Audio Engineering Society
Convention Paper
Presented at the 115th Convention
2003 October 10–13 New York, NY, USA

Lamps for Speaker Protection

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ABSTRACT
Incandescent lamps have been used for over fifty years as loudspeaker protection devices, but a large amount of misinformation about them exists. The author measures static and dynamic parameters of over thirty types of auto lamps, as well as tests some types for consistency between manufacturers and production. The results contradict a lot of the common wisdom about using lamps for protection and show serious linearity problems even at low operating levels.

1. FAILURE MODES OF LOUDSPEAKERS

There are two primary failure modes of overloaded loudspeakers. The first is the result of mechanical damage in which the voice coil itself is ejected from the gap. This is most normally the result of a sharp pulse of short duration and high amplitude.

The second failure mode is failure of the voice coil itself due to overheating. This is normally a slower failure, caused by large currents in the coil over the course of minutes or even hours. This most notably occurs when there is power which cannot be dissipated as mechanical motion, normally either ultrasonic or DC content. [1]

A protection device designed to prevent the first failure mode would need to have a short time of action, and it would need also to have an abrupt knee, that is to say it should have no effect on the signal below a certain point and above that point it should immediately act to limit current into the load. A fuse is a good (though nonresettable and slow-acting) example of a device with an abrupt nonlinear transition point.

A protection device designed to prevent the overheating mode does not need to be as fast acting, but it requires an even sharper knee because the amount of current involved is lower, and therefore closer to the normal operating current of the device. Without a sharp knee, there will be audible compression artifacts during normal operation.

2. USING LAMPS

Light bulbs have long been used as series elements for protection of speakers. The #211 automotive lamp, originally intended for dome lights, shows up in a considerable number of commercial designs, while others employ brake light bulbs and turn signal bulbs. It is common wisdom that the action of these devices is to present a low resistance to current until they heat up. As they heat up, they begin to glow and at the point where they begin to glow, the series resistance begins to rise. The original intent of this paper was to measure a variety of lamps to provide valid selection criteria for different speakers by determining at what point the change in resistance occurred with lamps of various types. Unfortunately, in this testing, we failed to find any such discontinuity.

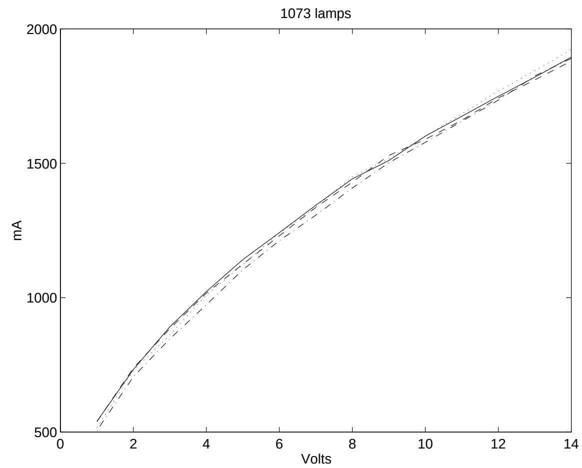
Now, this seems reasonable, in that what we have is a system in which the resistance is linearly proportional to the temperature and the amount of heat going into the system is equal to the input power (V^2/R). On the other side of the equation, we have heat loss from the filament which is almost entirely radiative and therefore proportional to the fourth power of difference between ambient and filament temperatures (by Stefan's Law of Radiation).

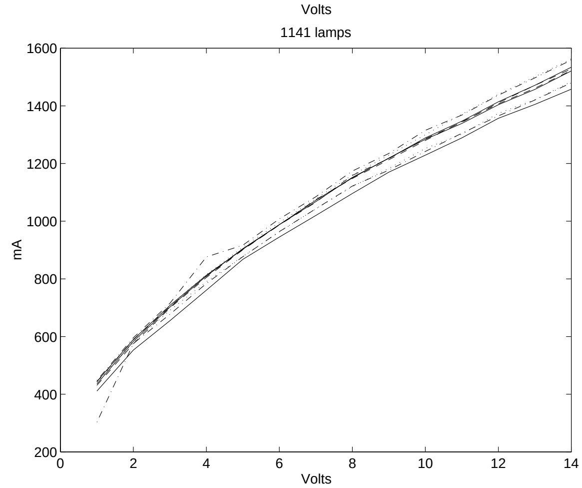
3. STATIC OPERATION

Table 0.1 gives a chart of static resistances of various automotive lamps measured at 72° F., as our baseline for cold operation.

Note that both Vendor P 97 lamps read very high cold resistance (6.6 ohms and 66.5 ohms) before first illumination. Afterward, cold resistance dropped down to 2.5 ohms. We have no explanation for this initially high resistance except a possible surmise of some sort of poor contact between the support wire and the filament which was improved on first heating.

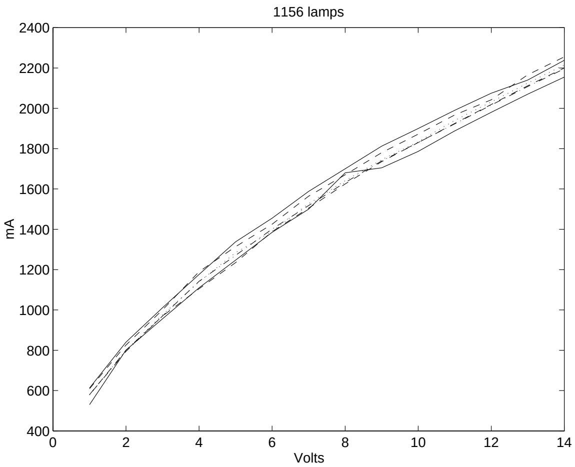
Now, to determine when a given lamp begins to limit, we drew static I/V curves. Taking a bench supply, we set it to a given voltage using a reference Fluke 87 meter, then used the same meter to measure current into various lamps at that voltage level. Each series of lamps was measured at each voltage level in turn, with increments of one volt, so they all started out cold when each measurement was made. The measurements themselves were taken at given voltages after the current stayed within a 1 mA increment for 5 seconds. Note that all lamps tested began to glow between 2V and 3V except for the 1683 which is the only 24V lamp listed.

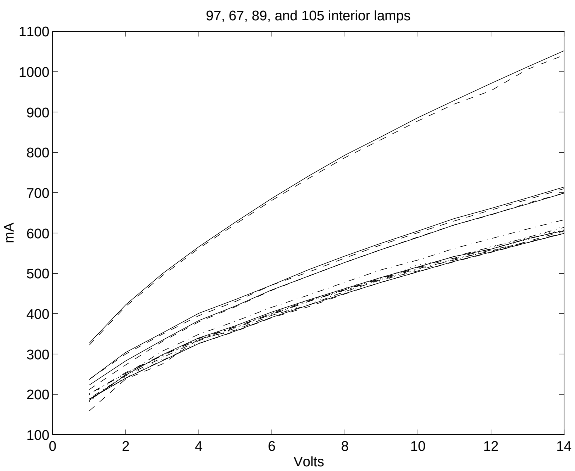




Mfg	No	Origin	Volt	Candle power	Cold Res	Sample Size	Comments
Vendor G	67	Hungary			2.8-2.9	2	
Vendor S	67	Taiwan			2.5-3.2	2	
Vendor G	89	USA			3.1-3.2	2	
Vendor P	89	Hungary	12		2.6	2	license plate
Vendor S	89	Taiwan			6.9-8.6	2	
Vendor S	93	Taiwan			1.7	2	Under Hood/Trunk
Vendor G	97	Taiwan			2.5	2	
Vendor P	97	Hungary			2.5	2	Dome/trunk
Vendor S	97	Hungary			2.4-2.6	2	
Vendor S	105	Taiwan			2.6	2	Map/Overhead/Trunk
Vendor P	1003	Taiwan			1.6	2	Dome/trunk
Vendor W	1003	Mexico	13	15	1.5-1.6	2	Dome/trunk
Vendor S	1073	USA			1.2-1.3	2	Back up/Turn
Vendor W	1073	Mexico	13	32	1.4-1.5	2	
Vendor W	1137	Mexico			0.8-0.9	2	Brake fil
Vendor W	1137	Mexico			2.7	2	Running fil
Vendor P	1141	France			1.2-1.3	2	Back up light
Vendor G	1141	Hungary			1.4	2	
Vendor S	1141LL	USA			1.3	2	Back up – long life
Unknown	1141	China			1.4	1	Back up light
Vendor W	1141	Mexico	13	21	1.3-1.5	2	Back up light
Vendor G	1156	Hungary			1.0	2	
Vendor S	1156	Slovakia			1.3-1.4	2	
Vendor W	1156	Mexico	13	32	0.9-1.3	2	
Vendor W	1295	Mexico	12.5	50	1.2	2	
Vendor W	1683	China	28	32	2.6	2	Dual fil
Vendor W	3497	China	12	45	0.8-0.9	2	
Vendor G	211-2	Mexico			4.0-4.2	2	Long tubular
Vendor S	211-2	USA			1.6	2	Long tubular Blue Dot
Vendor W	211-2	?	13	12	?	2	Long tubular Blue Dot
Vendor S	212-2	USA			2.1	2	Long tubular Green Dot
Vendor W	212-2	?	14	6	?	2	Long tubular Green Dot

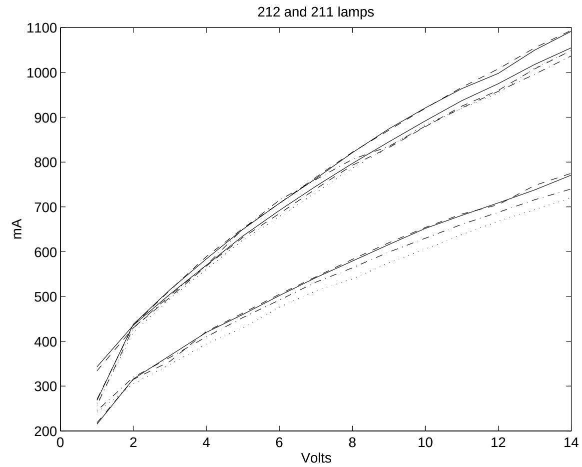
Table 0.1: DC Characteristics of Automotive Lamps



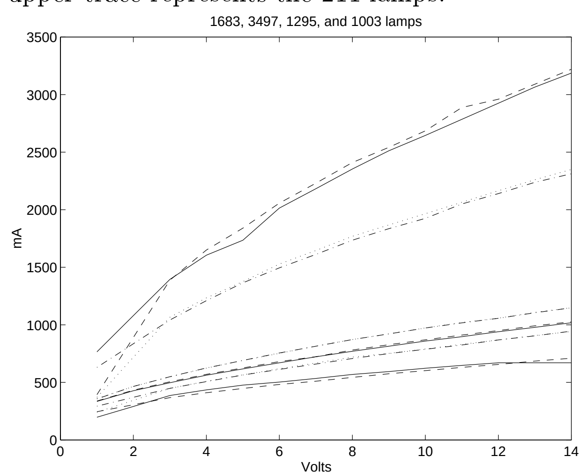


The figures above show the actual measurement of various lamps from different manufacturers and of different types. As you can see, the curves are fairly smooth with no real knee, and the limiting effect begins well below the point at which a glow is visible by the naked eye.

All of these curves were drawn manually with a considerable amount of time spent per measurement to eliminate any time-domain effects. They should therefore be a direct indication of the monotonicity of the lamps. Note that this last chart represents curves of several different types of lamps intended for interior lighting, which have smaller filaments than the others tested.



This figure shows measurements of various 211 and 212 lamps, again from different manufacturers. Some of these lamps appear to show a knee on the lowest measurement. It is, however, a very slight one and may well be a measurement error. Note that the lower trace here represents the 212 lamps, while the upper trace represents the 211 lamps.



Here is another odd one. The lowest trace on this chart represents the 1683 lamps, the next one up the 1003 and 93 lamps, and the top two groupings are the 3498 and (topmost) 1295 lamps. The first set of measurements I did of the 1683 lamps showed a severe nonlinearity at low voltages but this does not seem to be repeatable at all.

4. SPEED OF LIMITING

The speed at which the device changes resistance has a lot to do with the mass of the filament, in that the rate of heating is inversely proportional to the mass.

In the case of the first failure mode, we want a device which limits as quickly as possible, and to that end we applied static 12V square waves to various lamps to draw I/T curves to see how rapid the onset of action would be. We found a clear logarithmic curve, with instantaneous current I_t easily modelled as $I_t = I_0 e^{-t/k} + I_{static}$ where k is a specific time constant for each lamp type, I_0 is the initial (surge) current, and I_{static} is the static operating current.

Using a chart recorder, we measured these numbers at turn on with a nominal 12V supply. Note that the static operating currents we measured can be compared with those in the static measurements above, and the initial currents can be compared with the expected currents from the static resistances in the static parameters chart above, to find good correlation. Table 0.2 summarizes the derived time constants (measured to within 5 mS).

As you can see from the chart, there is a considerable variation in time constant between different lamps, probably mostly due to different filament masses. But even variations within the same type are a bit higher than we would like to see for a protection device.

4.1. How Dynamic Effects relate to protection

In the case of the direct overheating failure mode, it could be argued that the mode of failure itself was caused by heating, and that a given waveform would cause the same degree of heating in the lamp as it would in the voice coil, and therefore this can be considered an effective protection method in that the protective resistance would remain more or less proportional to the degree of heating in the coil, but of course in the real world the thermal time constant on the lamp is much faster than that of the coil. So we cannot claim that using the lamp as a slow compression device is effective in reducing damage caused by voice coil heating, unless a large safety margin is employed. Adding that safety margin means that there will be audible effects on short peaks due to the mismatch in times. Some information on the effective time constants involved in loudspeaker heating can be derived from [2] and they are quite long.

5. CONSISTENCY

Automotive lamps are generally not specified as to I/V curves, or as to time constants. So, how consistent are they from one unit to the next? Between manufacturers? The rough measurements above would indicate that repeatability isn't very good. Some lamp types seem to be more consistent than others but we have not had the opportunity to test a large number of any type.

6. ARE ARTIFACTS AUDIBLE?

We took a commercial horn-loaded loudspeaker employing a #211 lamp for protection, and replaced that lamp with a 2.0 ohm resistor, that being the measured cold resistance at 72° F. of the original lamp shipped with the speaker. We then took three sample recordings and played them back with either the resistor or the #211 lamp in series with the horn, with an average level of 85 dB measured A-weighted with the slow setting on a GenRad meter.

Three untrained listeners were used in a single-blind testing methodology, all undergraduates from the music program at a local college. All three of them identified the resistive link as sounding better, in spite of the operating level of the speaker being well below the point at which any speaker protection device effects should occur.

This was not a particularly well-conducted or careful listening study, but the effects are so significant even at comparatively low levels that we don't think a more careful study is warranted.

7. SO WHAT NOW?

There are a number of commercially available thermal devices, from thermistors to "resettable fuses" which employ a number of different technologies but which are intended to have positive temperature coefficients. Many of these are intended to have knees in their I/V curve, and many of them have much more controlled time domain characteristics. Do these have less audible effect than lamps? This is worth future testing.

This study was hampered severely by the lack of a good mathematical model for loudspeaker failure. A literature search brought up only two mathematical models for estimation of heating effects [1,2], and no data at all connecting this with real-world devices. There is no data at all on damage due to momentary overexcursion.

Mfg	No	Origin	I_0 mA	I_{static} mA	K mS	Comments
Vendor S	67	Taiwan	280	60	10	
Vendor P	89	Hungary	250	60	15	
Vendor S	89	Taiwan	230	55	5	
Vendor S	93	Taiwan	460	120	10	
Vendor S	105	Taiwan	320	100	15	
Vendor P	1003	Taiwan	400	100	10	
Vendor S	1141LL	USA	500	150	20	
Vendor W	1141	Mexico	510	150	25	
Vendor S	1156	Slovakia	800	220	40	
Vendor G	211-2	Mexico	260	100	20	Blue dot
Vendor G	211-2	Mexico	370	100	20	Blue dot
Vendor S	211-2	USA	400	100	10	Blue dot
Vendor S	211-2	USA	460	100	15	Blue dot
Vendor W	211-2	?	480	110	15	Blue dot
Vendor S	212-2	USA	400	80	15	Green dot
Vendor S	212-2	USA	320	80	25	Green dot
Vendor W	212-2	?	320	80	10	Green dot
Vendor W	212-2	?	320	80	10	Green dot

Table 0.2: Dynamic Characteristics of Automotive Lamps

8. ACKNOWLEDGEMENTS

Many thanks for Dick Pierce, consultant, and Fred Lallman of NASA Langley for their input and suggestions. Thanks to Auto Parts and Supply in Williamsburg, Virginia for tracking down some odd lamps.

9. REFERENCES

[1] Henricksen, C.A., "Heat-Transfer Mechanisms in Loudspeakers: Analysis, Measurement, and Design", J. Audio Eng Scoeity, vol. 35, no. 10, pp. 778-791 1987 Oct.

[2] Klippel, W., "Nonlinear Modeling of the Heat Transfer in Loudspeakers," AES convention paper 5733, Presented at the 114th convention (2003).