Lab 5: Resonant Pipes & Harmonic Series

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1 Introduction

We are going to study different resonant systems and try to model them as either **open** or **closed** resonant pipes. Of course, real systems are not quite so simple, so we will be studying how closely such a real system matches the theoretical ideal.

2 Experiment

2.1 Practice

You will be given a resonant pipe. Spend a few minutes experimenting with it to discover how to efficiently generate as many resonant frequencies as possible. *Take your time!* This is not easy and it will take a little practice. Ask other groups for help if you are having trouble.

When you have mastered your instrument and are ready for performance, proceed to a tuner to measure the frequencies of these resonances. You should be able to generate at least three resonances.

2.2 Performance

(A sample data table is provided below.)

Measure the frequencies of as many resonances as possible. Have one person play the instrument and center the tone without looking at the meter, and have a second person take a reading. Be sure to stay on the resonance and not change the pitch by changing your mouth shape. You will know you are on the resonance when you feel a significant vibration on your face. This effect goes away quickly as you move off resonance.

Fill in the notes in a table starting from the highest resonance you can play and working down.

Most of you will be using musical chromatic tuners to determine your frequencies. The tuner will tell you the note (e.g. $F^{\#}$), and the cents above or below this note (e.g. +40). Record the notes as follows: $(F_5^{\#} + 40)$. You must figure out the octave by comparing the sound you hear to a keyboard. There will be a keyboard available to assist you.

2.3 Frequencies

Once you have determined the note and octave (e.g. $F_5^\# + 40$), use the table at the end of this lab to compute your frequency (three digits of precision should be plenty). Then compute the difference between the two frequencies. (Note: If you made an error, or are missing a resonance, it will show up at this point in the differences. If you find an anomaly, go back to your experimental setup and check for mistakes in your data.)

2.4 Fundamental Frequency

You may or may not have measured the fundamental (lowest) frequency. Assuming you did not, you can estimate what it should be by stepping down the frequency.

- First, compute the average difference between the different resonances.
- Then use this average difference to step down from your lowest frequency until you reach a frequency that is about zero.
- The fundamental frequency is the frequency before the one that is approximately zero.

In the example table, I measured down to the 700 Hz resonance. Using the average difference of 200 Hz, I was able to determine the fundamental frequency was 100 Hz. I indicate that the values below 700 Hz are theoretical predictions (not measurements) using the last column.

2.5 Length of Instrument

Measure the length of your instrument in meters. Compute the expected fundamental if this were an open pipe and the fundamental for a closed pipe (hint: Look back at the prelab). How does this compare with what you found in your measurements? Be sure to use the real value value for the speed of sound, not my fake 400 m/s.

As always, the speed of sound is given by,

$$v = 332 \, \left(\frac{\mathrm{m}}{\mathrm{s}}\right) + 0.6 \, \left(\frac{\mathrm{m}}{\mathrm{s} \, {}^{\circ}\mathrm{C}}\right) \, T \, .$$

2.6 Repeat

Repeat the above steps so that you perform this experiment for three different resonant pipes.

3 Questions

- How closely did your real instruments match the theoretical models?
- Do the resonant notes from your instrument appear to be multiples of the fundamental frequency (e.g. $1f_0, 2f_0, 3f_0, 4f_0, 5f_0, \ldots$) or only the odd multiples (e.g. $1f_0, 3f_0, 5f_0, 7f_0, \ldots$)?
- Does your instrument appear to be harmonic or odd-harmonic?
- What elements would make the real instruments differ from the models?
- Identify at least two sources of statistical error and state how you would correct for them.
- Identify at least two sources of systematic error and state how you would correct for them.
- As always, do not forget to write an Abstract and Conclusion in your lab notebook.
- Can you make any other general conclusions or observations?

Example Data with Calculation

4.1 <u>Data</u>

Note	Frequency	Difference	Measured?		
$F_6^\# + 20$	1500	n/a	yes		
$E_6 - 20$	1300	200	yes		
$C_6^{\#} - 10$	1100	200	yes		
$A_5 + 40$	900	200	yes		
	500	200	no		
	300	200	no		
	$100 = f_0$	200	no		

4.2 Calculations
$$f_{\rm closed} = \frac{v_{\rm sound}}{4L} = 100 \; \rm Hz$$

$$f_{\rm open} = \frac{v_{\rm sound}}{2L} = 200 \; \rm Hz$$

$$f_{\text{open}} = \frac{v_{\text{sound}}}{2L} = 200 \text{ Hz}$$

5 Frequency Tables

A	440	-50	-40	-30	-20	-10	0	10	20	30	40	50
0	С	15.886	15.978	16.071	16.164	16.257	16.352	16.446	16.542	16.637	16.734	16.831
0	C#	16.831	16.928	17.026	17.125	17.224	17.324	17.424	17.525	17.627	17.729	17.832
0	D "	17.832	17.935	18.039	18.143	18.248	18.354	18.460	18.567	18.675	18.783	18.892
0	D# E	18.892	19.001	19.111	19.222	19.333	19.445	19.558	19.671	19.785	19.900	20.015
0	F	20.015	20.131	21.452	21.576	20.483	20.602 21.827	20.721	20.841	20.962	22.337	22.466
0	F#	22.466	22.596	22.727	22.859	22.991	23.125	23.259	23.393	23.529	23.665	23.802
0	G G	23.802	23.940	24.079	24.218	24.359	24.500	24.642	24.784	24.928	25.072	25.218
0	G#	25.218	25.364	25.511	25.658	25.807	25.957	26.107	26.258	26.410	26.563	26.717
0	A	26.717	26.872	27.028	27.184	27.342	27.500	27.659	27.820	27.981	28.143	28.306
0	A#	28.306	28.470	28.635	28.801	28.967	29.135	29.304	29.474	29.645	29.816	29.989
0	В	29.989	30.163	30.337	30.513	30.690	30.868	31.047	31.226	31.407	31.589	31.772
1	С	31.772	31.956	32.141	32.328	32.515	32.703	32.893	33.083	33.275	33.468	33.661
1	C#	33.661	33.856	34.053	34.250	34.448	34.648	34.849	35.050	35.253	35.458	35.663
1	D	35.663	35.870	36.077	36.286	36.497	36.708	36.921	37.135	37.350	37.566	37.784
1	D#	37.784	38.003	38.223	38.444	38.667	38.891	39.116	39.343	39.571	39.800	40.030
1	E	40.030	40.262	40.496	40.730	40.966	41.203 43.654	41.442	41.682	41.924	42.167	42.411
1	F#	44.933	45.193	45.455	45.718	45.983	46.249	46.517	46.787	47.058	47.330	47.605
1	G	47.605	47.880	48.158	48.437	48.717	48.999	49.283	49.569	49.856	50.145	50.435
1	G#	50.435	50.727	51.021	51.317	51.614	51.913	52.214	52.516	52.821	53.126	53.434
1	A	53.434	53.744	54.055	54.368	54.683	55.000	55.319	55.639	55.961	56.286	56.612
1	A#	56.612	56.940	57.269	57.601	57.935	58.270	58.608	58.948	59.289	59.632	59.978
1	В	59.978	60.325	60.675	61.026	61.380	61.735	62.093	62.453	62.815	63.178	63.544
2	С	63.544	63.913	64.283	64.655	65.030	65.406	65.785	66.166	66.550	66.935	67.323
2	C#	67.323	67.713	68.105	68.500	68.897	69.296	69.697	70.101	70.507	70.915	71.326
2	D	71.326	71.739	72.155	72.573	72.993	73.416	73.841	74.269	74.699	75.132	75.567
2	D#	75.567	76.005	76.446	76.888	77.334	77.782	78.232	78.686	79.141	79.600	80.061
2	E F	80.061 84.822	80.525 85.313	80.991 85.807	81.460	81.932 86.804	82.407 87.307	82.884 87.813	83.364 88.322	83.847 88.833	84.333 89.348	84.822 89.865
2	F#	89.865	90.386	90.910	91.436	91.966	92.499	93.034	93.573	94.115	94.661	95.209
2	G G	95.209	95.761	96.315	96.873	97.434	97.999	98.567	99.138	99.712	100.289	100.870
2	G#	100.870		102.043	102.634	103.228	103.826	104.428	105.033	105.641	106.253	106.869
2	A	106.869		108.110	108.737	109.366	110.000		111.278	111.923	112.571	113.223
2	A#	113.223	113.879	114.539	115.202	115.870	116.541	117.216	117.895	118.578	119.265	119.956
2	В	119.956	120.651	121.350	122.053	122.760	123.471	124.186		125.629	126.357	127.089
3	C	127.089		128.565	129.310	130.059	130.813	131.571	132.333	133.099		134.646
3	C# D	134.646	135.426	136.210 144.310	136.999	137.793 145.987	138.591 146.832	139.394	140.202	141.014		142.652 151.135
3	D#	151.135	152.010	152.891	153.777	154.668	155.563	156.465	157.371	158.283	159.200	160.122
3	E	160.122	161.049	161.982	162.921	163.865	164.814	165.769	166.729	167.695	168.666	169.643
3	F	169.643	170.626	171.614	172.609	173.608	174.614	175.626	176.643	177.666		179.731
3	F#	179.731	180.772	181.819	182.872	183.932	184.997	186.069	187.147	188.231	189.321	190.418
3	G	190.418	191.521	192.631	193.746	194.869	195.998	197.133	198.275	199.424	200.579	201.741
3	G#	201.741	202.910	204.085	205.267	206.456	207.652	208.855	210.065	211.282	212.506	213.737
3	A	213.737	214.975	216.221	217.473	218.733	220.000	221.274	222.556	223.846	225.142	226.446
3	A# B	226.446	227.758 241.301	229.078	230.405	231.739 245.519	233.082 246.942	234.432	235.790 249.811	237.156 251.258	238.530 252.714	239.912 254.178
4	c	254.178	255.650	257.131	258.621	260.119	261.626	263.141	264.666	266.199		269.292
4	C#	269.292	270.852	272.421	273.999	275.586	277.183	278.788	280.403	282.028	283.661	285.305
4	D D	285.305	286.957	288.620	290.292	291.973	293.665	295.366	297.077	298.798		302.270
4	D#	302.270	304.021	305.782	307.553	309.335	311.127	312.929	314.742	316.565	318.399	320.244
4	E	320.244	322.099	323.965	325.841	327.729	329.628		333.458	335.389	337.332	339.286
4	F	339.286						351.251				
4	F#	359.461	361.544	363.638	365.745	367.863	369.994		374.294	376.462	378.643	380.836
4	G G#	380.836	383.042	385.261	387.493	389.738	391.995		396.550	398.847		403.482
4	G#	403.482	405.819	408.170	410.535	412.913	415.305 440.000		420.130	422.564	425.012 450.285	427.474
4	A A#	452.893	455.517	452.441	460.809	463.479	466.164	442.549	471.580	474.312	477.060	479.823
4	В	479.823	482.603	485.399	488.211	491.039	493.883	496.744	499.622	502.516		508.355
5	С	508.355	511.300	514.262	517.241	520.237	523.251	526.282	529.331	532.397	535.482	538.584
5	C#	538.584	541.704	544.842	547.998	551.172	554.365	557.577	560.807		567.323	570.609
5	D	570.609	573.915	577.240	580.583	583.947	587.330		594.154	597.596	601.058	604.540
5	D#	604.540	608.042	611.564	615.107	618.670	622.254	625.859	629.484	633.131	636.798	640.487
5	E	640.487	644.198	647.930	651.683	655.458	659.255	663.074	666.915	670.779	674.664	678.573
5	F	678.573	682.504	686.457	690.434	694.434	698.456	702.503	706.572	710.665	714.782	718.923
5	F#	718.923 761.672	723.087 766.084	727.276	731.489	735.727 779.475	739.989 783.991	744.276	748.587	752.924 797.695	757.285 802.316	761.672 806.964
5	G#	806.964	811.638	816.340	821.069	825.825	830.609	835.421	840.261	845.128	850.024	854.948
5	A	854.948	859.901	864.882	869.892	874.932	880.000	885.098	890.225	895.382	900.569	905.786
	A#	905.786	911.033	916.311	921.619	926.958	932.328		943.161	948.624		959.647
5 5	В	959.647	965.206	970.797	976.421	982.077	987.767				1010.855	
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6 C C 6 D D 6 D 7 C 6 F 7 D D 7 C 7 F F 7 F	; # ; ; # ; ; ; ; ; ; ; ; ; ; ; ; ; ; ;	1016.7 1077.2 1141.2 1209.1 1281.0 1357.1 1437.8 1523.3 1613.9 1709.9 1811.6 1919.3 2033.4 2154.3	1022.6 1083.4 1147.8 1216.1 1288.4 1365.0 1446.2 1532.2 1623.3 1719.8 1822.1 1930.4	1028.5 1089.7 1154.5 1223.1 1295.9 1372.9 1454.6 1541.0 1632.7 1729.8 1832.6	1034.5 1096.0 1161.2 1230.2 1303.4 1380.9 1463.0 1550.0 1642.1 1739.8	1040.5 1102.3 1167.9 1237.3 1310.9 1388.9 1471.5 1559.0	1046.5 1108.7 1174.7 1244.5 1318.5 1396.9	1052.6 1115.2 1181.5 1251.7 1326.1	1058.7 1121.6 1188.3 1259.0 1333.8 1413.1	1064.8 1128.1 1195.2 1266.3 1341.6 1421.3	1071.0 1134.6 1202.1 1273.6 1349.3	1077.2 1141.2 1209.1 1281.0 1357.1
6 D 6 D 6 E 6 F 6 F 6 G 6 G 6 A 6 A 7 C 7 D 7 D 7 F 7 F))# : ; ; ; ; ; ; ; ; ; ; ; ;	1141.2 1209.1 1281.0 1357.1 1437.8 1523.3 1613.9 1709.9 1811.6 1919.3 2033.4	1147.8 1216.1 1288.4 1365.0 1446.2 1532.2 1623.3 1719.8 1822.1 1930.4	1154.5 1223.1 1295.9 1372.9 1454.6 1541.0 1632.7 1729.8	1161.2 1230.2 1303.4 1380.9 1463.0 1550.0 1642.1	1167.9 1237.3 1310.9 1388.9 1471.5 1559.0	1174.7 1244.5 1318.5	1181.5 1251.7 1326.1	1188.3 1259.0 1333.8	1195.2 1266.3 1341.6	1202.1 1273.6 1349.3	1209.1 1281.0
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6 E E 6 F f 6 G G 6 A 4 6 B 7 C C f 7 D 7 D f 7 E 7 F	;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;	1281.0 1357.1 1437.8 1523.3 1613.9 1709.9 1811.6 1919.3 2033.4	1288.4 1365.0 1446.2 1532.2 1623.3 1719.8 1822.1 1930.4	1295.9 1372.9 1454.6 1541.0 1632.7 1729.8	1303.4 1380.9 1463.0 1550.0 1642.1	1310.9 1388.9 1471.5 1559.0	1318.5	1326.1	1333.8	1341.6	1349.3	
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6 G# 6 A# 6 B 7 C 7 C# 7 D 7 D# 7 E 7 F	5# \# 3 ::	1613.9 1709.9 1811.6 1919.3 2033.4	1623.3 1719.8 1822.1 1930.4	1632.7 1729.8	1642.1		1480.0	1488.6	1497.2	1505.8	1514.6	1523.3
6 A 6 A 6 B 7 C 7 C 7 D 7 D 7 E 7 F	\# 3 : :#	1709.9 1811.6 1919.3 2033.4	1719.8 1822.1 1930.4	1729.8			1568.0	1577.1	1586.2	1595.4	1604.6	1613.9
6 A d d d d d d d d d d d d d d d d d d	\# 3 : :#	1811.6 1919.3 2033.4	1822.1 1930.4			1651.7	1661.2	1670.8	1680.5	1690.3	1700.0	1709.9
6 B 7 C 7 C 7 D 7 D 7 E 7 F	; ; ;#	1919.3 2033.4	1930.4	1830 6		1749.9	1760.0	1770.2	1780.5	1790.8	1801.1	1811.6
7 C 7 C 7 D 7 D 7 E 7 F	: :#)	2033.4			1843.2	1853.9	1864.7	1875.5	1886.3	1897.2	1908.2	1919.3
7 C# 7 D 7 D# 7 E 7 F	:#)			1941.6	1952.8	1964.2	1975.5	1987.0	1998.5	2010.1	2021.7	2033.4
7 D 7 D 7 E 7 F)	2154.31	2045.2	2057.0	2069.0	2080.9	2093.0	2105.1	2117.3	2129.6	2141.9	2154.3
7 D# 7 E 7 F			2166.8	2179.4	2192.0	2204.7	2217.5	2230.3	2243.2	2256.2	2269.3	2282.4
7 E 7 F)#	2282.4	2295.7	2309.0	2322.3	2335.8	2349.3	2362.9	2376.6	2390.4	2404.2	2418.2
7 F		2418.2	2432.2	2446.3	2460.4	2474.7	2489.0	2503.4	2517.9	2532.5	2547.2	2561.9
		2561.9	2576.8	2591.7	2606.7	2621.8	2637.0	2652.3	2667.7	2683.1	2698.7	2714.3 2875.7
7 F#		2714.3 2875.7	2892.3	2745.8	2761.7	2777.7	2793.8 2960.0	2810.0	2826.3	2842.7 3011.7	2859.1	3046.7
7 G		3046.7	3064.3	3082.1	3099.9	3117.9	3136.0	2977.1 3154.1	2994.3 3172.4	3190.8	3029.1	3227.9
7 G		3227.9	3246.6	3265.4	3284.3	3303.3	3322.4	3341.7	3361.0	3380.5	3400.1	3419.8
7 A		3419.8	3439.6	3459.5	3479.6	3499.7	3520.0	3540.4	3560.9	3581.5	3602.3	3623.1
7 A		3623.1	3644.1	3665.2	3686.5	3707.8	3729.3	3750.9	3772.6	3794.5	3816.5	3838.6
7 B		3838.6	3860.8	3883.2	3905.7	3928.3	3951.1	3974.0	3997.0	4020.1	4043.4	4066.8
8 C	,	4066.8	4090.4	4114.1	4137.9	4161.9	4186.0	4210.3	4234.6	4259.2	4283.9	4308.7
8 C#		4308.7	4333.6	4358.7	4384.0	4409.4	4434.9	4460.6	4486.5	4512.4	4538.6	4564.9
8 D	••	4564.9	4591.3	4617.9	4644.7	4671.6	4698.6	4725.9	4753.2	4780.8	4808.5	4836.3
8 D#	#	4836.3	4864.3	4892.5	4920.9	4949.4	4978.0	5006.9	5035.9	5065.0	5094.4	5123.9
8 E	:	5123.9	5153.6	5183.4	5213.5	5243.7	5274.0	5304.6	5335.3	5366.2	5397.3	5428.6
8 F	•	5428.6	5460.0	5491.7	5523.5	5555.5	5587.7	5620.0	5652.6	5685.3	5718.3	5751.4
8 F#	' #	5751.4	5784.7	5818.2	5851.9	5885.8	5919.9	5954.2	5988.7	6023.4	6058.3	6093.4
8 G	;	6093.4	6128.7	6164.2	6199.9	6235.8	6271.9	6308.3	6344.8	6381.6	6418.5	6455.7
8 G#	;#	6455.7	6493.1	6530.7	6568.6	6606.6	6644.9	6683.4	6722.1	6761.0	6800.2	6839.6
8 A	1	6839.6	6879.2	6919.1	6959.1	6999.5	7040.0	7080.8	7121.8	7163.1	7204.6	7246.3
8 A		7246.3	7288.3	7330.5	7373.0	7415.7	7458.6	7501.8	7545.3	7589.0	7633.0	7677.2
8 B		7677.2	7721.6	7766.4	7811.4	7856.6	7902.1	7947.9	7994.0	8040.3	8086.8	8133.7
9 C		8133.7	8180.8	8228.2	8275.9	8323.8	8372.0	8420.5	8469.3	8518.4	8567.7	8617.3
9 C‡		8617.3	8667.3	8717.5	8768.0	8818.8	8869.8	8921.2	8972.9	9024.9	9077.2	9129.8
9 D		9129.8	9182.6	9235.8	9289.3	9343.1	9397.3	9451.7	9506.5	9561.5	9616.9	9672.6
9 D#	**	9672.6	9728.7	9785.0	9841.7	9898.7	9956.1	10013.7	10071.7	10130.1	10188.8	10247.8
9 E		10248	10307	10367	10427	10487	10548	10609	10671	10732	10795	10857
9 F		10857	10920	10983	11047	11111	11175	11240	11305	11371	11437	11503
9 F#	••	11503	11569	11636	11704	11772	11840	11908	11977	12047	12117	12187
9 G 9 G		12187	12257	12328	12400	12472 13213	12544	12617	12690	12763 13522	12837 13600	12911 13679
9 G#		12911 13679	12986 13758	13061 13838	13137 13918	13213	13290 14080	13367 14162	13444	14326	13600	13679
9 A		14493	13758	13838	14746	14831	14080	15004	15091	15178	15266	15354
9 A	••	15354	15443	15533	15623	15713	15804	15004	15988	16081	16174	16267
10 C		16267	16362	16456	16552	16648	16744	16841	16939	17037	17135	17235