Quality of Organ Tones

HARVEY FLETCHER, E. DONNELL BLACKHAM, AND DOUGLAS A. CHRISTENSEN

Brigham Young University, Provo, Utah
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The tones were produced by the pipe organ in the Smith Auditorium at Brigham Young University. They were picked up by a microphone placed at various positions in the auditorium and recorded on magnetic tape. The tape was taken into the laboratory where analyses of the tones were made. The structure of full organ tones becomes very complicated. For example, when the three keys for the major chord were depressed, there were 229 partials whose frequency and level were measured.

After the analysis of the tone was made, a synthetic tone was constructed by our synthesizer. Judgment tests were made by juries to see if synthetic tones could be distinguished from real tones. These juries were unable to distinguish between them. The paper discusses musical warmth. It shows that it is definitely related to the level variation of the partials. These variations are due to the frequencies of several partials being close together, causing beats.

Methods and apparatus were developed so that a tone could be warmed to any extent without using the large number partials produced in the pipe organ. A method of rating the warmth of organ tones is proposed and will be used in our future work on all musical tones.

THIS paper reports that part of our general research study of the quality of musical tones which is concerned with organ tones. The general procedure used in this study is the same as used in our study of piano tones, and which was described in the paper[1] on piano tones. Briefly stated it is as follows. The organ tone is recorded on tape. The tape is then used for analyzing the tone. Next, a synthetic tone is produced from this analysis and then compared to the real tone by judgment tests. This is followed by a search for new synthetic tones that are considered interesting and useful by a jury of musicians. The synthesizer, frequency shifter, and other apparatus are the same as used in our study[1] of piano tones.

The real organ tones were obtained from the organ that was formerly in the Salt Lake Tabernacle and now installed in the Smith Auditorium at Brigham Young University. The auditorium is considered very good for musical performances. The reverberation times (T) are given below for tones of the frequencies shown.

f=50	100	200	500	1000	2000	3000	4000	cps;
T=1.6	1.4	1.4	1.4	1.4	1.7	1.3	1.5	sec.

[1] H. Fletcher, E. D. Blackham, and R. Stratton, J. Acoust. Soc. Am. 34, 749–761 (1962).

Some of the organ tones were sustained for 40 or 50 sec and recorded on our tape recorder. Others had duration times about the same as those used in playing the instrument. The reel of tape was then transferred to the tape recorder controlled by a "frequency-shifter." The use of tones of long duration made it easier to obtain an accurate analysis of the partial structure of the tone.

ANALYSIS OF ORGAN TONES FROM SINGLE PIPES

Analyses were made of the following organ tones produced by single pipes: namely, G‴, G″, G′, G, G_1, and G_2, the G‴ being the third bass G below middle C, and G_2 being the third treble G above middle C. These tones were produced by use of typical stops from the four families of organ tone:

Flutes —Gedeckt 8′
Strings —Gamba 8′
Diapasons—First Diapason 8′
Reeds —Fagotto 8′.

From this analysis a synthetic tone was created by the synthesizer. The analysis was considered satisfactory only when a comparison between the synthesized and real tones showed that the two sounded alike. The attack and decay characteristics were duplicated approximately by turning the dials to the corresponding proper position on the attack and decay amplifiers. In order to match the decay characteristics more exactly the synthetic tone was produced in one of the laboratory rooms having about the same reverberation characteristics as the auditorium and the sound then picked up by a microphone and recorded on magnetic tape.

The measurement of the partial structure of the organ tones revealed that the partials were harmonics within the observational error of our measurements, which was about 1 cycle in 1000. To illustrate this, the measurements of the frequencies of the first fourteen partials of the diapason tone G'' and the reed tone G'' are given in Table I.

The data for the 24 analyzed organ tones from single pipes are shown in the charts of Fig. 1.

The points represent the sound-pressure levels (SPL's) of the partials of the four kinds of organ pipes. These levels correspond to that produced in the auditorium at about one-third of the distance from the organ to the back of the hall. The wide-band wind-noise level at this location, which was produced when the organ was turned on, was found to be approximately 50 dB$\pm$3 dB. For example, the SPL of the fundamental of the G''' diapason pipe was found to be at 76 dB, which was 26 dB above the wind noise. The wind-noise level in $\frac{1}{2}$-octave bands was measured, and from this the levels in the critical bands were calculated. The results are given by the solid curves in the charts. As is well known, this curve is also the threshold of hearing for pure tones in the presence of this wind noise. It is seen that the 12th, 13th, and 14th partials of the string tone G'' are below the threshold of hearing, and consequently could not be heard. But they could be measured because the bandwidths in our analyzer were much narrower than the critical bandwidth.

In many cases the levels of the organ tones from single pipes are not much above the wind noise. When only a single pipe was speaking, the noise was very prominent. However, when the full organ was playing, the sound-pressure intensity level was 85 to 90 dB, so the wind noise was not noticeable.

TABLE I. Frequencies in cps of the partials of a single-pipe reed tone and diapason tone.

No. of partial	Frequency (reed)	Frequency (diapason)
1	98	99
2	196	198
3	294	297
4	392	396
5	490	496
6	587	594
7	686	694
8	784	791
9	882	891
10	979	989
11	1079	1089
12	1176	1188
13	1274	...
14	1372	...

SYNTHESIS AND IDENTIFICATION TESTS OF TONES FROM SINGLE PIPES

The harmonic structures shown in Fig. 1 were used to produce synthetic tones. In the first trial a constant decay rate was used for all the partials. A comparison of such synthetic tones to real organ tones showed that the real tones could be identified without too much difficulty due principally to the very different decay characteristics.

In the second trial the synthetic tones were produced in a room having similar reverberation characteristics to those in the auditorium. Also wind noise was introduced into this room, which had the same relative level to the tone as that in the auditorium. The tone and noise were then picked up by a microphone and recorded. In both trials wind noise at the proper level was introduced into the recording.

Using the second technique, a program consisting of real and synthetic tones was made for identification tests. The program in Table II illustrates the order in which these tones were presented for judgment tests of reed tones. The (S) indicates synthetic tones and the (R) indicates real tones.

TABLE II. Program of tests on single-pipe organ tones.

Tone 1 $G''(S)$	Tone 13 $G'''(S)$	Tone 25 $G'(R)$
Tone 2 $G_1(S)$	Tone 14 $G(S)$	Tone 26 $G(S)$
Tone 3 $G_2(S)$	Tone 15 $G''(S)$	Tone 27 $G_2(S)$
Tone 4 $G'''(S)$	Tone 16 $G'(S)$	Tone 28 $G(R)$
Tone 5 $G_2(R)$	Tone 17 $G''(R)$	Tone 29 $G''(R)$
Tone 6 $G(S)$	Tone 18 $G_2(S)$	Tone 30 $G_2(R)$
Tone 7 $G'(S)$	Tone 19 $G_1(R)$	Tone 31 $G_1(S)$
Tone 8 $G'''(R)$	Tone 20 $G_1(S)$	Tone 32 $G'''(R)$
Tone 9 $G''(R)$	Tone 21 $G(R)$	Tone 33 $G_1(R)$
Tone 10 $G(R)$	Tone 22 $G'(R)$	Tone 34 $G'''(S)$
Tone 11 $G'(R)$	Tone 23 $G'''(R)$	Tone 35 $G''(S)$
Tone 12 $G_1(R)$	Tone 24 $G_2(R)$	Tone 36 $G'(S)$

A similar program was set up for the string tones.

A jury of nine persons having had musical training from 2 to 15 years listened to these tones and marked on a data sheet which they thought were the real tones. The results of these judgment tests are presented in Table III.

There were 36 tones in the test. When the number judged to be correct is near 18 or less, the observer is simply guessing. It will be seen that none of the observers could recognize the difference between the real and the synthetic tones. It is therefore concluded that synthetic tones can be made to sound like real tones from single pipes.

The synthetic tones have one great advantage; namely, the wind noise may be eliminated.

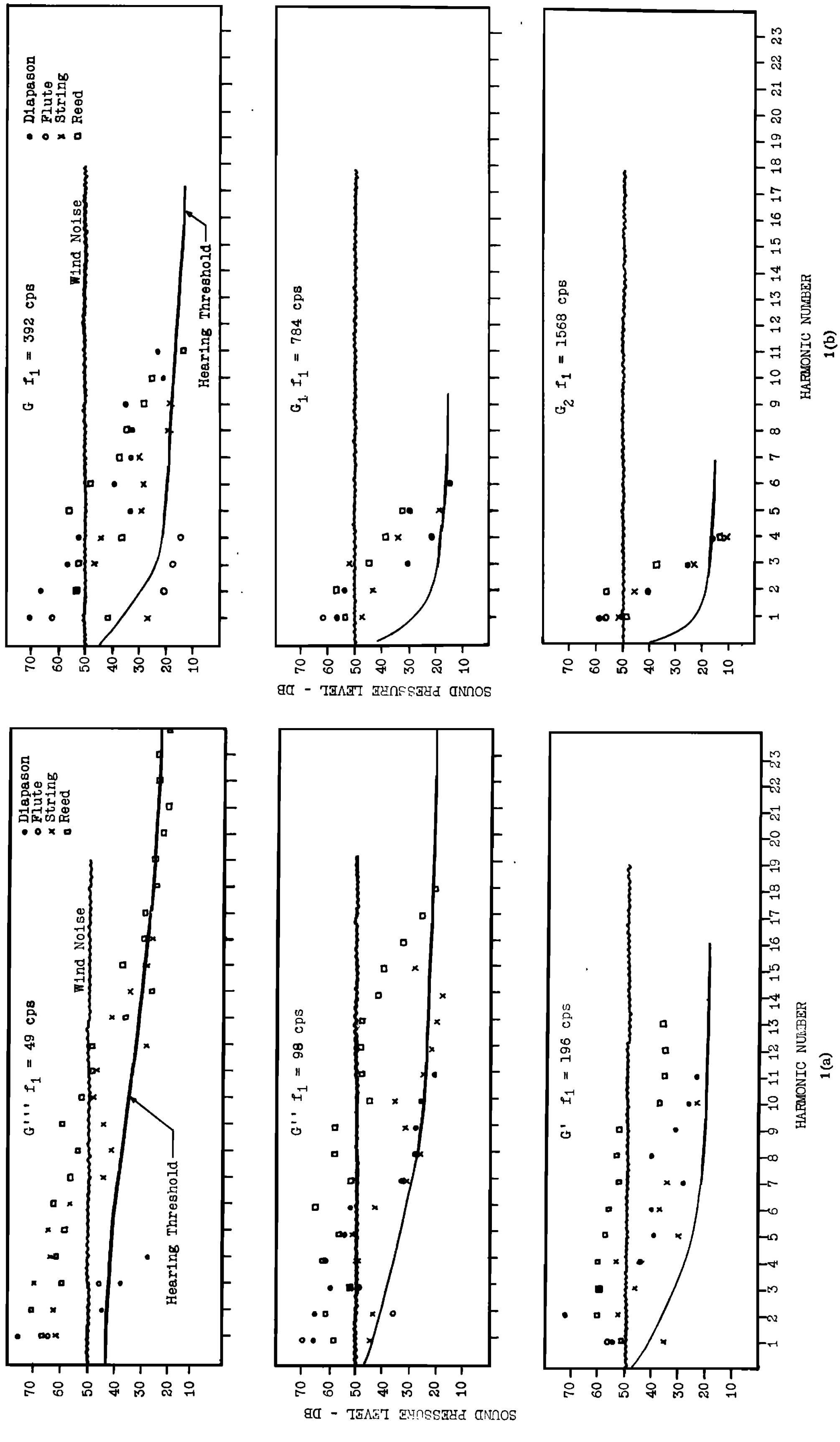


FIG. 1. Levels of G''', G'', G', G, G_1, and G_2 organ tones from single pipes. The solid curves represent the wind noise computed for critical bands from measurements in half-octave bands.

EFFECT ON HARMONIC STRUCTURE OF LISTENING AT DIFFERENT POSITIONS IN THE AUDITORIUM

As is well known, the harmonic structure of a sustained organ tone is different in different parts of the auditorium due to the standing wave pattern. To show the extent of this effect the harmonic structure of G‴ (reed) tone from a single pipe was taken at three different positions in the hall, which were about ten feet apart. The data presented in Fig. 2 give the results. The three points on each partial ordinate give the three values of the sound-pressure level at three positions. It will be seen that the levels of the harmonics vary 10 or 15 dB, depending upon the position in the auditorium. It is obvious then that a recording of the tone at each of these three positions should result in three tones of different quality. Judgment tests with such recordings confirmed that these differences in quality were greater than any difference between the synthetic and real tones discussed above.

TABLE III. Number correct out of 36 tries in judgment tests on single-pipe organ tones.

	Strings	Reeds
	15	22
	17	16
	18	12
	15	14
	27	13
	17	17
	18	18
		19
		16
Average	18.6	16.3

CHARACTERISTIC PARTIAL STRUCTURES OF REED, STRING, DIAPASON, AND FLUTE ORGAN TONES

Boner[2] and others have made measurements of the harmonic structures of such tones. Even when the blowing is under laboratory control and free from wind noise, the differences between the tones from these four classes of organ tone are not too clearly defined, as will be seen from examining his curves. The analysis shown by the curves in Fig. 1 is subject to the variations found in the auditorium, as shown in Fig. 2. However, one can deduce the following general characteristics.

Reed tones. In the lower three octaves, the first nine partials have approximately the same SPL. From the ninth to the twentieth, the level decreases at about 4 or 5 dB per partial. For G, G_1, and G_2, the first three or four partials have equal levels, then they decrease in level per harmonic approximately 6 or 8 dB per octave.

String tones. In these tones the levels are about 5 or 10 dB lower than the reed tones. For the lower three octaves only the first four or five partials have the same level and then decrease in level per partial about the same as the reeds.

[2] C. P. Boner, J. Acoust. Soc. Am. **10**, 32–40 (1938).

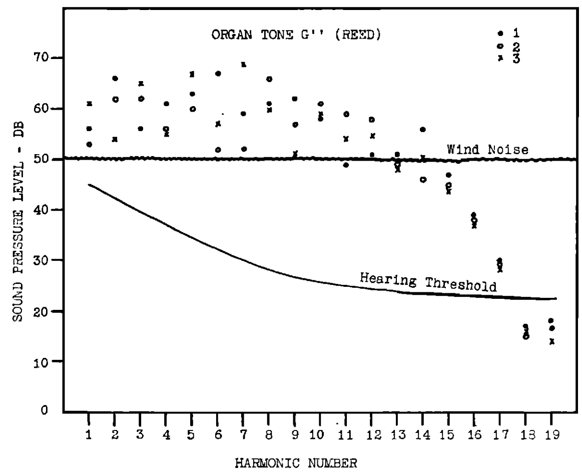


FIG. 2. Reed-organ tones at three positions in auditorium.

Diapason tones. These tones produce the highest levels, being from 5 to 10 dB above the reed tones. Only two or three of the first partials have the same level, and then the level of the harmonics decreases at the same rate as the reed tones.

Flute tones. These tones are in a class by themselves. The even partials are extremely low in level. The third and fifth partial tones are near the threshold of hearing in the noise. The flute tones are characterized by being almost pure tones.

COMBINATION AND FULL ORGAN TONES

A pipe organ of modest proportions is sufficient to offer to the performer a large variety of tone color by the addition of stops in different combinations. Each stop has its characteristic tone color, and for the most part consists of a separate pipe for each key encompassed in the range of the keyboard. In other words, when the first diapason 8′ stop is activated and a G key played, there is a corresponding G pipe which sounds. By adding stops it is possible to have one or many pipes sounding for each key played.

A part of this study is the investigation of the effect upon the partials of a tone by the addition of stops which introduce new pipes into the ensemble. Twelve stops were selected from all the stops found on the organ in the Smith Auditorium. These stops were selected because each produced an audible effect when added consecutively to the rest. The stop list is as follows:

No. 1 First Diapason 8′
No. 2 Second Diapason 8′
No. 3 Gedeckt 8′
No. 4 Principal 4′
No. 5 Octave 4′
No. 6 Twelfth $2\frac{2}{3}$
No. 7 Horn Diapason 8′
No. 8 Fifteenth 2′
No. 9 Fagotto 8′
No. 10 Trompette 8′
No. 11 Clarion 4′
No. 12 III Mixture.

TABLE IV. Frequencies in cps present in a combination organ tone consisting of a G-major triad with twelve stops.

Partial	First diapason 8′	Second diapason 8′	Gedeckt 8′	Principal 4′	Octave 4′	Twelfth $2\frac{2}{3}$	Horn diapason 8′	Fifteenth 2′	Fagotto 8′	Trompette 8′	Clarion 4′	III mixture
G1	393.5	393.5	394				388		388	389		
B1	497	497	495				488		487	489		
D1	591	591	591				580		580	581		
G2	787	787	788	787	786		776		776	778	775	785
B2	994	992	990	990	989		976		974	978	975	988
[D2]	1182	1182		1176	1177	1182	1160		1160	1162	1158	1176
[G3]	1181	1181					1164		1164	1167		
B3	1491	1488	1485			1191	1464		1461	1467		
G4	1574	1574		1573	1571		1552	1575	1552	1556	1550	1570
D3	1773	1773				1777	1740		1740	1743		
[G5]	1968	1968					1940		1940	1945		
[B4]	1988	1984	1980	1980	1979		1952	1987	1968	1956	1950	1976
[D4]	2364	2364		2352	2354	2364	2320	2360	2320	2324	2316	2352
[G6]	2361	2361		2360	2356		2328		2328	2334	2325	2355
B5	2485	2480					2440		2435	2445		
G7	2755	2755					2716		2716	2723		
[D5]	2955	2955					2900		2900	2905		
[B6]	2982	2976		2970	2967	2982	2928		2922	2934	2925	2964
G8	3148	3148		3146	3142		3104	3150	3104	3112	3100	3140
B7	3479	3472					3416		3409	3423		
[D6]	3546	3546		3528	3521	3554	3480		3480	3486	3474	3528
[G9]	3542	3542				3546				3505		
[G10]	3940	3940		3933	3927				3880	3890	3875	
[B8]	3976	3968		3964	3956		3904	3974	3906	3912	3900	3952
D7	4137	4137					4060		4060	4067		
G11	4329									4279		
B9	4473					4474			4383			
[D8]	4728			4704	4696	4728		4720	4640	4648	4632	4704
[G12]	4722			4719				4725		4668	4650	4710
B10				4950	4045				4870	4890	4875	4940
G13										5057		
D9										5329		
B11										5379		
G14				5506								
D10				5880						5810	5790	
B12				5940		5964		5961		5868	5850	5928
G12						6300						
D12								7080				

In the nomenclature of organ stops are found numerals denoting the pitch length of the respective stops, viz.: 16′, 8′, 4′, and 2′. 8′ denotes normal pitch and produces a tone the same pitch as the corresponding key depressed. A 4′ stop will cause a tone to sound an octave higher than the key depressed, 2′ two octaves higher, and 16′ one octave lower. A harmonic brilliancy in a tone can be achieved by the addition of stops of different pitch lengths. Among organ stops can also be found mutations and mixtures. A mutation such as the twelfth $2\frac{2}{3}$ produces a tone an octave and a fifth above the key played. Mixtures are used as a means of supplying artificial harmonics that will contribute to the brilliancy of the tone.

The tone used for analysis was the G-major triad. The three notes of the triad (G, B, and D) were played simultaneously as each stop was added until the 12-stop ensemble was built up. A recording was taken of each successive step at three different positions. The positions were about ten feet from each other and in front of the organ at one-third the distance from the organ to the back of the auditorium. A sound-level meter placed at these positions indicated that the total SPL was varying about an average of 80 dB. A recording was also made of the tones from the G, B, and D pipe from each individual stop. Each stop contributed three pipes to the G-major triad, with the exception of the III mixture, which added nine pipes. The final 12-stop tone contained a total of 42 pipes.

As a recording had been taken of each separate pipe, it was possible to obtain the fundamental frequency of that pipe more accurately than had two or more pipes been sounded together. The fundamental was determined by dividing the observed frequencies by the corresponding number of the component and then averaging the results.

Table IV is a compilation of all the frequencies present in the G-major triad produced by twelve stops. The harmonic frequencies are the integral multiples of the fundamental of each pipe. G1, B1, and D1 are used to identify the fundamentals generated by each pipe; G2, B2, and D2 identify the second partials; G3, B3, and D3 identify the third partials, etc. The vertical columns present the frequencies present in the three pipes from each stop. A horizontal reading of the table will give all the frequencies associated with any given partial. Brackets indicate that the frequencies of the enclosed partials were too close together to be effectively resolved by the analyzer, had they been sounded together.

Some interesting observations can be made from this table. The 42 pipes sounding together produce a total of 229 measured frequencies. Of the 229 frequencies there are 182 different frequencies. If all the pipes were exactly in tune, there would be only 38 different frequencies. The beating between many of these frequencies that are close together would certainly be a contributing factor to the warmth of the tone, which will be discussed later in this paper.

The tone produced by an 8′ pipe contains all integer multiples of the fundamental. A 4′ pipe has a fundamental an octave higher and reinforces all the even partials. A 2′ pipe has a fundamental 2 octaves higher and reinforces the 4th, 8th, 12th, 16th, etc. partials.

From Table IV it can be noted that stop Nos. 7, 9, 10, and 11 produce frequencies that are somewhat out of tune with the remainder of the stops. This can be explained by the fact that the pipes from these four stops are enclosed in a swell box of the organ. This box is equipped with shutters across the front, which serve as a means of varying the dynamics of this section of the organ. The swell box had been closed during the evening prior to when the recordings were made, with the result that these pipes had not warmed up to the room temperature and were sounding flat with the rest of the organ.

Due to the fact that the organ was out of tune when the recordings were taken, the range of the frequencies associated with any one partial is rather wide. These ranges are not as wide but, nevertheless, present in the tones that are analyzed and discussed in the following sections of this paper.

The relative levels of the partials were measured in the laboratory. These observed values were difficult to determine accurately due to the fact that the level of the partial was not constant but varied with time as much as 10 dB. It was not only difficult to determine the level, but also difficult to set the analyzer to obtain the proper maximum reading and thus accurately determine the frequency. In some cases the beating pattern enabled an estimate of the relative levels at two frequencies.

Further inquiry was made into the range of frequencies associated with a given partial. The type of results obtained from this inquiry is presented in Table V. The partial G2 will serve as an example. The analyzer was set at the various frequencies associated with this partial and the 12 triads produced by the addition of stops. These results give the SPL in dB.

By underscoring the highest SPL in each column, it can be noted that the highest level associated with the partial shifts from the highest to the lowest frequency as the stops are added. The same results can be obtained by turning the analyzer into the highest level in the frequency range of the harmonic.

TABLE V. SPL in dB at nearby frequencies as stops are added.

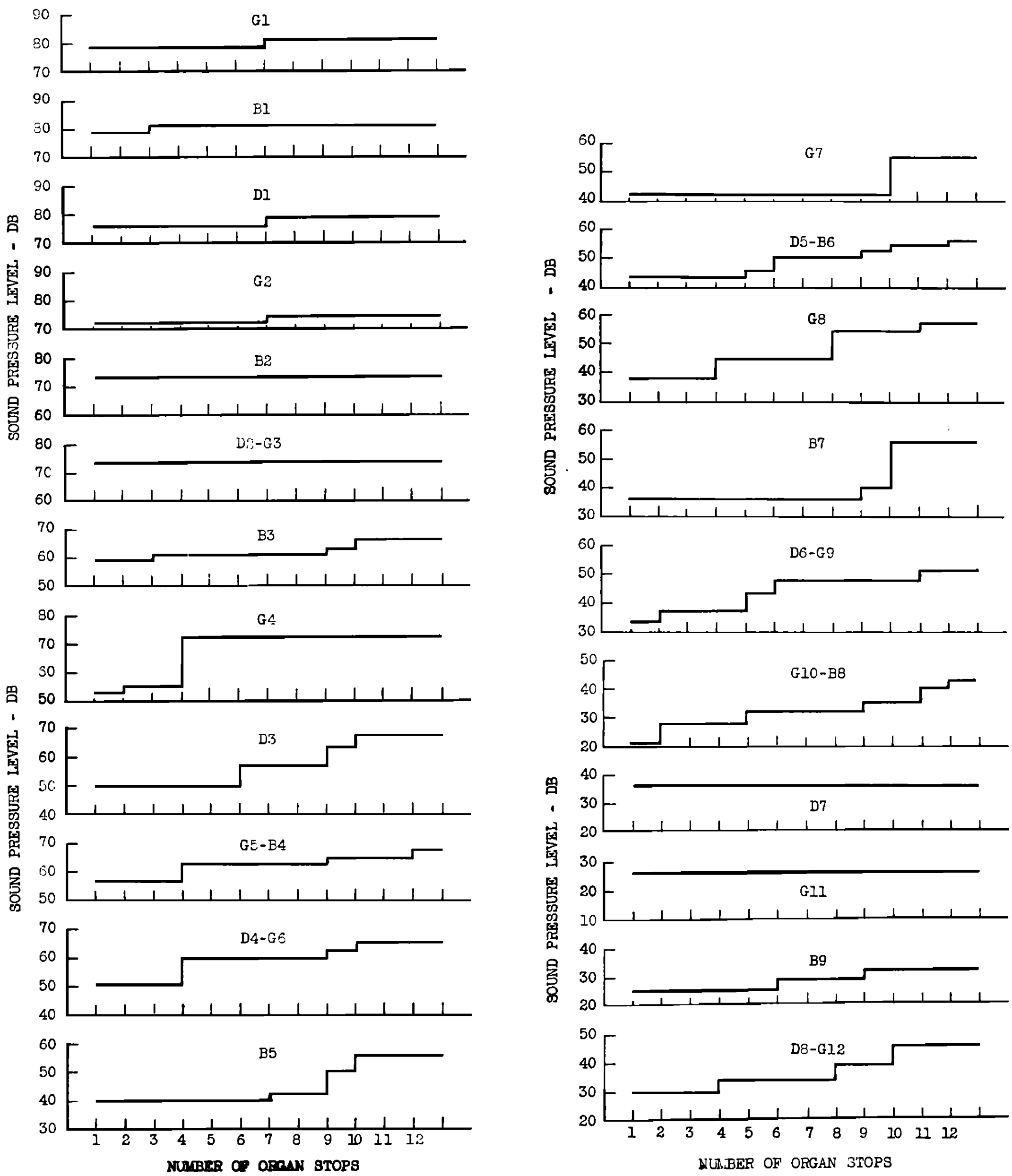
	Stop number											
F, cps	1	2	3	4	5	6	7	8	9	10	11	12
775	35	33	39	44	48	50	65	*65*	*66*	*66*	*65*	*70*
776	33	35	40	45	51	55	64	64	*66*	*66*	63	67
778	38	40	45	52	56	60	63	*65*	65	65	64	67
785	59	*61*	*62*	*70*	*69*	*69*	*68*	62	62	65	60	65
786	*61*	*61*	60	68	*69*	68	67	61	59	60	55	63
787	*61*	*61*	61	66	64	60	57	57	55	53	51	60
788	*61*	*61*	61	66	61	57	57	49	49	51	47	58

The change in levels associated with a given harmonic due to the addition of stops can best be observed from graphically plotting the data as shown in Fig. 3. These graphs include the partial up to the D8–G12 partial and represent a range of 50 dB. The points plotted represent an average of the two highest levels from the three positions recorded. The step-wise change of the SPL indicates the manner in which the corresponding partial in the added stop reinforced the ensemble.

The total effect upon the partial structure of the entire tone due to the added stops can be seen in Fig. 4. The other nine intermediate structures can be obtained by plotting the points from the graphs of Fig. 3.

This illustrates the complicated nature of pipe-organ tones as they are usually played by an organist. Let us now consider various other tones taken from the broad field of combination or ensemble tones. Two types of combination tones were used. The first type consisted of tones produced by a typical number of stops being used. The second type consisted of tones produced when the entire resources of the organ were brought into play. These two types will be referred to respectively as combination tones and full-organ tones. The G′ and G tones, as well as the G-major and C-major triad from each type, were analyzed. Additional work was also done on the G-major triad (full organ) with the G doubled in the pedal.

The first example presented will be the full-organ tone for the G-major triad. This tone was produced in the auditorium and recorded at a position in front of the organ one-third the distance from the organ to the back of the auditorium. A sound-level meter placed at this position indicated that the total SPL was varying around an average of 85 dB. No attempt was made to measure the level at all the frequencies such as exhibited in Table IV. Since the level reading of each partial was varying with time, a level reading 3 dB less than the maximum was taken as best representing the level of each partial. These are values given in Table VI. On the tempered scale the fundamental frequencies of the notes G, B, and D are 392, 493.9, and 587.4 cps, respectively. It should be noted that this is a full-organ tone utilizing the 16′ couplers of the organ. These



3(a) 3(b)

FIG. 3. Effect of adding stops upon the level of partials present in the G-major triad.

couplers automatically add pipes an octave below the keys played, and therefore add the fundamental frequencies 196, 246.9, and 293.7 cps and their harmonics. In the upper part of the table, the observed SPL's of the partials are given when this major-triad tone sounds. The fundamental frequency from the longest pipe used to produce the tone G was 196 cps. All integer multiples of this should be present. A second pipe with a fundamental frequency of 392 cps reinforces all the even partials, and a third pipe with a fundamental frequency of 784 cps reinforces the 4th, 8th, 12th, 16th, etc. partials. The level values show this effect. Several sets of pipes of different quality are used, and they may not be exactly in tune. Similarly the tones B and D are made by many pipes, but the resultant levels are given in this table.

In the lower half of this table is shown a comparison between the ideal harmonic frequencies and those experimentally determined by the technique already described. Due to the varying level of the component, it was difficult to set the analyzer to give a maximum deflection. The frequencies of the partials that are

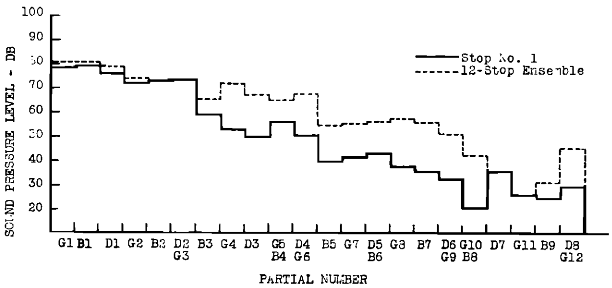


FIG. 4. Effect of adding stops upon the harmonic structure of the G-major triad.

bracketed are too close together to be resolved by the analyzer. It is concluded that within the observational error the frequencies of the partials are harmonic. This is borne out by similar data in Tables VI–IX. However, it was seen that the partials from the different pipes are not exactly in tune. A component of the combined tone that is measured is actually a combination of tones that have their frequencies close together. Therefore, they cause the measured level of this component to vary due to the beating effect of these several partials. Our technique was not sufficiently accurate to determine the levels and frequencies of these several components, but a method of warming the synthetic tones was found which would give the equivalent effect.

TABLE VI. Partial-tone structure of G-major triad with full organ with pedal. Matching warmth = 0—0—0—0.

G (49 cps)				B (247 cps)		D (293.6 cps)	
n	dB	*n*	dB	*n*	dB	*n*	dB
1	95	17	53	1	75	1	74
2	80	18	···	2	74	2	74
3	62	19	44	3	67	3	69
4	84	20	···	4	75	4	74
5	···	21	42	6	60	5	60
6	···	22	50	8	63	6	60
7	66	23	41	10	55	7	···
8	80	24	···	12	56	8	64
9	59	26	48	16	53	12	48
10	74	28	63	19	42	16	42
11	74	32	72				
12	74	34	42				
13	63	44	50				
14	62	56	59				
15	···	64	55				
16	79						

n	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*
G1	49.0	49	G14	686	686	G28	1372	1370
G2	98.0	98	[G15	735		B6	1482	1480
G3	147.0	147	*B3*]	741	742	G32	1568	1566
G4	196.0	196	G16	784	785	G34	1666	1667
G5	245.0	245	G17	833	831	D6	1762	1760
[D1	293.0	294	[D 3	881	883	B8	1976	1977
G6]	294.0		G18]	882		G44	2156	2160
G7	343.0	343	G19	931	929	[D8	2349	2349
G8	392.0	393	[G20	980	982	G48]	2352	
G9	441.0	441	B4]	988		B10	2469	2464
[G10	490.0		G21	1029	1025	G56	2744	2741
B2]	494.0	494	G22	1078	1080	[D10	2937	2951
G11	539.0	537	G23	1127	1125	B12]	2963	
[D2	587.3		[D4	1175	1175	G64	3136	3129
G12]	588.0	588	G24]	1176		D12	3524	3524
G13	637.0	636	G26	1274	1276	B16	3951	3938
						B19	4692	4680

TABLE VII. Partial-tone structure of G(392 cps) with combination tone. Matching warmth = 0—11—11—.

n	dB	*n*	dB	*n*	dB	*n*	dB
1	80	4	75	7	47	10	52
2	82	5	56	8	59	11	30
3	67	6	68	9	44	12	45

TABLE VIII. Partial-tone structure of G′(196 cps) with full organ. Matching warmth = 0—0—.

n	dB	*n*	dB	*n*	dB	*n*	dB
1	80	5	64	9	50	16	66
2	86	6	74	10	72	18	54
3	76	7	50	12	78	20	58
4	86	8	83	14	70	24	49

The synthesizer was tuned to the observed frequencies and set to the levels of the partials as indicated in Table X. The resulting synthetic G-major triad was fair match for the real tones, but it lacked what musicians call warmth.

As stated above, the warmth is due to the beating effect of several components having frequencies close together. This beating may be caused in several ways. These frequencies in Table X which are bracketed will cause beats, even though all the pipes used are exactly in tune. However, the beating for these particular components was not greater than for other components. This bears out the fact that the different pipes that were used to produce the tone have slightly different fundamental frequencies.

To show this level variability of the component, the real organ tone from the tape recorder was sent through the analyzer, which was set to pass 196, 588, 1175, and 1980 cps. It was then sent from the analyzer to the level recorder. The "levelgrams" thus produced are shown in Fig. 5.

TABLE IX. Partial-tone structure of G′(196 cps) with combination tone. Matching warmth = 0—5—.

n	dB	*n*	dB	*n*	dB	*n*	dB
1	78	6	64	11	38	16	48
2	82	7	49	12	52	17	25
3	72	8	66	13	35	18	29
4	74	9	44	14	33		
5	61	10	52	15	28		

TABLE X. Partial-tone structure of G-major triad with full organ, the SPL of each partial measured in the auditorium being tabulated against the number of partial *n*. Matching warmth =0−6−8−9.

G (196 cps)		B (247 cps)		D (293.6 cps)	
n	dB	*n*	dB	*n*	dB
1	75	1	77	1	69
2	85	2	81	2	83
3	60	3	65	3	67
4	81	4	78	4	79
5	63	5	45	5	69
6	79	6	60	6	69
7	48	7	43	7	51
8	78	8	73	8	70
9	67	9	···	9	40
10	62	10	60	10	40
11	45	11	···	11	···
12	70	12	59	12	57
13	40	13	···	13	···
14	63	14	47	14	40
16	63	16	61	16	53

n	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*
G1	199	196	B5	1235	1231	G13	2548	2544
B1	247	245	B7	1372	1369	D9	2643	2540
D1	294	293	D5	[1468	1470	G14	2744	2733
G2	392	393	B6	1482]		D10	[2937	
B2	494	494	G8	1568	1561	G15	2940]	2947
D2	[587	584	B7	1728		B12	2963	
G3	588]		D6	[1762	1757	G16	3136	3123
B3	741	740	G9	1764]		B14	3447	
G4	784	782	G10	[1960		D12	[3524	3507
D3	881	879	B8	1976]	1971	G18	3528]	
G5	[980		D7	2056	2053	B16	3951	3937
B4	988]	983	G11	2156	2156	D14	[4111	4097
D4	[1175	1175	D8	[2349	2344	G21	4116]	
G6	1176]		G12	2352]		B19	[4692	4681
			B10	2469	2464	D16	4699]	

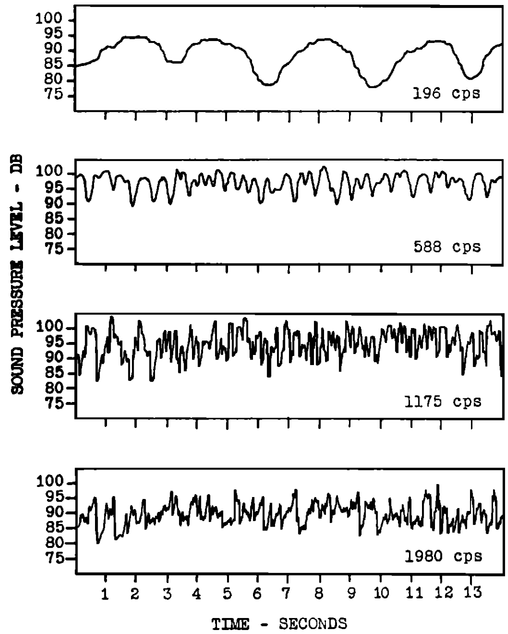


FIG. 5. Levelgrams indicating the variations with time of four partials of an organ tone.

These levelgrams indicate the level variation with time of these four partials. All of the sixty-two harmonics were treated similarly. The ones shown are typical. It is this variation in the level of the partials that gives the tone its warmth.

METHOD OF WARMING ORGAN TONES

A method of warming synthetic organ tones so that they could not be identified from the real organ tones has been found. It will now be described. It uses a 5-track tape-recording machine by placing the following recordings on each channel.

(1) A 1000-cps tone is recorded on track 5. The tone from this track is sent to the electronic counter. If the speed of reproducing is exactly the same as of recording, then this counter will read 1000. Since this 5-track machine is driven by a high-power oscillator, its speed can be changed by any desired amount within a range of 1 to 3. It is convenient to designate the speed in terms of the count from the 1000-cps tone recorded on track 5. For example, if the recording speed is the same as that when the 1000-cps tone was recorded, it is designated as 1000. If the speed is increased 2/10 of 1%, the speed is designated 1002, etc. (2) The tone from the synthesizer made up in accordance with Table X is recorded on track 1 with speed 1000. (3) The same tone is recorded on track 2 with speed 1002.5. (4) It is again recorded on track 3 with speed 1005. (5) It is again recorded on track 4 with speed 1007.5.

All four tracks are then played together and the

TABLE XI. Partial-tone structure of G′ single tone with full organ. Matching warmth=0−0−.

n	dB	*n*	dB	*n*	dB	*n*	dB
1	81	13	···	25	···	37	···
2	81	14	63	26	41	38	···
3	71	15	···	27	···	39	···
4	85	16	72	28	63	40	44
5	57	17	···	29	···	41	···
6	79	18	65	30	39	42	···
7	44	19	···	31	···	43	···
8	84	20	66	32	55	44	···
9	61	21	···	33	···	45	···
10	70	22	51	34	···	46	···
11	44	23	···	35	···	47	···
12	75	24	65	36	50	48	39

n	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*
1	98	98	10	980	979	26	2548	2547
2	196	196	11	1078	···	28	2744	2743
3	294	293	12	1176	1177	30	2940	···
4	392	393	14	1372	1373	32	3136	3140
5	490	490	16	1568	1566	36	3528	3514
6	588	589	18	1764	1765	40	3920	3922
7	686	···	20	1960	1961	48	4704	4799
8	784	785	22	2156	2156			
9	882	886	24	2352	2351			

TABLE XII. Partial-tone structure of G-major triad with combination tone. Matching warmth=0−11−11−11.

G (392 cps)		B (494 cps)		D (587 cps)	
n	dB	*n*	dB	*n*	dB
1	76	1	78	1	71
2	80	2	73	2	74
3	70	3	62	3	55
4	68	4	62	4	58
5	57	5	45	5	51
6	58	6	51	6	48
7	34	7	31	7	29
8	54	8	51	8	48
9	28	9	29		
10	45	10	37		
11	21				
12	44				

levels of each adjusted until the proper warmth is obtained. The warmth then for these organ tones can be designated by giving the levels in dB of the tone from each of these four channels. For example, the warmth of the tone G-major triad full organ was matched by a warmth of 0–6–8–9, meaning that track 2 was reproduced at 6-dB level lower than track 1, that track 3 was reproduced at 8 dB, and track 4 at 9 dB lower than track 1.

TABLE XIII. Partial-tone structure of C-major triad with full organ. Matching warmth=0−0−0−.

C (130.8 cps)				E′ (164.8 cps)		G′ (196.0 cps)	
n	dB	*n*	dB	*n*	dB	*n*	dB
1	82	13	43	1	73	1	77
2	82	14	63	2	85	2	79
3	82	15	40	3	71	3	71
4	84	16	71	4	81	4	79
5	60	20	67	5	47	5	57
6	82	25	53	6	78	6	77
7	48	28	58	7	48	7	50
8	81	30	50	8	79	8	83
9	48	32	52	9	···	9	50
10	77	36	47	10	65	10	68
11	47			12	71	14	67
12	83			14	53	18	47
				19	65	20	52

n	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*
C1	131.0	131	C8	1047	1047	G11	2156	
E1	165.0	165	E7	1154	1155	[E14	2307	2307
G1	196.0	196	[G6	1176	1176	G12]	2352	
C2	262.0	263	C9]	1177		C20	2616	2623
E2	330.0	330	C10	1308	1308	[G14	2744	2741
[G2	392.0		E8	1319	1320	C21]	2747	
C3]	392.4	394	G7	1372	1372	E19	3131	3136
E3	494.0	497	C11	1439	1440	C25	3270	
C4	523.0	524	[G8	1568	1567	E20	3296	3285
G3	588.0	588	C12]	1570		[G18	3528	3525
[C5	654.0		E10	1648	1650	C27]	3532	
E4]	659.0	659	C13	1701	1694	C28	3663	3655
[G4	784.0	784	G9	1764		[G20	3920	
C6]	785.0		C14	1831	1829	C30]	3924	3924
E5	824.0	825	[G10	1960		C32	4186	4195
C7	916.0	918	C15	1962		[G24	4704	4697
[G5	980.0		E12]	1978	1978	C36]	4709	
E6]	989.0	990	C16	2093	2093			

TABLE XIV. Partial-tone structure of C-major triad with combination tone. Matching warmth=0−11−11−14.

C (261.1 cps)		E (330 cps)		C (392 cps)	
n	dB	*n*	dB	*n*	dB
1	70	1	83	1	81
2	86	2	81	2	80
3	75	3	71	3	69
4	79	4	77	4	72
5	60	5	57	5	57
6	70	6	50	6	60
7	50	7	···	7	42
8	68	8	60	8	60
9	45	9	···	9	40
10	60	10	52	10	47
11	···	11	···	11	27
12	60	12	58	12	45
16	48	16	42		

n	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*	*n*	cal. *f*	obs. *f*
C1	262	262	[E4]	1319	1319	[E8]	2637	2636
E1	330	330	[G4	1568	1569	G7	2744	
G1	392	390	C6]	1570		[G8	3136	
C2	523	522	E5	1648	1653	C12]	3139	3139
E2	659	662	C7	1831	1830	E10	3296	3298
[G2	784		[G5	1960	1962	G9	3528	
C3]	785	785	E6]	1978		[G10	3920	
E3	989	992	C8	2093	2090	E12]	3955	3953
C4	1047	1046	[G6	2352	2350	C16	4186	4176
G3	1176	1177	C9]	2354		G11	4312	
[C5]	1308		[C10]	2616		G12	4704	4713
						E16	5274	5279

A similar analysis and synthesis were made for G′ full organ, G″ major-triad full organ with pedal, G combination tone, F′ full organ with subcouplers, G combination tone, G-major triad-combination tone, C-major triad-combination tone, and C′ major-triad full organ. The results are given in Tables XI, VI, VII, VIII, IX, XII, XIII, and XIV, respectively.

It will be seen that the frequencies of the partials are harmonic within the observational error. Observed frequencies were not taken for the three G's shown in Tables VII–IX. They were considered to be harmonic.

IDENTIFICATION TESTS FOR FULL ORGAN AND COMBINATION TONES

Synthetic tones were made in accordance with these tables and then warmed with the technique described above. The matching warmth is given with each table. A program of identification tests using the real and synthetic tones was recorded. The make-up of this program is given in Table XV. (*S*) and (*R*) signify synthetic and real tones, respectively. The number preceding these symbols identifies the tone used, e.g., tone 6 is the same as that found in Table VI, tone 7 is the same as that found in Table VII, etc.

The results obtained when this test was given to a jury of six musicians and five nonmusicians are presented

TABLE XV. Program for identification tests on combination and full organ tones.

Test 1	11 (*S*)	Test 21	10 (*S*)	Test 41	11 (*R*)
Test 2	9 (*R*)	Test 22	9 (*S*)	Test 42	10 (*S*)
Test 3	8 (*S*)	Test 23	7 (*R*)	Test 43	14 (*R*)
Test 4	14 (*S*)	Test 24	6 (*R*)	Test 44	12 (*R*)
Test 5	6 (*S*)	Test 25	13 (*R*)	Test 45	6 (*S*)
Test 6	8 (*R*)	Test 26	12 (*S*)	Test 46	...
Test 7	7 (*R*)	Test 27	...	Test 47	14 (*S*)
Test 8	10 (*R*)	Test 28	9 (*R*)	Test 48	11 (*S*)
Test 9	13 (*R*)	Test 29	8 (*R*)	Test 49	12 (*S*)
Test 10	...	Test 30	6 (*S*)	Test 50	8 (*R*)
Test 11	...	Test 31	7 (*S*)	Test 51	13 (*S*)
Test 12	14 (*R*)	Test 32	10 (*R*)	Test 52	7 (*R*)
Test 13	6 (*R*)	Test 33	14 (*R*)	Test 53	7 (*S*)
Test 14	7 (*S*)	Test 34	13 (*S*)	Test 54	8 (*S*)
Test 15	12 (*R*)	Test 35	12 (*R*)	Test 55	9 (*S*)
Test 16	9 (*S*)	Test 36	11 (*S*)	Test 56	9 (*R*)
Test 17	11 (*R*)	Test 37	...	Test 57	6 (*R*)
Test 18	10 (*S*)	Test 38	14 (*S*)	Test 58	13 (*R*)
Test 19	12 (*S*)	Test 39	8 (*S*)	Test 59	10 (*R*)
Test 20	13 (*S*)	Test 40	11 (*R*)	Test 60	...

in Table XVI. Each of the nine synthetic tones and each of the nine real tones occur three times in the test. The jury of musicians has a chance to make 18 errors, and the nonmusicians have a chance to make 15 errors on each of the nine synthetic and each of the nine real tones used in the test, or a total of 324 for the musicians and 270 for the nonmusicians. It can be verified from Table XVI that 333 errors were committed out of 594 tries. In other words, 44% of the tones were correctly judged. When the scores made by the jury members are in the area of 50%, it must be concluded that the members of the jury are simply guessing. Obviously the observers were unable to recognize the difference between the real and synthetic tones. These results show that synthetic tones can be made to sound like full organ and combination tones produced by many pipes speaking together.

A POSSIBLE SCALE OF WARMTH

It has been shown that a method has been found for increasing the warmth of a musical tone. It has been observed that using the following ratios of tape speed on the 5-track tape recorder—namely, 1000, 1003, 1005, 1008, and 1011—produces a range of tone warmths that will match nearly any tone. The tape having the speed 1011 begins to sound out of tune with the tone from the track having the speed 1000. The warmth then can be defined by giving these ratios and the levels on the 5 tracks. For example, for the speed ratios mentioned above and for equal levels on all tracks, the warmth can be designated 00—30—50—80—110. If the level in the second and third tracks was decreased 8 dB below the others, then the warmth would be designated 00—38—58—80—110, and so forth. When the partial-tone content of a synthetic tone is approximately the same as a real musical tone, then the warmth of that tone can be matched by judgment tests and given a number like that above. The warmth specified in the nine previous tables is indicated only by the difference in dB between tracks. The above designations also include the track speed. This warmth must also be closely related to the levelgrams like those shown in Fig. 5.

It seems possible to work out a single figure for the warmth. It will depend upon the following factors: (1) the variation of the level of each partial component, (2) the frequency of this component, and (3) the frequency of the amplitude variation. A figure for each partial must then be combined in some way to find the final figure.

Some preliminary work has been done which indicates the possibilities. This part of the work is continuing. Many more experimental data are necessary before we know how to assess the various factors.

TABLE XVI. Results of judgment tests on combination and full organ tones.

Tone no.	Errors by five nonmusicians (*R*)	(*S*)	Errors by six musicians (*R*)	(*S*)
6	4	6	18	5
7	7	8	16	6
8	5	11	8	15
9	9	6	16	6
10	10	5	17	3
11	9	6	15	6
12	4	10	11	10
13	5	9	12	12
14	5	8	16	14
Total errors	58	59	129	77

44% of the tones judged correctly

With the above notation some judgment tests were made to determine what warmth is considered best by a jury of musicians and nonmusicians. These preliminary results indicate that the warmth preferred by both groups is about the same as that obtained in matching the original organ tone. Where there were differences, all nonmusicians indicated that they preferred a warmer tone than this, and none preferred cooler tones. Among the musicians there were those who had a preference for warmer tones and those who had a preference for cooler than the real organ tones.

PREFERENCE TESTS OF ELECTRONIC ORGAN VS PIPE ORGAN

Tones from an electronic organ have been used in tests to determine if they are preferred over the tones of a pipe organ. The quality of electronic organ tones depends to a great extent upon the installation of the speakers. The conclusions of these tests are based upon only one installation.

Results indicate that when a jury judged between a tone produced by a commercial electronic organ and that of a pipe organ, there was a preference for the pipe organ tone in the majority of cases.

Some tests have also been carried out wherein the electronic organ tone was warmed by the use of the 5-track recorder. After this warming process some of the observers preferred the warmed electronic organ tone, but the majority still had a preference for the pipe organ. The results of these tests are still rather inconclusive, requiring more work until more valid conclusions can be ascertained.