The Physics of Tremolo

by Dennis Hedberg

Much has been written and spoken about theatre organ tremolos (tibias in particular) in the brief history of the instrument. Unfortunately, virtually all of what has been spoken and written about this subject is based upon passed-down information and the belief if Wurlitzer, Kimball or Morton built it a certain way, who are we mere mortals to question their dicta? The obvious should now be noted. All of the above-mentioned builders have been out of business for decades. Many reasons have been postulated for the demise of the theatre organ but might it be possible another cause simply be that far too many theatre organs basically did not sound good with lethargic tremolos as a significant reason? Perhaps the few outstanding instruments are the way they are more out of chance than design. Did those early designers really understand the physics of tremolo or did they extrapolate upon established practices of church organ design? More to the point: Are the present day keepers of theatre organs, the American Theatre Organ Society, doing any better? From much of what this writer sees and hears, with few exceptions, I think not.

At the recent 1987 National ATOS Convention, the author noted a sagging Tibia tremolo in the Orpheum 3/13 Wurlitzer during Dan Bellomy's performance. Organist Jonas Nordwall has a habit of switching off most tremulants in full organ combinations in order to achieve a more incisive, articulate sound. He did not do so during his outstanding performance on the equally outstanding 5-manual Möller organ in the Pasadena Civic Auditorium. Mr. Nordwall later told the author the tremolos failed of their own accord while playing full organ combinations under heavy load conditions. Nevertheless, in this particular instance the instrument's sound was still awesome.

About one year of research, experimentation and consultation with university physics and chemistry professors is the basis for the findings about to be presented. The experiments were conducted on the author's own instrument, the 4/44 Wurlitzer in the Organ Grinder Restaurant, Portland, Oregon. Other test apparatus utilized was a Tektronix SC 502 oscilloscope, DC 504 counter/timer, DM 502 multimeter with temperature probe, Honeywell-Microswitch 160 PC pressure transducer, stop watch and interface electronics of the author's design.

Author conducting tremolo frequency and waveform experiments.

A number of individuals have been able to obtain good quality, musical tibia tremolos under light to medium load conditions. For this article's purposes, light load is defined as one or two pipes speaking and a medium load as six to ten pipes speaking. However, under heavy load conditions the tremolo breaks down. Very heavy load conditions are defined as 16', 8', 4', 2' Tibia with sub-octave and octave couplers playing an F6-9 chord in the 2nd inversion (keys 37, 39, 42, 44, 46, 49). With pipe #1 being 8'C, this massive chord causes pipes 13, 15, 18, 20, 22, 25, 27, 30, 32, 34, 37, 39, 42, 44, 46, 49, 51, 54, 56, 58, 61, 63, 66, 68, 70, 73, 75, 78, 80, 82 and 85 to speak. Success is defined as being able to hold this chord indefinitely without any discernable change in tremolo speed and/or depth compared to no-load or light-load conditions.

Tremolo is an infra-sonic wave of enormous intensity. Assume a rank blowing on 10" wind pressure. Further, assume this rank's tremulant causes its wind to fluctuate 4" above and below 10". Within this closed system for Eq. 1 we get 14.92 psia (pounds per square inch absolute) for 6" pressure and 15.21 psia for 14" pressure. Eq. 2 converts pounds/inch^2 to Pascals, a metric unit of pressure. Therefore, 15.21 psia = 1.05×10^3 Pa and 14.92 psia = 1.02×10^3 Pa for a difference of 2×10^3 Pa. This amplitude of pressure variation is equivalent to a sound pressure level of 160db or 10^4 watts/meter^2. 120db is considered to be the threshold of pain for audible frequencies. It is no wonder, then, that doors, floors, windows, even theatre balconies flex when theatre organ tremolos are operating.

Eq. 1

$$\text{Pounds/in}^2\text{ absolute} = (\text{wind pressure} \times 3.613 \times 10^{-2}) + 14.7$$

Eq. 2

$$1\text{ Pascal} = 1.45 \times 10^{-4}\text{ lb/in}^2$$

Treating tremolo as sound allows us to take advantage of the considerable body of research done in the fields of loudspeaker and loudspeaker enclosure design. Let us look at the similarities between an electro-dynamic loudspeaker (the most common variety) and a theatre organ regulator top board with hold-down springs. Notice how they both relate to the classic physics demonstration of a mass oscillating on the end of a spring. See Figs. 1A, 1B, 1C.

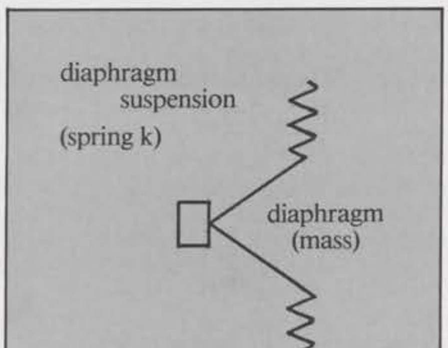

Fig. 1A

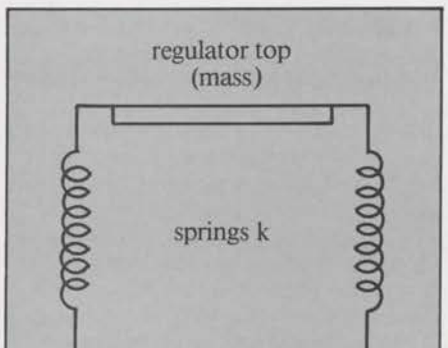

Fig. 1B

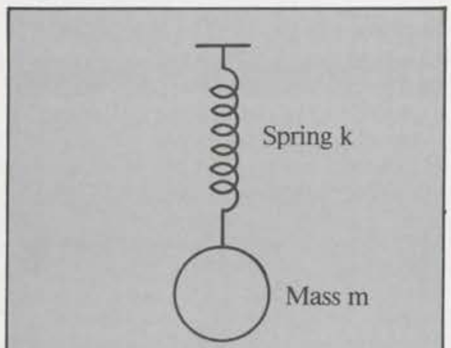

Fig. 1C

The frequency at which the mass m of Fig. 1C will bob up and down in a sinusoidal fashion when suspended by a spring of stiffness k is given by Eq. 3. Frequency increases as the spring (suspension) becomes stiffer and decreases as the mass (speaker diaphragm or regulator top board) becomes greater. The diaphragm mass of Fig. 1A is supported by its suspension (spring). The regulator's top board mass is offset by the hold-down springs.

Eq. 3

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where: f = frequency in hertz (Hz) (cycles per second)
m = mass in kilograms (kg)
k = spring stiffness in kilograms per second squared (kg/s^2)
π = constant 3.1416

Moving a little closer to the real world, we now install the speaker in a sealed box, Fig. 2A. We fit fold boards and a bottom board to the regulator top board, Fig. 2B. Assume for the moment there are no valves or other openings in the regulator. In other words, it doesn't need to be releathered.

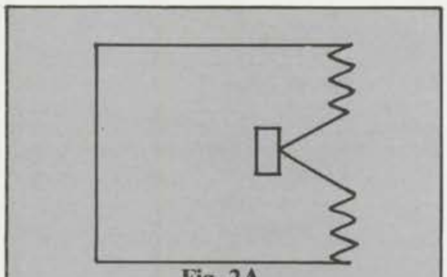

Fig. 2A

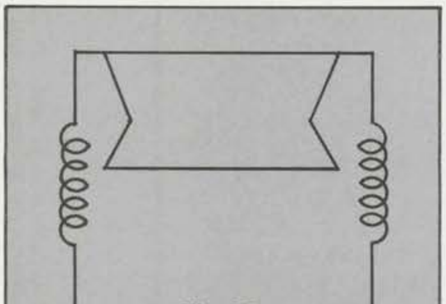

Fig. 2B

The volume of air enclosed by the box of Fig. 2A and the volume of air enclosed withint the regulator, Fig. 2B, will behave as springs. The stiffness factors, k, of these air springs will add to the k of the speaker's suspension spring and the regulator's hold-down springs. Determining the k of the springs of Figs. 1B and 1C is easily found by solving Eq. 3 for k.

Eq. 4

$$K = (2\pi f)^2 m$$

K of the air springs is more difficult to determine. A certain volume of air molecules of a certain density, moving at a certain velocity, striking a plane surface of a certain area, with a certain force, will result in a certain stiffness for that particular volume of air. Loudspeaker enclosure research gives us this relationship in terms of compliance.

Eq. 5

$$C = \frac{V}{dc^2 A^2}$$

where: C = compliance in sec^2/kg
d = density of air in kg/m^3
c = velocity of sound in m/s
V = volume of enclosed air in m^3
A = area of plane surface in m^2

k's units are in kg/s^2. Therefore,

Eq. 6

$$K = \frac{1}{C} = \frac{dc^2 A^2}{V}$$

Substituting Eq. 4 for k of Eq. 6 yields:

Eq. 7

$$(2\pi f)^2 m = \frac{dc^2 A^2}{V}$$

Solving Eq. 7 for V:

Eq. 8

$$V = \frac{dc^2 A^2}{4\pi^2 mf^2}$$

Solving Eq. 8 for f:

Eq. 9

$$f = \frac{CA}{2\pi}\sqrt{\frac{d}{mV}}$$

Eqs. 8 and 9 assume a sealed, enclosed volume of air.

Let us now move into the organ chamber keeping Eq. 9 in mind. Mass m is in reality the top board of the regulator plus any additional weights which may be attached to it. Volume V is the sum of chest, windline, regulator and tremulant volumes. In this article tremulant shall refer to the organ component . . . the dump valve. Tremolo shall refer to the musical wavering of the pipe's voice.

Historically organ technicians adjust tremolos by increasing weight on the regulator to achieve a slower, deeper tremolo and by removing weight and tightening hold-down springs to realize more shallow and faster tremolos. Some designers and technicians provide for longer or shorter windlines between the regulator and chest and between chest and tremulant. Others prefer adding a number of elbows to windlines and everyone has his own ideas about how the inlet and outlet valves of the tremulant should be set. Looking at Eq. 9 we see, indeed, that tremolo frequency will decrease as weight (mass) and/or length and size of windlines (volume) is increased. Actually, frequency varies inversely as the square root of mass and volume.

Auditioning old 78 recordings of theatre organs, dance bands and vocalists reveals a preference for faster, more shallow tremolos than we are accustomed to today. Furthermore, theatre organ technicians today have a propensity for winding bass offset notes of a given rank independently from the manual chest. As we shall see later this habit, while advantageous in terms of bass offset notes, wreaks havoc upon attempts to achieve steady tremolos. In a given installation, as we attempt to slow down tremolos by adding weight to the regulator and/or enlarging the tremulant's outlet valve setting, we can quickly encounter problems. Opening the outlet valve or adding weight to the tremulant will certainly slow the tremolo but it won't necessarily make it any deeper. So we open the inlet valve. Now the tremolo is deeper and it picked up a little speed in the process. Unfortunately, the tremolo has probably lost whatever musical quality it may have had because the violent action of the tremulant has introduced a chopped, abrupt, jerky characteristic. See Photo 1. The circled portion of Photo 1 increases as the tremulant's inlet valve is opened. A little is necessary for color but excess results in chop-chop.

Another aberration of tremolo performance caused by the waveform of Photo 3 is a rise (sharp) in average pitch of the affected rank(s) when the tremulant is operating referred to that pitch when the tremulant is not operating. The usual explanation for this phenomenon is that the tremulant caused the wind pressure to deviate on the rise a greater amount than on the fall. The waveform of Photo 3 indicates no further deviation in the positive (sharp) direction than in the negative (flat). However, because of the clipped nature of the positive portion, wind pressure remains at its maximum for a longer time period than it would if there were no clipping. Therefore, an undesirable sharp pitch offset results.

The desperate technician then increases the length of the windline between chest and tremulant thinking the added volume of this line will cushion the harsh, violent action of the tremulant. He is right. It will reduce the harshness because the tremulant is now being de-coupled from the chest and its regulator. We now have a tremulant doing one thing and a regulator most likely doing something quite different, but both trying to act upon the same chest and pipes. This tremolo system is not in resonance. Its components are not acting in harmony. This tremolo system, while it may do something remotely musical under light load conditions, is doomed to abject failure under demanding heavy load situations.

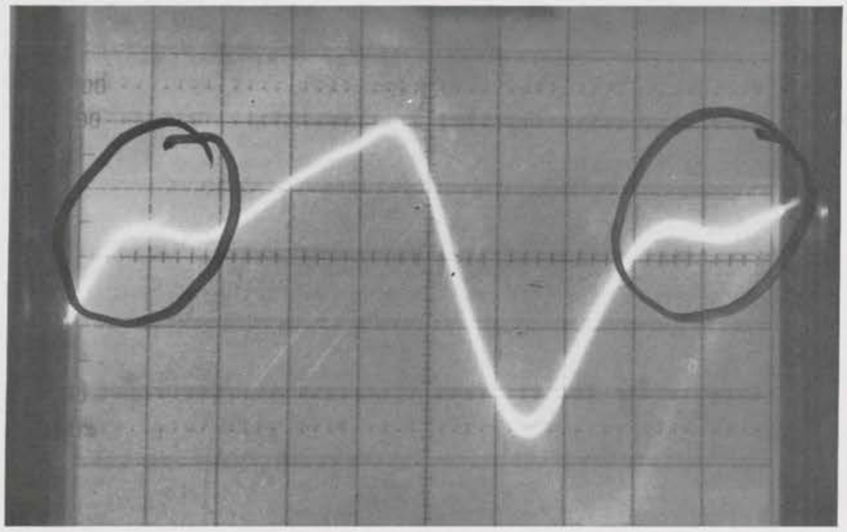

Photo 1: Slightly excessive tremulant inlet valve opening.

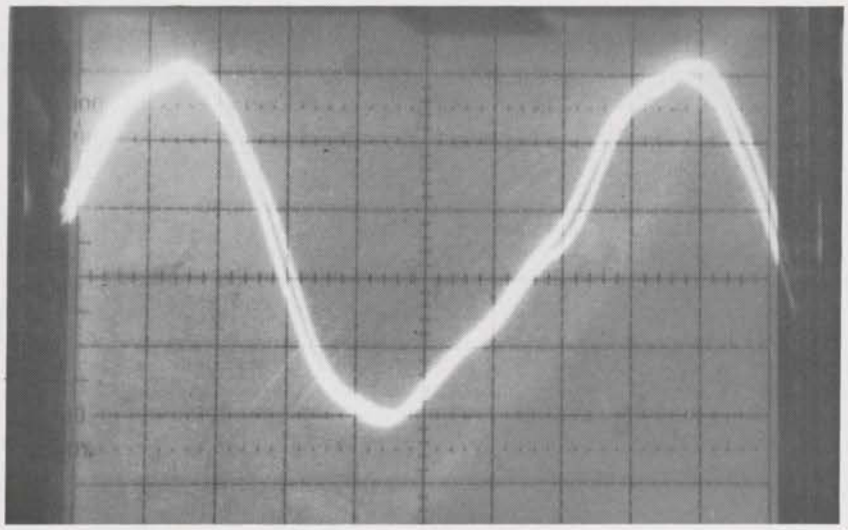

Photo 2: Insufficient tremulant inlet valve opening. Notice sinusoidal characteristic.

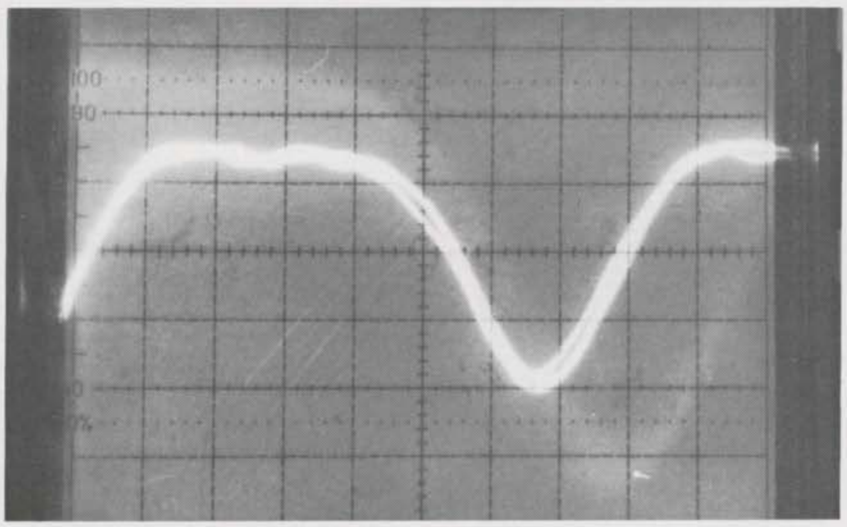

Photo 3: Maximum tremulant inlet valve opening. Note the clipped waveform resulting in a choppy, abrupt tremolo.

Let's approach this problem from the regulator's point of view. We add weight to the regulator. That will certainly slow the tremolo down. Eq. 9 says it will. But adding weight increases wind pressure. That's easy to fix. Just reduce tension on the hold-down springs until the presure returns to its original setting. This will slow the tremolo down even more. If very much weight is added the regulator's mass will be so great that inertia will prevent the regulator from accurately responding to varying load conditions as the organ is played. Furthermore, depth may be extreme to the point where pipes are flying off speech. We go back to the poor tremulant. It gets blamed for everything. Close the inlet valve. That will reduce depth but at the same time reduce speed (frequency). Close the outlet valve slightly. We didn't want the speed to go any slower. Refer to Photo 2. With the inlet valve shut down so far there is little harmonic development in the tremolo's pressure waveform. Like a sine wave, the tremolo now lacks color. It is boring, insipid, and just plain dumb. By now we should consider ourselves lucky if the tremulant will even start beating when the stop-tab is switched on. Once again, the system is not in resonance. Its various components are incompatible. This tremolo system is also condemned to failure.

Now, let's put the physics to work and see if there is any hope of salvaging this tremolo. Eq. 9 states volume plays an important role in determining the frequency of a tremolo. More important, Eq. 9 describes a tremolo's natural resonant frequency in a closed system. The climactic statement of this entire article follows:

If a tremolo's natural resonant frequency can be made equal to the desired tremolo frequency, that tremolo cannot be disturbed by dramatically varying load conditions!!

The tremulant will now float like a butterfly upon a cushion of wind in perfect harmony with the regulator. Its only task will be to serve as the trigger mechanism and affect minute modifications in speed, depth, and harmonic content of the tremolo's pressure waveform. This is that utopian pinnacle of transformation where the engineering of organ-building gives way to the art of organ-playing.

The very narrow, musically acceptable range of frequency for a tibia tremolo is about 6.2 Hz to 6.5 Hz with 6.3 Hz satisfying most people. The majority of modern theatre organ installations have insufficient total volume in their tibia tremolo systems. Therefore, their natural resonant frequencies will be too high and their depths too shallow.

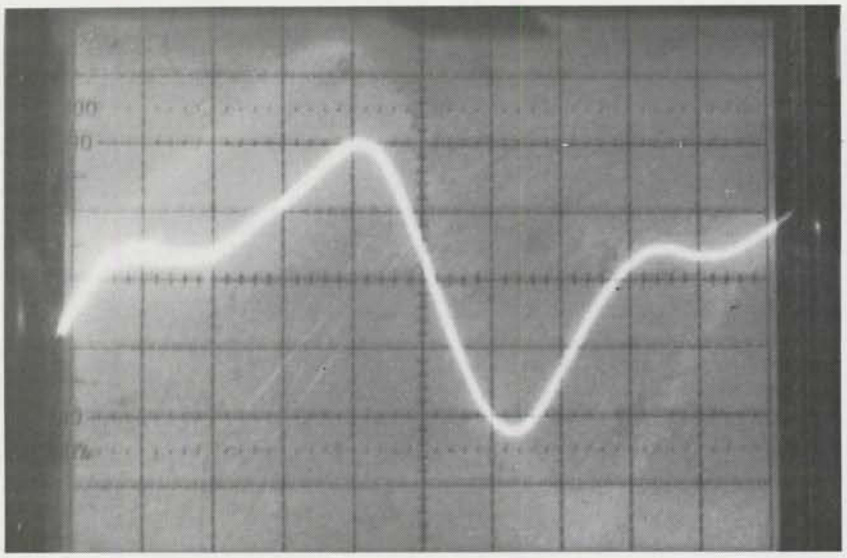

Photo 4: Normal tremolo waveform.

Most 1920's factory installations' tremolo systems were more successful for two reasons: 1. Tremolo frequencies, as a rule, were a little higher than today's tastes provide. 2. System volumes were greater (especially in larger instruments in larger chambers) because all bass offset chests were tremoloed with their associated manual chests. These two reasons together would have the effect of bringing natural resonant frequency closer to desired tremolo frequency. Most tremolo systems can be improved by increasing their total system volume.

Eq. 8 gives total volume of a closed system. Measure the volumes of the chest, regulator, tremulant and windlines and subtract them from the volume of Eq. 8. The difference is the additional volume required. This sounds simple enough, but the real work is just beginning.

The physics are done in the metric system so English to metric and back to English conversions will be plentiful. Readers accustomed to the metric system have a definite advantage.

The factors of Eq. 8 are:

V = total volume of closed system in cubic meters (m^3)
d = density of air in kilograms per cubic meter (kg/m^3)
c = velocity of sound in meters per second (m/s)
A = area of regulator top board in square meters (m^2)
m = mass of regulator top board plus additional weights in kilograms (kg)
f = desired frequency of tremolo in hertz (Hz)
π = constant pi 3.1416

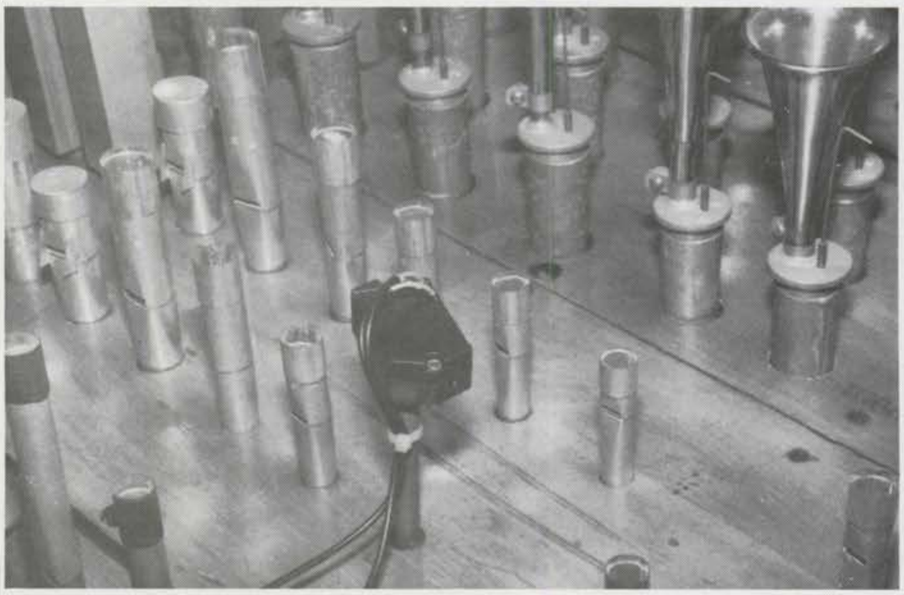

Photo 5: Pressure transducer inserted in place of a tibia pipe.

Determining the density of air and the velocity of sound in air are the two most intriguing factors governing the accuracy of Eq. 8. Air density is determined by altitude, wind pressure, temperature and humidity. Velocity is independent of pressure and density. However, it is dependent upon temperature, molecular weight and the ratio of specific heats. This relationship is given by Eq. 10:

Eq. 10

$$C = \sqrt{\frac{yRT}{M}}$$

where: c = velocity of sound in Ms
R = universal gas constant 8.314×10^3 J/kmol-K
T = temperature in degrees Kelvin (Note: $K^\circ = C^\circ + 273$)
M = molecular weight of gas in question in kg/kmol
y = ratio of specific heats (1.39 for polyatomic gasses)

A companion equation for the velocity of sound given in terms of pressure is:

Eq. 11

$$C = \sqrt{\frac{yP}{d}}$$

where: P = absolute pressure in Pascals
d = density in kg/m^3

We have previously stated that velocity was independent of pressure and density. Eq. 11 seems to refute that statement. The Ideal Gas Law states:

Eq. 12

$$PV = (m/M)(RT)$$

where: P = pressure absolute
V = volume
m = mass
M = molecular weight
R = universal gas constant
T = temperature

Solving Eq. 12 for P yields:

$$P = \frac{mRT}{VM}$$

, since density is mass per unit volume (m/V)

Eq. 13

$$P = \frac{dRT}{M}$$

Substituting Eq. 13 into Eq. 10:

Eq. 14

$$C = \sqrt{\frac{y\cancel{d}RT}{\cancel{d}M}} = \sqrt{\frac{yRT}{M}}$$

Therefore: Eq. 10 and Eq. 11 are equal

$$C = \sqrt{\frac{yRT}{M}} = \sqrt{\frac{yP}{d}}$$

Returning to Eq. 8 we can now substitute Eq. 11 for c:

Eq. 15

$$V = \frac{\cancel{d}yPA^2}{4\pi^2 mf^2 \cancel{d}} = \frac{yPA^2}{4\pi^2 mf^2}$$

We now have expressed total system volume in terms of the variables: mass, area, frequency and absolute pressure. Absolute pressure is wind gauge pressure plus atmospheric pressure. At or near sea level, atmospheric pressure is 1.013×10^5 Pascals. Therefore:

Eq. 16

$$P_{\text{absolute}} \text{ in Pascals} = (\text{wind pressure} \times 249.1) + 1.013 \times 10^5$$

According to the National Weather Service, a rule-of-thumb for elevations up to 10,000 feet above sea level is that atmospheric pressure decreases approximately 1 inch of mercury for each 1,000 feet rise in elevation. By adding this factor to Eq. 16 we can now determine P for Eq. 15 simply by measuring the wind pressure in the usual manner and by knowing the altitude in feet above sea level.

Eq. 17

$$P_{abs} = (\text{wind pressure} \times 249.1) + \frac{1.013 \times 10^5 \left[29.92 - \left(\frac{\text{elevation}}{1{,}000}\right)\right]}{29.92}$$

Area, volume and mass of the three most common sizes of Wurlitzer regulators are given in Table 1.

If we were to now construct this tremolo system (regulator, tremulant, chest and windlines) we would be horribly disappointed. The frequency would be much lower than we had desired. What went wrong? Thus far all tremolo systems discussed have been qualified as being closed systems. Common sense tells us a working theatre pipe organ tremolo is anything but a closed system. Regulator valves are always open to some extent. As they open, the organ's blower and its windlines become more and more coupled to our otherwise closed tremolo system. This pseudo extra volume explains why a system constructed strictly according to Eq. 15 will result in a natural resonant frequency much lower than desired. An additional factor, b, recognizing the blower's influence must be included in Eq. 15 which then becomes:

Eq. 18

$$V = \frac{byPA^2}{4\pi^2 mf^2} = \frac{.035bPA^2}{mf^2}$$

Solving Eq. 18 for f:

Eq. 19

$$f = .187A \sqrt{\frac{bp}{mV}}$$

The blower factor was determined by experimentation. A tibia tremolo system was refined (The Organ Grinder's small scale 10" main tibia.) by manipulating volume and mass until this tremolo could no longer be disturbed by varying load conditions. The inlet pressure to the tibia regulator was varied in one-inch, water pressure increments. With all else being equal, the tremolo's frequency was recorded at each increment of inlet pressure change. The frequency increases with pressure rise and decreases as inlet pressure falls. The tremolo failed when the regulator's differential pressure was decreased to about 2 inches. As each recorded frequency was inserted into Eq. 15, new volumes were obtained based on varying inlet pressures. The ratio between these *calculated* total volumes and the actual *measured* total volume results in the blower factor tabulated in Table 2.

Since all single rank (i.e., tibia tremolo systems) have insufficient total volume, additional volume must be generated. The usual method would be to increase length and/or size of windlines — particularly the windline between regulator and chest. This is not the correct method. According to the model presented here, tremolo is infra-sonic sound. A tremolo pressure wave is, therefore, traveling through windlines at a velocity of approximately 68,300 feet per minute! Extrapolating from data published by the American Society of Heating, Refrigeration and Air-Conditioning Engineers yields friction losses in circular wind lines expressed in inches of water pressure per foot as presented in Table 3.

Organ-builders sometimes use rectangular windlines. Losses will be greater in rectangular windlines than in circular windlines because, for equal area, the perimeter of a rectangle is greater than the circumference of a circle. The relationship between circular and rectangular windlines of equal capacities and friction losses is given by Eq. 20.

Eq. 20

$$D = 1.3 \sqrt[8]{\frac{(a\,b)^5}{(a+b)^2}}$$

where: D = diameter in inches
a & b = width and depth in inches

TABLE ONE

SIZE	AREA OF TOP BOARD	MASS OF TOP BOARD	VOLUME (Assume 4" Rise)
20" x 30"	$.388m^2$	7.49 kg	$.039m^3$
26" x 35"	$.588m^2$	11.35kg	$.060m^3$
32" x 35"	$.723m^2$	13.96kg	$.073m^3$

TABLE TWO

BLOWER FACTOR	BLOWER STATIC PRESSURE (Inches/Water)
.467	11
.484	12
.491	13
.492	14
.499	15
.502	16
.504	17
.507	18
.508	19
.517	20
.520	21
.522	22
.523	23

TABLE THREE

DIAMETER (Inches)	INCHES WATER PRESSURE (Lost/Foot)
6	0.14
5	0.18
4	0.25
3	0.375
2.5	0.5
2	0.6
1.5	0.75

(Editor's note: Author/researcher Dennis Hedberg will conduct a seminar, with a working model demonstrating his thesis, at the 1988 ATOS Convention in Portland.)

Even with many, many pipes speaking, the velocity of wind through a given line with the tremulant off will be a minute fraction of the tremolo wavefront's velocity. As an illustration, consider the ten-member team of runners shown in Fig. 3. Assume the runners are equal in all respects. They are to start running simultaneously through a dark, straight tunnel and a specified amount of time to reach the end.

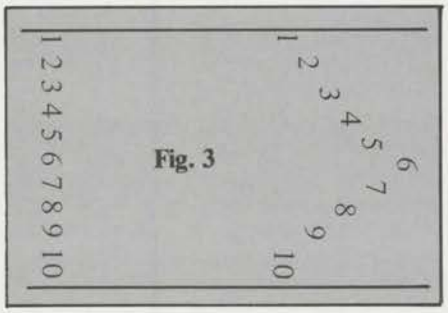

Fig. 3

Runners 5, 6 and 7 in the middle of the pack will exit the tunnel ahead of those runners closer to the tunnel walls because runners 1, 2 and 9, 10 are more likely to scrape the walls and be slowed down than are those runners in the middle. We started with a team of ten runners and finish with only three. Therefore, the strong, ten-member team at the start has become a weak, three-member team at the finish. In the case of an oscillating sound pressure wave we have a clean, well-defined pattern at the beginning of the windline (tunnel), Fig. 4A, and a somewhat skewed pattern at the end, Fig. 4B

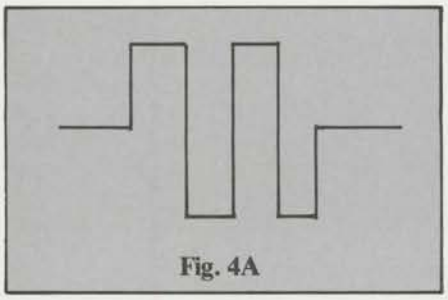

Fig. 4A

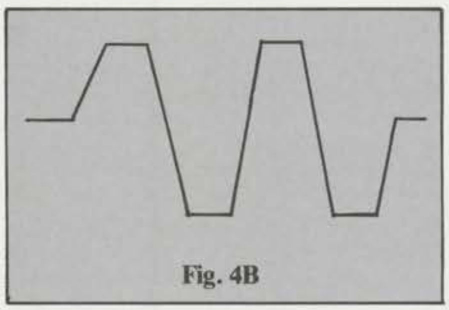

Fig. 4B

Thus, it is important to use large diameter and as short as possible windlines in order to keep friction losses to a minimum.

The correct technique of adding volume to a tremolo system in this model, is to run a separate, large-diameter, short windline from the regulator to a box or some other cavity of suitable volume as established by subtracting the total measured original volume from the calculated volume of Eq. 18. Examination of Eq. 18 reveals the calculated volume will be most affected by the area of the regulator's top board since this is a squared function. Therefore, if the area is doubled, the volume required to maintain constant frequency will be quadrupled. We now have a possible explanation as to why Wurlitzer built three common sizes of regulator, all of which have the same size valves and therefore, the same air-handling capabilities. Since the larger size regulators require greater volumes to maintain constant tremolo speed, we can easily satisfy the increased volume demands by feeding multiple chests (ranks). Supplying adequate wind to multiple ranks is not the issue. The smallest regulator will do just as well as the largest in that respect. Supplying an adequate tremolo pressure waveform is the issue. When volume and mass have been properly manipulated to produce a good, robust, MUSICAL tremolo it will not be possible to successfully wind more than three or four ranks from a 20" x 30" regulator. Correspondingly, more ranks may be successfully winded with larger regulators.

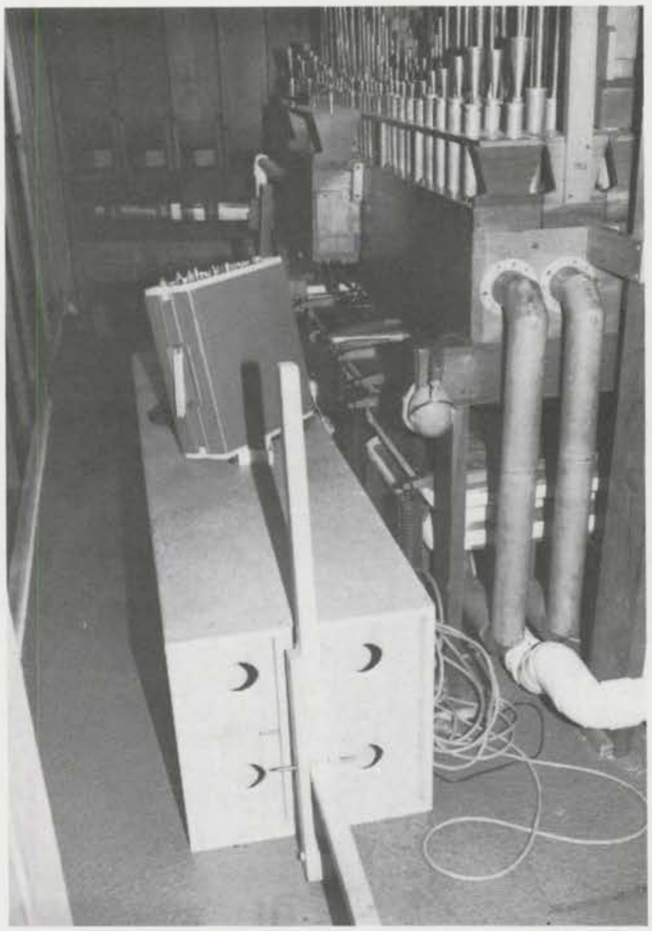

Photo: 6
Adjustable cavity for varying total system volume.

This model is not perfect. There is a tendency towards self-stimulation because a properly tuned tremolo system is very efficient. Little is required to initiate and maintain oscillation. Self-stimulation is most likely to occur under no-load and medium-to-heavy load conditions. No-load self-stimulation is caused by the cone valve allowing excessive wind to pass with the smallest of valve movement. Ironically, this condition is aggravated by good workmanship! It is also aggravated by high differential pressures. The solution is to bleed off a small amount of wind. Medium-to-heavy-load self-stimulation is triggered in much the same way as no-load conditions. That is, the small pallet valve admits too much wind for very small movements. Short of re-designing the entire valve assembly (which might not be a bad idea), the best way to alleviate this type of self-stimulation is to adjust the cone valve for more travel before the small pallet is engaged. 5/8" to 3/4" is usually sufficient. Much more than this and the regulating action will not be smooth. A more complicated approach would be to de-tune the tremolo by reducing regulator mass and/or total system volume thus raising the natural resonant frequency. It will then be up to the tremulant to work harder to maintain the desired frequency. However, this could be self-defeating.

It all comes down to priorities. In modern theatre organ playing, the tibia is seldom used without tremolo unless some sort of comic effect is desired. Diapasons, strings, flutes and reeds are quite another matter. Undesired tremolo on these ranks caused by self-stimulation could have a serious negative impact. The organ-builder/technician and the musician must cooperate to find mutually acceptable tremolo performance and stable wind supply with tremulants off.

The author is well aware of the controversial nature of tremolo performance. This article is meant to be thought-provoking. If it has helped some, fine. If it has confounded others and dumbfounded a few, that's fine too. This model really works. The physics and mathematics say it works. This technique will stand scrutiny and the Organ Grinder instrument is daily, demonstrable proof it does, indeed, work. Readers should not think the author is attempting to establish himself as the "guru" of tremolo but rather as a researcher who is trying to make it possible for tremolo performance to be predicted by designing to tolerances sufficiently narrow so the performing artist's acute ear can replace the calculator and make magic out of the mundane.

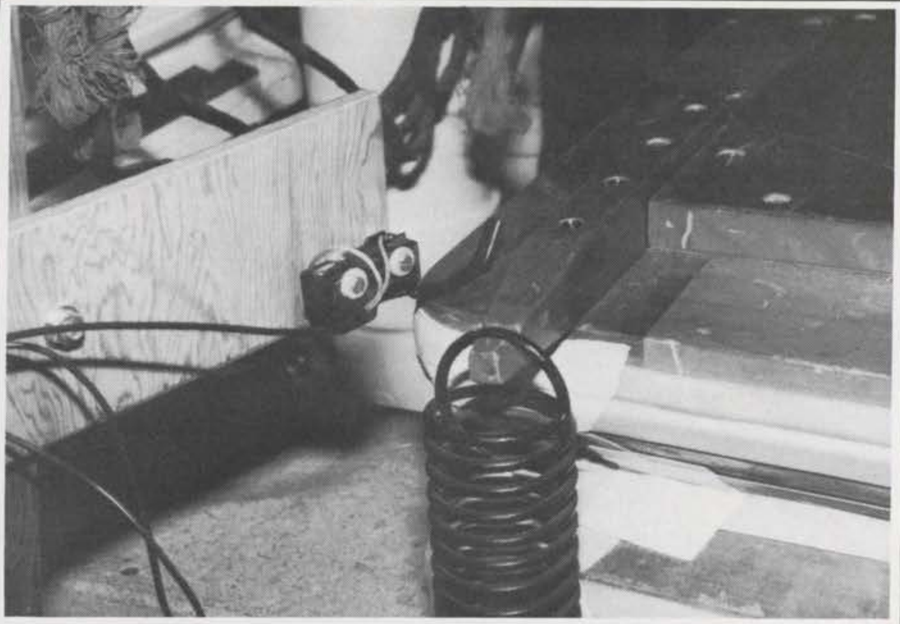

Photo 7: Counter trigger-switch for determining tremolo frequency.

Other Useful Information

$1\ \text{lb/ft}^3$	$= 16.02\ \text{kg/m}^3$
1 m	= 1 ft x 0.305
$1\ \text{m}^2$	$= 1\ \text{ft} \times 0.305^2$
$1\ \text{m}^3$	$= 1\ \text{ft} \times 0.305^3$
1 kg force	= 1 lb x 0.454
$1\ \text{lb/in}^2$	= 27.68" water pressure
1 Pascal	$= 1.45 \times 10^{-4}\ \text{lb/in}^2$
Standard pressure	$= 1$ Atmosphere $= 14.7\ \text{lb/in}^2 = 29.95$" Hg (Mercury)
	$= 1.03 \times 10^4\ \text{kg force/m}^2 = 1.013 \times 10^5$ Pascals
1" water pressure	$= 3.613 \times 10^{-2}\ \text{lb/in}^2 = 5.202\ \text{lb/ft}^2 = 25.39\ \text{kg force/m}^2$
	= 249.1 Pascals
Fahrenheit° - 32 (5/9)	= Centigrade°

$$\text{Velocity of sound in dry air in m/s} = 331\ \frac{1 + \text{Centigrade}^{\circ}}{546}$$

$$\text{Density of dry air at 1 Atm. and given temp. C}^{\circ} \text{ in kg/m}^3 = \frac{352.17}{\text{C}^{\circ} + 273}$$

Allowing for channeling, magnets, pneumatic blocks, etc., the volume of a Wurlitzer flute chest is $3{,}354.6\ \text{in}^3$. The volumes of other Wurlitzer chests may be found by Eq. 21.

Eq. 21

$$V = 3{,}354.6 + 798\ (\text{toe board width inches} - 6.5)$$

Hence, a Wurlitzer tibia chest's toe board width is 9" and its volume is therefore $5{,}349.6\ \text{in}^3$ or $0.088\ \text{m}^3$.

Volume of large Wurlitzer tremulant is $612\ \text{in}^3$ or $0.01\ \text{m}^3$.

Volume of small Wurlitzer tremulant is $341\ \text{in}^3$ or $0.0056\ \text{m}^3$.