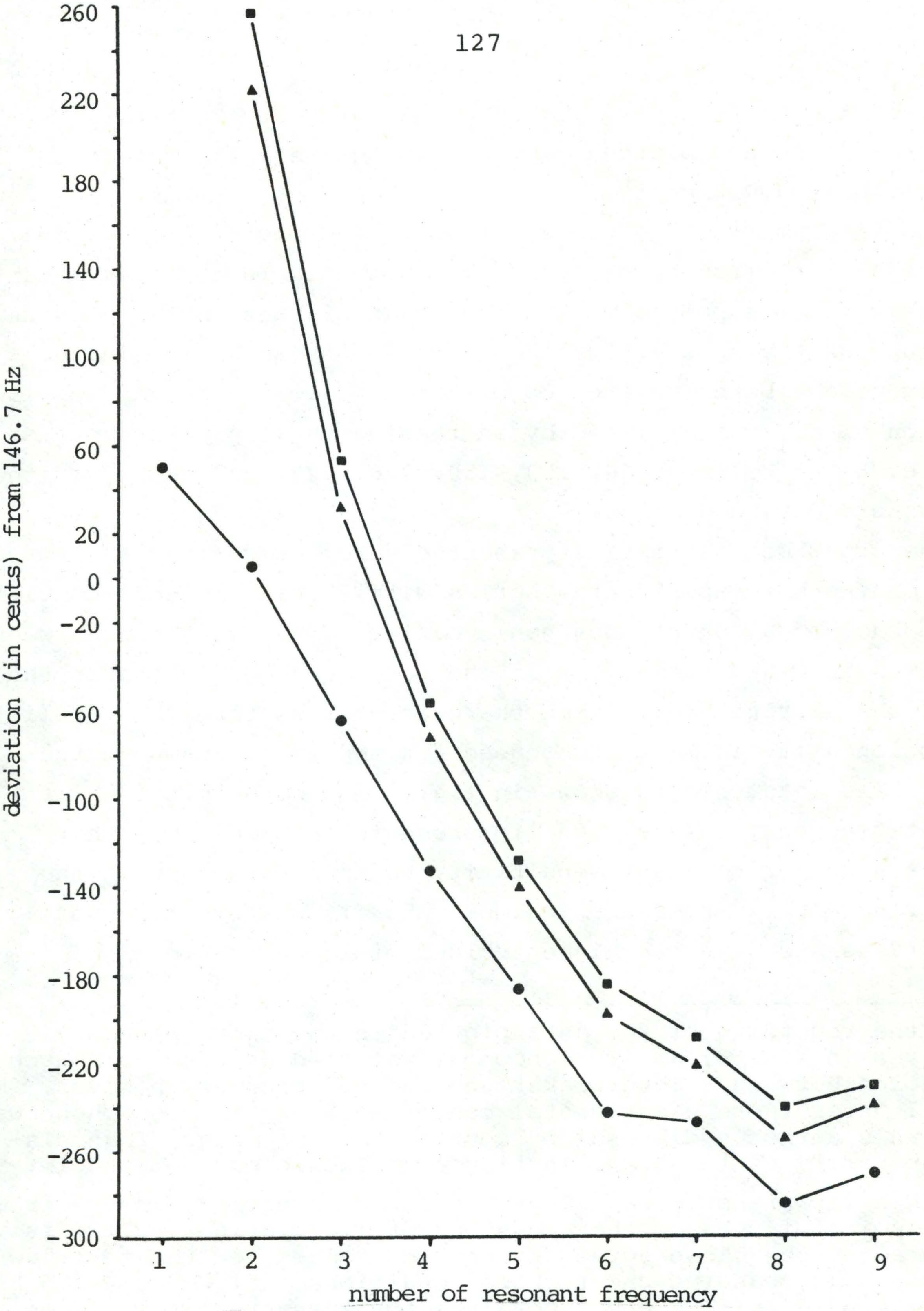

Figure 6

Diagram showing the result of three series of resonance measurements made with the setup shown in fig. 4, but with a pad of plasticine replacing the reed. This diagram shows the deviation (in cents) of the actual resonant frequencies from those of an ideal quarter-wave resonator tuned for a first resonant frequency of 146.7 Hz (corresponding to the note D3). The curves represent different degrees of aperture at the embouchure end (see text for details). - For limitations of space the deviation of the first harmonic is omitted from two of the curves; the values are respectively 880.8 cents (for the next highest value of H) and 937.4 cents (for the highest value of H).

triangles) the deviation was 880.8 cents, and for the higher value of H (the data plotted with filled squares) the deviation was as much as 937.4 cents.[1]

The diagram fig. 7 gives a more detailed picture of the dependence of the first harmonic on slit height. In this experiment the clarinet was supplied with a reed made of cane, but otherwise the setup was the same as for the measurements shown in fig. 6. The slit height being controlled by the artificial lip, a stepwise reduction of H_{II} was achieved by increasing the lip pressure from 0 g (i.e. $H_{II} = H_I$) over 50, 100, 150, 200, 223, 249 to 269 g (the lip pressure giving $H_{II} = 0$).[2]

The experimental results presented here, as well as the results of the many other experimental series within this project, confirm the presence of a conspicuous nonlinearity in the relation between variations in H and variations in the resonance conditions in the bore of the clarinet (even when there is no flow through the slit). This nonlinearity is most pronounced for the first resonant frequency. The measurements shown in fig. 7 indicate that the first resonant frequency varies with lip pressure in such a way that there is a rather constant sensitivity to this parameter in the lowest range of lip pressure (ca. 0 - 150 g), whereas the sensitivity rises steeply with higher values of lip pressure.

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1) In the recording of the data plotted in the two uppermost curves in fig. 6, an STL-Ionophone was used as a sound source (the choice between a loudspeaker and a Ionophone was, however, immaterial under these experimental conditions). - The Ionophone was put at this author's disposal by courtesy of the Speech Transmission Laboratory of the Royal Institute of Technology, Stockholm.

2) With a lip pressure of 269 g, there was effective closure from the point of view of the acoustics of the clarinet. This is documented by the close agreement between values for the four lowest resonances measured under these conditions (151.2 Hz, 441.5 Hz, 706.0 Hz, and 951.7 Hz) and the values for these resonances measured (two days earlier) with the plasticine pad replacing the reed and forming a tight closure with the lay (resonant frequencies: 151.1 Hz, 441.7 Hz, 706.9 Hz, and 951.9 Hz). (The ambient temperature was 25° C in both experiments.)

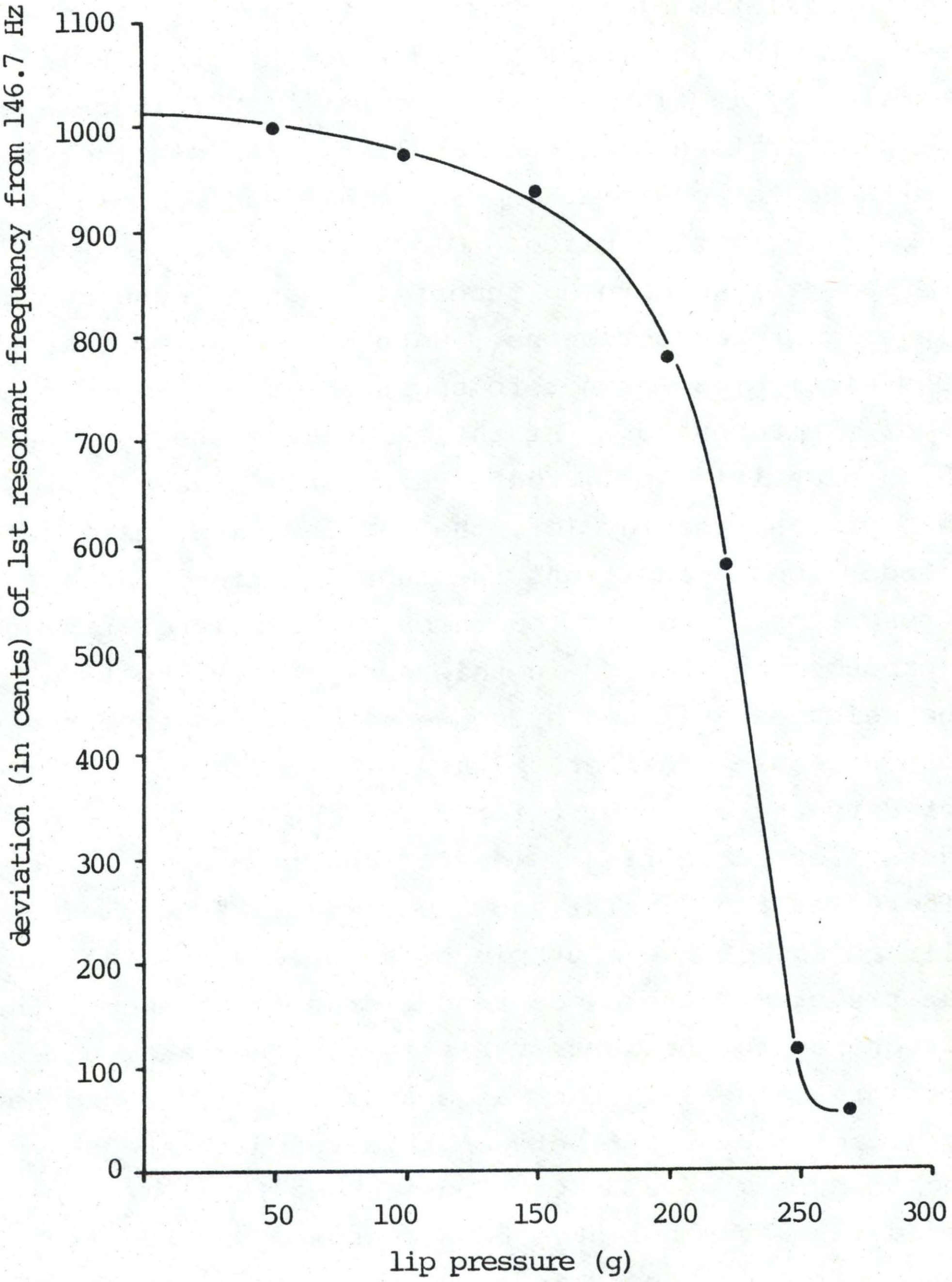

Figure 7

Diagram showing how much the first harmonic deviates (in cents) from the blowing frequency of 146.7 Hz (the note D3) as a function of lip pressure. Measurements were made at lip pressures of 0, 50, 100, 150, 200, 223, 249 and 269 g. Experimental setup as in fig. 4.

5.3 The dependence of resonance conditions on flow through the slit

One of the experimental setups used to investigate the relation between flow through the slit and resonant frequencies is shown schematically in fig. 8. The resonator in this case was the cylindrical plastic tube mentioned earlier. The clarinet mouthpiece was attached at one end, and the other end was closed by means of a closely fitting plate. Close to this latter end admittances were made for an earplug functioning as a sound source, and for the tip of a probe microphone. Care was taken to make these perforations airtight so as not to spoil the conditions at this closed end of the resonator. At the embouchure end the reed was replaced by a plasticine pad, there being only a very narrow slit between this pad and the lay (cf. the earlier experiment described in 5.2). Under these conditions the tube functioned as a (quasi-) half-wave resonator. The airflow through the slit of the mouthpiece was produced by suction in this setup, the "negative pressure" in the tube being established by connecting a hose from the vacuum cleaner to the acoustic center of the resonator. An U-tube manometer was connected to the same point for measuring P.

The data plotted in fig. 9 (deviations from F_{blow}, the latter being indicated on the Y-axis) show that when a "negative pressure" was established inside the mouthpiece (as well as in the rest of the resonator system), there occurred a drastic change of the first resonant frequency for pressure variation in the range 0-10 cm H_2O, whereas pressure changes in the range above 10 cm H_2O did not substantially affect the offset between this resonant frequency and the blowing frequency of 220 Hz. Considering that all experimental data reported in this paper have been measured in order to throw light on the parameters determining P_{thr}, it is evident that this is a crucial point.

5.4 A qualitative assessment of the resonator Q as a function of (i) flow and (ii) slit height

As mentioned in section 5.2, the external excitation does not make it possible to elicit quantitative information about the Q of the bore of a wind instrument. An arrangement that would make

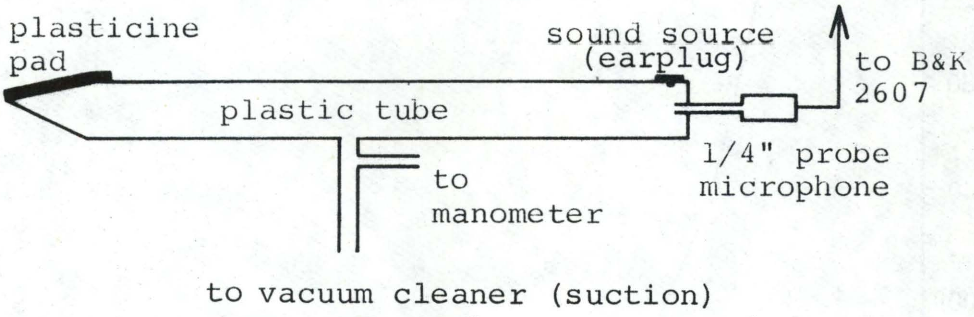

Figure 8

Schematic drawing of a half-wave resonator with a mouthpiece attached at one end, and an earplug, used as a sound source, and a probe microphone inserted at the opposite, closed end. At the mouthpiece end a tiny slit was formed between the lay and the plasticine pad which otherwise covered the opening. The hose attached to the acoustic center of the tube served to remove air by suction so as to cause a flow inwards through the slit at the mouthpiece end because of the "negative pressure" in the system.

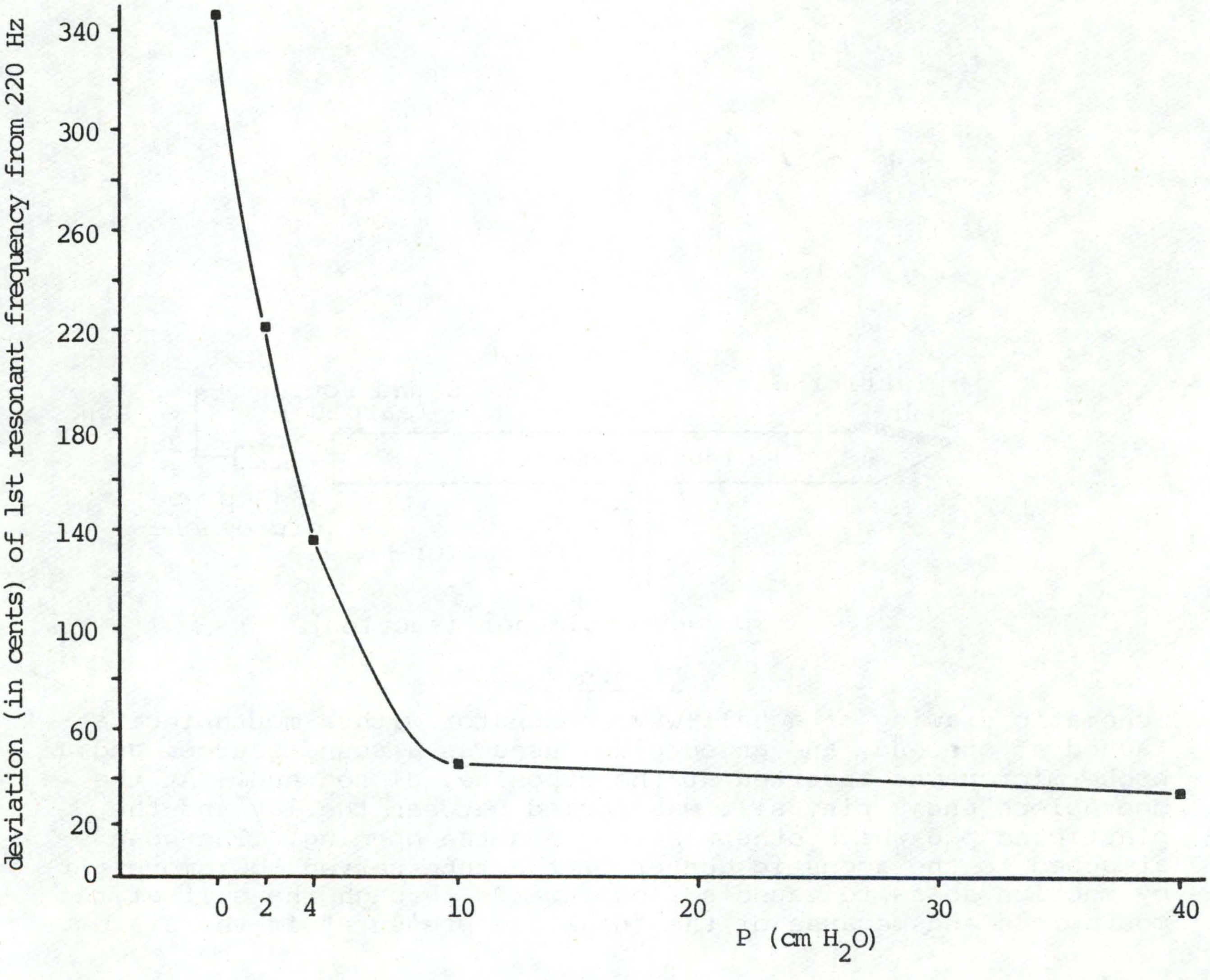

Figure 9

Diagram showing the deviation of the first resonant frequency from a reference blowing frequency, as a function of the "negative pressure" inside the system. The reference, viz. 220 Hz, represents the fundamental frequency of the tone produced by the setup with an artificial embouchure (as mentioned earlier), and a suitable "negative pressure" inside the system. (The blowing frequency had been determined in some earlier experiments.) - The setup shown in fig. 8 was employed.

such measurements possible is described by Backus (1974, p. 1266ff). It is, however, possible to acquire certain qualitative information. Figs. 10 and 11 show the results of some series of measurements illustrating how the Q varies as a function of lip pressure or of blowing pressure. (Cf. figs. 4 and 5.)

Each figure presents a series of curves recorded one after another on a B&K Level Recorder type 2305 attached to the analyzer (B&K type 2010). The curves are placed with an offset of 10 dB between each pair of curves in order to keep them visually apart. In each figure vertical (broken) lines serve to mark the harmonic frequencies for a hypothetical, naturally blown tone with a fundamental frequency of 220 Hz. The uppermost curve in fig. 10 as well as fig. 11 is a reference curve showing the frequency response of the clarinet with fingering for the note A_3 and complete closure at the embouchure end. The bottom curve shows the frequency response of the loudspeaker used as a sound source. These measurements of the frequency response were performed in the anechoic chamber, without the clarinet present and with the microphone placed at a distance from the loudspeaker corresponding to the length of the clarinet plus 50 cm. The other curves (i.e. the resonance curves) were measured with the same setup except that the clarinet was placed adjacent to the probe microphone (thus with a distance of 50 cm between the open end, the flare, of the clarinet and the loudspeaker). The analysis was made automatically, using the sweep tone from the tone generator of the analyzer, geared to the level recorder.[1]

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1) The determination of frequencies from these automatically recorded curves is inherently less accurate than the results obtained with manual operation of the analyzer, as used for the other experimental series reported on here (cf. section 5.2). Backus has estimated that frequencies determined from automatically recorded curves "should be accurate to within some 20-30 cents" (Backus 1968, p. 1276). As for the frequency axis, Backus' curves and the curves shown in this paper differ very much. (Backus used a paper speed three times lower than the one employed by the present author, but it seems reasonable to assume that the accuracy of frequency measurement does not differ markedly for that reason, the limitations of accuracy having to do with the use of automatic registration rather than with the paper speed. Thus the determination of frequencies from the curves in the present case may be assumed to exhibit the same degree of accuracy as Backus' measurements.)

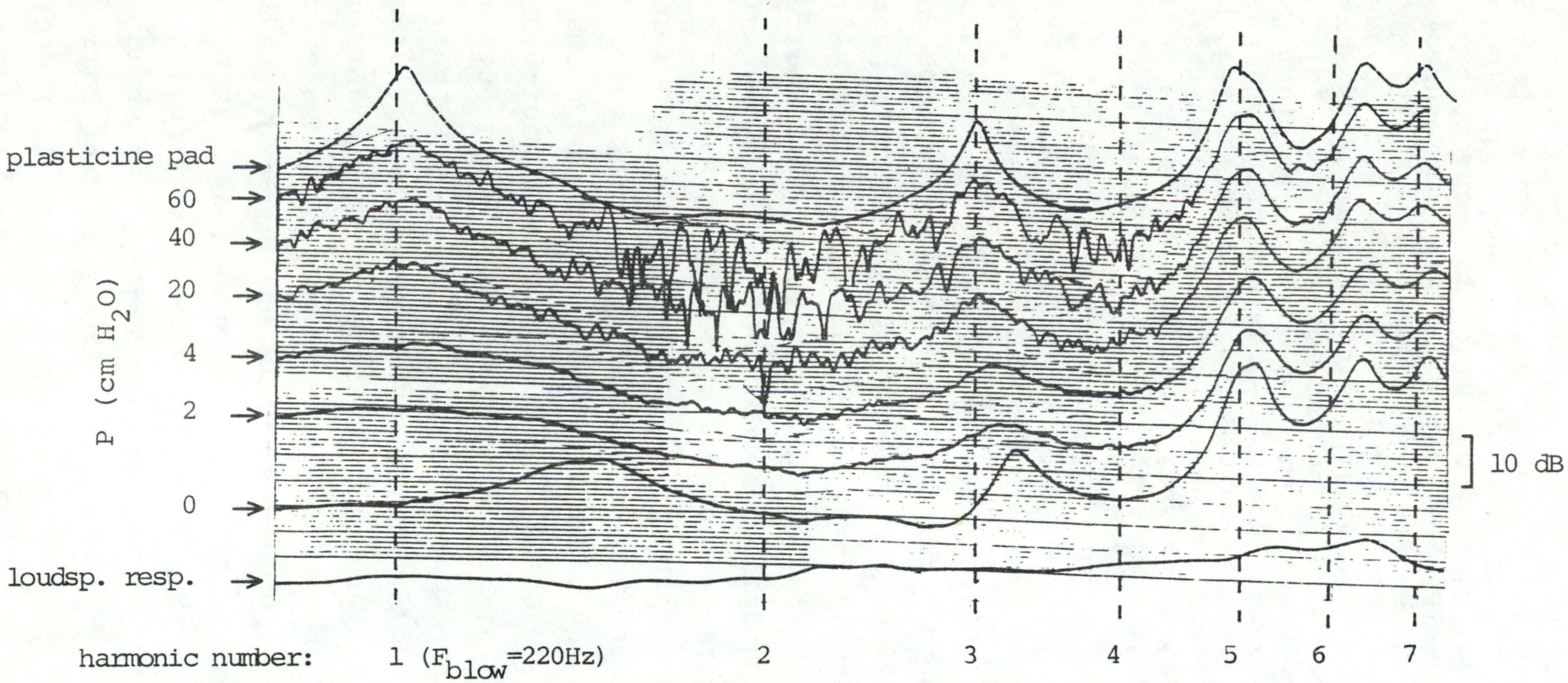

Figure 11

Automatically recorded impedance curves made with the setup shown in fig. 5 and fingering as for the note A_3. The uppermost and the lowest curves are reference curves corresponding to those of fig. 10. The intermediate curves were recorded with the following values of blowing pressure: 0, 2, 4, 20, 40 and 60 cm H_2O. A hard-walled slit was used in order to keep H constant during the recording of the impedance curves. - The skewness of the graph is due to optical distortion in the copying process.

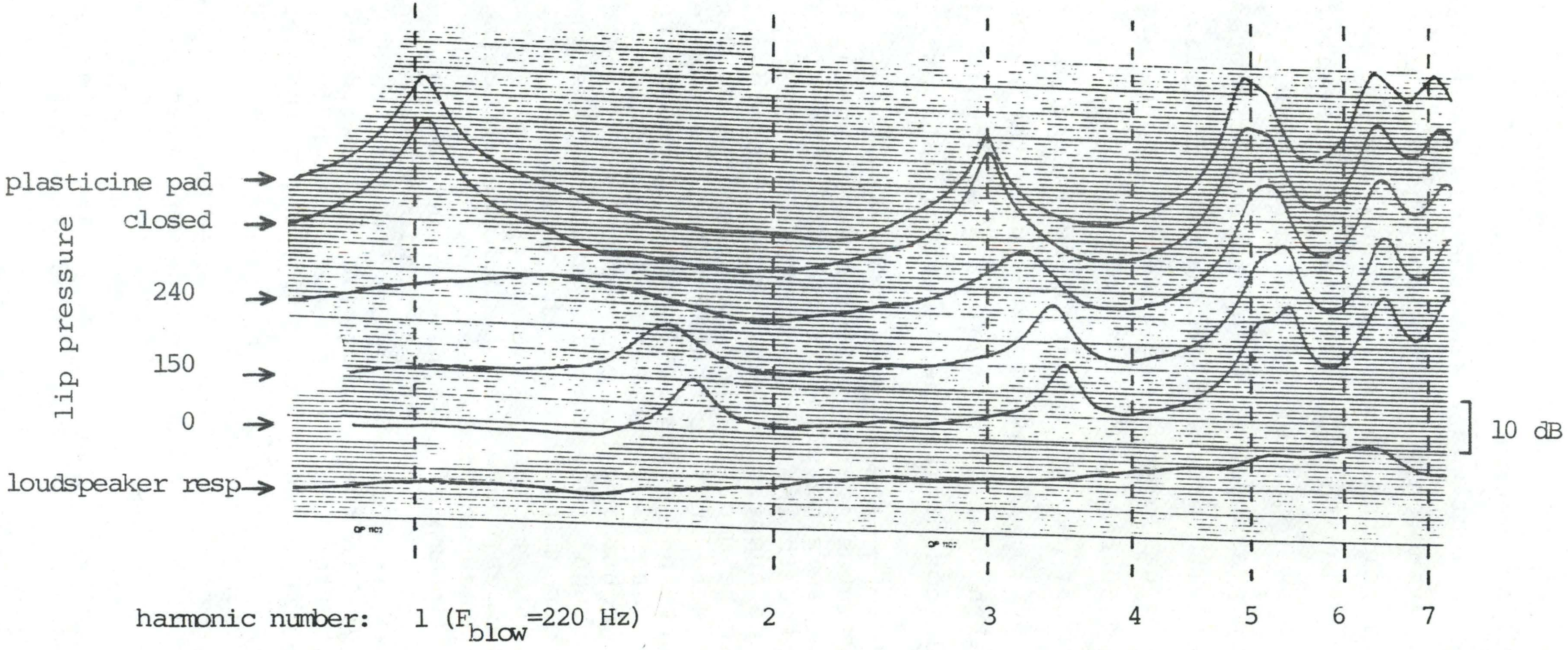

Figure 10

Automatically recorded data produced with the setup shown in fig. 4, and with fingering as for the note A_3. The lowest curve shows the amplitude response of the loudspeaker with the clarinet removed from the setup in the anechoic chamber. Curves nos. 2 to 4 from bottom are impedance curves for lip pressures ranging from 0 g over 150 g and 240 g to "high lip pressure". The uppermost curve, which was recorded on a different occasion, is an impedance curve showing the performance of the system with a plasticine pad replacing the reed and forming an airtight closure with the lay. - Here and in fig. 11 the curves are placed with a mutual offset of 10 dB. The vertical broken lines in figs. 10 and 11 mark the frequencies of the harmonics corresponding to a fundamental of 220 Hz. - The skewness of the graph is due to optical distortion in the copying process.

The difference between the two series of experiments was that in the case of fig. 10 the variable parameter was lip pressure (or the resulting slit height, which is dependent upon lip pressure), there being no suction, whereas in the case of fig. 11 the reverse obtained: the slit height was fixed, the reed being replaced by a metal strip leaving only a gap with a height of a small fraction of a mm at the tip of the mouthpiece, and the pressure drop across the slit was varied instead. In the first series the lip pressure was chosen so as to produce a variation in H_{II}/H_I ranging from 1 (at 0 g lip pressure) to 0 (at maximum lip pressure). In the second series, i.e. with pressure drop across the slit as parameter, the following values of the pressure difference were used: 0, 2, 4, 20, 40, and 60 cm H_2O.[1]

Although the independent variable controlled in the experimental series presented in fig. 10 was lip pressure, the parameter of direct interest is slit height. The two being obviously directly correlated (see fig. 3b concerning the general relationship

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[1] In reports on related investigations of the impedance as a function of airstream it is mentioned that turbulence in the airstream causes trouble for the measurements (Backus 1963, p. 311; Coltman 1973, p. 418). The question, then, is why the present series of recordings could be made in the presence of flow without posing serious problems. Note in this context that there were no sudden increases of the internal cross-sectional area downstream, as seems to have been the case with the setup used by Coltman for his measurements. On the contrary, the cross-sectional area inside the mouthpiece expands in such a way that it performs like an effective diffuser of the air streaming through the mouthpiece (cf. Ower and Pankhurst 1969, p. 110ff.). Thus it is very possible that there may, in specific circumstances, have been turbulence affecting Coltman's measurements. Presumably, in designing the mouthpiece, instrument designers have attempted to minimize such turbulence by giving the mouthpiece a quasi-conical shape. This explanation of the shape of the mouthpiece is corroborated by the fact that it is crucial to have laminar flow in the vicinity of the slit, even at high rates of flow. The better the flow passes straightly through the slit and onwards along the inner side of the reed, the more effectively will the (alternating) height of the slit be influenced by the Bernouilli force during tone production.

If the present measurements were less affected by noise from turbulent air than seemed to be the case in the experiments made by Backus under otherwise identical conditions, the reason probably is that the present author used a sweep tone with a very high sound pressure level (the loudspeaker producing its maximum effect according to specifications), because this had proved expedient. Thus the signal passing via the bore of the clarinet into the microphone probe in the mouthpiece has been so intense that noise from the flow has not been able to override it completely and hence to upset the recording of the response curve of the instrument.

between lip pressure and H_{II}), it may be concluded that these curves give just as reliable information on the impedance characteristics of the resonator as a function of slit height.

The most interesting feature of figs. 10 and 11 is that essentially the same changes occur, both with respect to resonant frequencies and with respect to the Q of the resonator at the various resonances (as indicated by the peakedness of the curves), irrespective of whether one or the other parameter is chosen as the independent variable. This similarity is most conspicuous for the first resonant mode. Note that for this mode one finds the highest resonant frequency when H is at its maximum, or P_{blow} at its minimum). Under these conditions one also observes a resonant peak indicating a fairly high Q. When the influence of the parameter in question is increased, changes occur which exhibit two distinct phases. In the first phase the resonant frequency is shifted downwards by a substantial amount, and the flattening of the peaks indicates a very considerable reduction of the Q (see the first resonant peak at 240 g lip pressure in fig. 10 and, correspondingly, at a P_{blow} of 4 cm H_2O in fig. 11). The second phase (i.e. the situation when the influence of the parameter in question is increased further) is characterized by two features: (i) the Q is increased (i.e., the influence on Q is reversed), and (ii) the resonant frequencies asymptotically approach a set of values which are only slightly higher than the ones measured with complete closure at the mouthpiece end (see the uppermost curve in figs. 10 and 11).

Since the presentation of data in this section is confined to analyses of the conditions for the note A_3, it is essential to emphasize that tracings made for other notes recorded under identical conditions, exhibit quite analogous shifts in resonant frequencies and Q as described for the note A_3.

Returning to fig. 9 it may be added that a similar effect - with two distinct phases - was found in experiments using the half-wave resonator and producing a stepwise increase in the flow through the slit by varying P. There was, however, a difference of degree in that the aperture occurring at the tip of the mouthpiece under these conditions was so small that the effect of the flow on the acoustic impedance and hence on the resonant properties was much less pronounced. Therefore, the first resonant frequency and the Q (which is not documented in this report) changed less as a function of variations in the parameter involved than in the experiments to which fig. 11 refers.

6. Discussion

Curves such as the one in fig. 7 and the next lowest curve in fig. 10 (lip pressure: 0 cm H_2O) suggest that as long as the combined reed-resonator system of the clarinet is not influenced by the player's embouchure, the tube acting as a resonator is a hybrid transitional type, being something in between a half-wave resonator and a quarter-wave resonator, although it is more closely related to the latter. It is seen from the same figures that the characteristics of the resonator become successively more like those of a quarter-wave resonator the more the player reduces the cross-sectional area of the aperture at the embouchure end (i.e. the slit) by means of his lip pressure.

It should be mentioned in passing that the blowing pressure applied by the player will contribute further to move the reed inwards toward the lay because of the pressure difference between the layers of air at the outside and at the inside of the reed. At the flexible tip of the reed the pressure drop is, furthermore, influenced by the Bernouilli effect which varies during a vibratory cycle because of the flow through the slit (cf. Benade 1976, p. 438). The issue here is, however, the acoustic effect of flow on the characteristics of the resonator as documented by the curves in fig. 11 and the curve in fig. 9. In agreement with results from numerous other similar measurements performed as part of the present project, these curves show that the clarinet bore behaves like a quasi-quarter-wave resonator if the blowing pressure exceeds a certain value, even though the clarinet is not totally closed at the embouchure end. This relationship is, of course, particularly important for the interpretation of the behaviour of the clarinet when there is not a complete closure between the reed and the lay during any interval within a vibratory cycle.

We return to the issue raised in section 1 of this paper. For obvious reasons a closure of the slit during tone production cannot be accomplished by using lip pressure (which would prevent the reed from oscillating). Thus the only type of sustained closure available is "acoustic closure".

The curve in fig. 9 may seem to indicate that a blowing pressure slightly exceeding 10 cm H_2O would suffice to establish this "acoustic closure". The values measured for P_{thr} spread evenly from some 10 to some 30 cm H_2O. It should be noted, however, that the clarinet reed used in these experiments had not been exposed to humidity except for that of the atmospheric air. In natural blowing the air exhaled by the player will cause the reed to absorb humidity because of condensation. If the reeds had been exposed to a similar absorption of humidity in connection with the present measurements, all measures of P_{thr} given in this report would have been slightly lower (the difference being of the order of a few cm H_2O, according to this author's estimate).

It may be added that in laboratory experiments involving artificial embouchure it is not very difficult to adjust the embouchure to a much lower P_{thr}. Thus, by using a soft plastic reed it proved possible to get a P_{thr} of no more than 6.6 cm H_2O. (In that extreme case the excitation was of no importance from the point of view of musical applications since no audible tone was produced. Vibrations of the air were, however, recorded via the probe microphone picking up the alternating pressure inside the mouthpiece, and were visible on the oscilloscope screen.)

This concludes the report on experiments serving to determine the influence of the parameters in question on P_{thr}.

7. Goals of the research project in its totality

As stated in the introductory section, this paper is confined to one aspect of the complex of relationships which must be studied in order to arrive at a complete description of clarinet embouchure. The results presented here are useful as a basis for further research on the acoustics of the clarinet and the conditions obtaining in blowing. This further research has been undertaken on the basis of a wealth of experimental data gathered during the work with the project but in part still awaiting processing.

One of the obvious tasks for further investigation is to examine what happens if the blowing pressure is increased successively as the only independent parameter, for given values of the other two parameters: lip position and lip pressure. The present author has found that this is a useful way of acquiring insight into the influence of the just mentioned parameters on the spectral composition of the tone, as well as on the dynamics of clarinet playing. It would lead too far to give details here, but it may be mentioned that the data clearly indicate that it is quite crucial both for the spectral composition of tones and for the dynamics how the two parameters conditioning H_{II} (cf. the graph fig. 3b) are weighted in relation to one another. Thus the following passage from Nederveen (1969, p. 36): "... the player has a wide choice of lip positions. So the mere excitation of the instrument is not very critical" can hardly be considered generally valid. It must be understood in the context of the specific assumptions on which it was based.

According to the experience gained from the experimental data of the present project it must be the case that a shift in lip position of the order of 1 mm or less may have a significant effect, e.g. on the timbre of the tone and on the dynamic variations which the clarinet player is able to perform.

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