AUDIO TRANSFORMER DESIGN FOR TUBE AMPLIFIER WITH IMPROVED QUALITY AND REDUCED COST

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INTRODUCTION

Audio equipment is used in many locations and facilities. Sound quality is the most important factor in any audio equipment. There are many producers (e.g. Marshall, Fender, etc.) [1] of audio equipment and systems capable of ensuring clear professional sound. As is generally the case, cost increases with quality, since higher quality means more costly components, and therefore often the only way to get a good sound is to pay a considerable amount of money.

The problem of getting high sound quality at reduced cost is thus an important issue for many people all over the world.

Amplifiers are among major special audio components. Tube amplifiers are the most commonly used amplifiers for professionals and sound experts. The cost of a tube amplifier mostly consists of the cost of an output transformer and tubes that is usually a factor limiting the sound quality.

Audio transformer is the primary part of a tube amplifier which generates an electromagnetic field. The objective of this project is to develop an output transformer for single-ended tube amplifiers with reduced magnetic fields while preserving an adequate sound quality. IEEE C95.6-2002, 4210-2003 National Standard of Ukraine and IEEE C95.3.1-2010 on electromagnetic fields and human exposure to these fields which are important standards for human health have been used in this project.

STRUCTURE OF TUBE AMPLIFIER

Tube amplifier consists of 4 main parts (fig. 1): **1. Power System** generates a stable DC voltage (250V) and AC heater voltage for tube lamps (6.3 V); **2. Preamplifier** consists of a 6n1p tube and is connected to the audio input; **3. Output amplifier** consists of a 6p1p output tube and output transformer (fig. 2); **4. Audio speakers.**

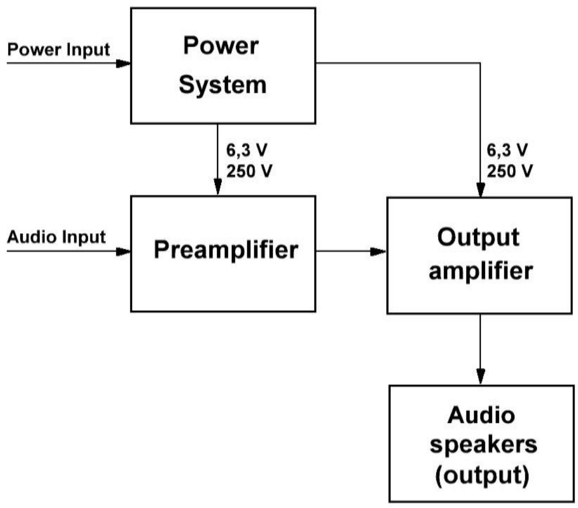

Fig. 1. Block scheme of tube amplifier

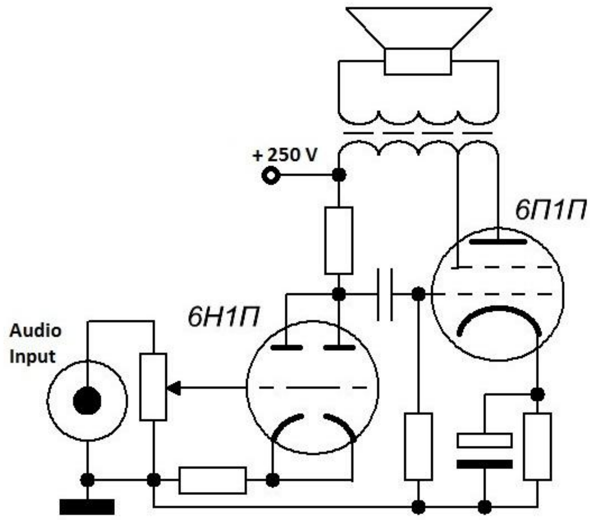

Fig. 2. Circuit of tube amplifier device

The output transformer is an important part of the amplifier requiring a thorough parameter determination. Building an amplifier is an important step in the experimental part of the project.

OUTPUT AUDIO TRANSFORMER DESIGN

The output transformer in a single-ended tube amplifier is the device which matches the high-output impedance of the tube to the low input impedance of the speaker load (4, 8 or 16 Ohm). To design an output transformer, it is necessary to determine the output power according to the tubes's characteristics, most notably the input and output impedance and total power. The 6p1p Russian tetrode, for example, produces 3.5W, with a 5 kOhm impedance.

The ratio of impedances produces the transformation ratio. The ratio of impedances is given by:

$$n=(Zp/Zs)^{1/2}$$

where Zp and Zs are primary and secondary transformer impedances. We selected a primary impedance of 4096 Ohm as this is the recommended impedance for the 6p1p tube lamp. The audio speaker impedance is 4 Ohm.

By using the above formula, we can calculate the turn number of windings required. It is proportional to the ratio of input and output impedances:

$$n=Np/Ns=(Zp/Zs)^{1/2}$$

where Np and Ns designate the primary and secondary turn numbers.

$$n=(4096/4)^{1/2}= 32;$$

The equivalent transformer impedance can be then calculated (tube impedance is 5 kOhm and Zp is the input impedance of 4096 Ohm)

$$Req = (Rtube*Zp)/(Rtube+Zp),$$

Based on the above: Req = 2251 Ohm

Based on the above, the inductance can be calculated:

$$L = Req/2*pi*f1$$

where pi is 3.1415…, f1 is the lower frequency of the amplifier.

Output transformers are generally designed for frequencies between 20 Hz and 20 kHz which are audible to the human ear. We assumed f1 to be equal to 40 Hz. In experiments, transformers operating in the range of 40 Hz to 18 kHz showed the best performance.

Based on the above: L = 9 H

The core size can be calculated based on the power level [2] and design of the transformer core. For this project it is preferential to use EI laminated iron core transformer since this type of transformers is most commonly used for the output stage of single-ended tube amplifiers. A 'EI' core is constructed of interleaved stacked 'E' and 'I' shaped pieces (fig. 3). Moreover 'EI' type cores provide better output characteristics than toroidal cores for single-ended tube amplifiers, with easier winding methods.

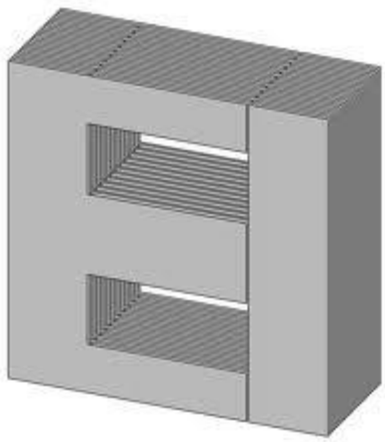

Fig. 3. EI type of transformer core

Based on an output power of 3.5 W, the size of transformer core has been chosen as EI 16*24 with 3.81 cm^2 middle leg (or tongue) area [2].

The number of windings was then calculated [3]:

$$w1=1200*(L)^{1/2}=3600;$$

$$w2=w1/n=112.5;$$

Wire type and thickness are as follows:

w1 is 0.125 mm, PEV-1 (enamelled copper wire, type 1);

w2 is 0.5 mm, PEV-1 (enamelled copper wire, type 1).

Audio output transformer is shown at fig. 4.

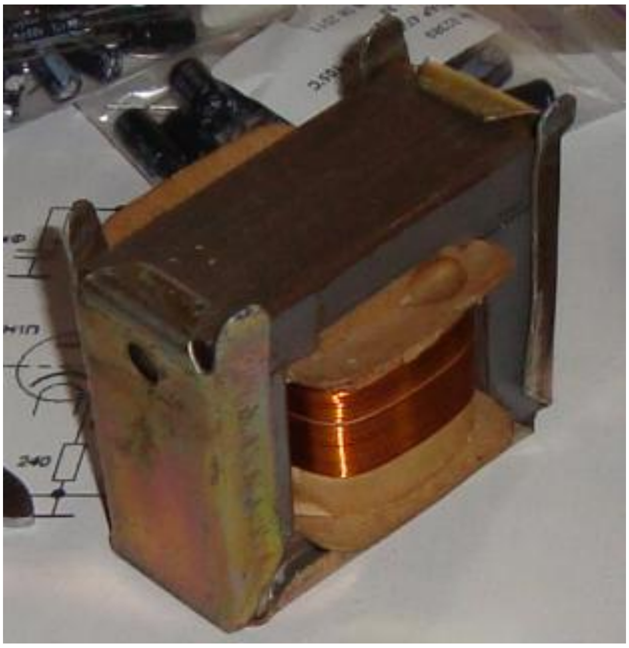

Fig. 4. Output audio transformer

Between part “E” and part “I” paper insulation is used.

DESCRIPTION OF STANDARDS

For this project we used IEEE C95.3.1-2010, 4210-2003 National Standard of Ukraine and C95.6-2002 standards.

IEEE Standard C95.3.1-2010 [5]. The first of the standards mentioned in our student application paper grant application abstract, IEEE C95.3.1-2010 IEEE Recommended Practice for Measurements and Computations of Electric, Magnetic, and Electromagnetic Fields with Respect to Human Exposure to Such Fields, 0 Hz to 100 kHz:

Scope of standard: This recommended practice describes 1) methods for measuring external electric and magnetic fields and contact currents to which persons may be exposed, 2) instrument characteristics and the methods for calibrating such instruments, and 3) methods for computation and the measurement of the resulting fields and currents that are induced in bodies of humans exposed to these fields. This recommended practice is applicable over the frequency range of 0 Hz to 100 kHz.

Purpose: The purpose of this recommended practice is to describe preferred measurement techniques and computational methods that can be used to ascertain compliance with contemporary standards for human exposure to electric and magnetic fields in the frequency range of 0 Hz to 100 kHz such as IEEE Std C95.1™-2005 [B55], IEEE Std C95.6™-2002 [B58], and similar standards. This document is intended primarily for use by engineers, biophysicists, and other specialists who are familiar with basic electromagnetic (EM) field theory and practice, and the potential hazards associated with exposure to EM fields. It will also be useful to bioeffects researchers, instrument developers and manufacturers, those developing calibration systems and standards, and individuals involved in critical hazard assessments or surveys.

We used the device (ELF Sensor [4]) complying with this standard. As this standard includes measurement techniques, we measured magnetic fields with a magnetic field meter.

4210-2003 National Standard of Ukraine [6]. This standard recommends measurements at a distance not less than 10 cm for frequency range from 45 Hz to 600 Hz. Temperature should be between 15°C and 30°C. We used 4210-2003 National Standard of Ukraine, when measuring distance was more than 10 cm.

<u>IEEE C95.6-2002 Standard [7].</u> In our student application paper grant application abstract we did not mention C95.6-2002. However, when the search was started, we needed to determine exposure limits for measurements. Based on this we decided to add standard IEEE C95.6-2002, IEEE Standard for Safety Levels with Respect to Human Exposure to Electromagnetic Fields, 0–3 kHz:

<u>Scope of Standard:</u> This standard defines exposure levels to protect against adverse effects in humans from exposure to electric and magnetic fields at frequencies 0–3 kHz. This standard was developed with respect to established mechanisms of biological effects in humans from electric and magnetic field exposures. It does not apply to exposures encountered during medical procedures. The defined exposure limits do not necessarily protect against interference of medical devices or problems involving metallic implants.

<u>Purpose of Standard:</u> The IEEE has previously defined safety standards for human exposure to electromagnetic fields in the frequency range from 3 kHz to 300 GHz (IEEE [B46]). The purpose of this standard is to define exposure standards for the frequency range from 0 to 3 kHz.

Exposure limits and exposure tables of magnetic fields were taken from Standard IEEE C95.6-2002. Low frequency measurement within the frequency range 45 Hz-600 Hz were made by using techniques of the standard.

The results from experimental records made under standard IEEE C95.3.1-2010 with regard to exposure limits defined in IEEE C95.6-2002 are given below.

Table 1.

Table 1—Basic restrictions applying to various regions of the body[a, b]

Exposed tissue	f_e (Hz)	General public	Controlled environment
		E_0 - rms (V/m)	E_0 - rms (V/m)
Brain	20	5.89×10^{-3}	1.77×10^{-2}
Heart	167	0.943	0.943
Hands, wrists, feet and ankles	3350	2.10	2.10
Other tissue	3350	0.701	2.10

[a]Interpretation of table is as follows: $E_i = E_0$ for $f \leq f_e$; $E_i = E_0\ (f/f_e)$ for $f \geq f_e$.
[b]In addition to the listed restrictions, exposure of the head and torso to magnetic fields below 10 Hz shall be restricted to a peak value of 167 mT for the general public, and 500 mT in the controlled environment.

Table 2.

Table 2—Magnetic maximum permissible exposure (MPE) levels: exposure of head and torso[a, b]

Frequency range (Hz)	General public		Controlled environment	
	B - rms (mT)	H - rms (A/m)	B - rms (mT)	H - rms (A/m)
< 0.153	118	9.39×10^4	353	2.81×10^5
0.153–20	$18.1/f$	$1.44 \times 10^4/f$	$54.3/f$	$4.32 \times 10^4/f$
20–759	0.904	719	2.71	2.16×10^3
759–3000	$687/f$	$5.47 \times 10^5/f$	$2060/f$	$1.64 \times 10^6/f$

[a]f is frequency in Hz.
[b]MPEs refer to spatial maximum.

According to the above tables, low frequency measurements were determined. Table 1 includes frequency ranges given in Table 2 and defines specific magnetic field density.

MEASUREMENT OF ELECTROMAGNETIC FIELD

We began with the amplitude-frequency curve measurement (fig. 5):

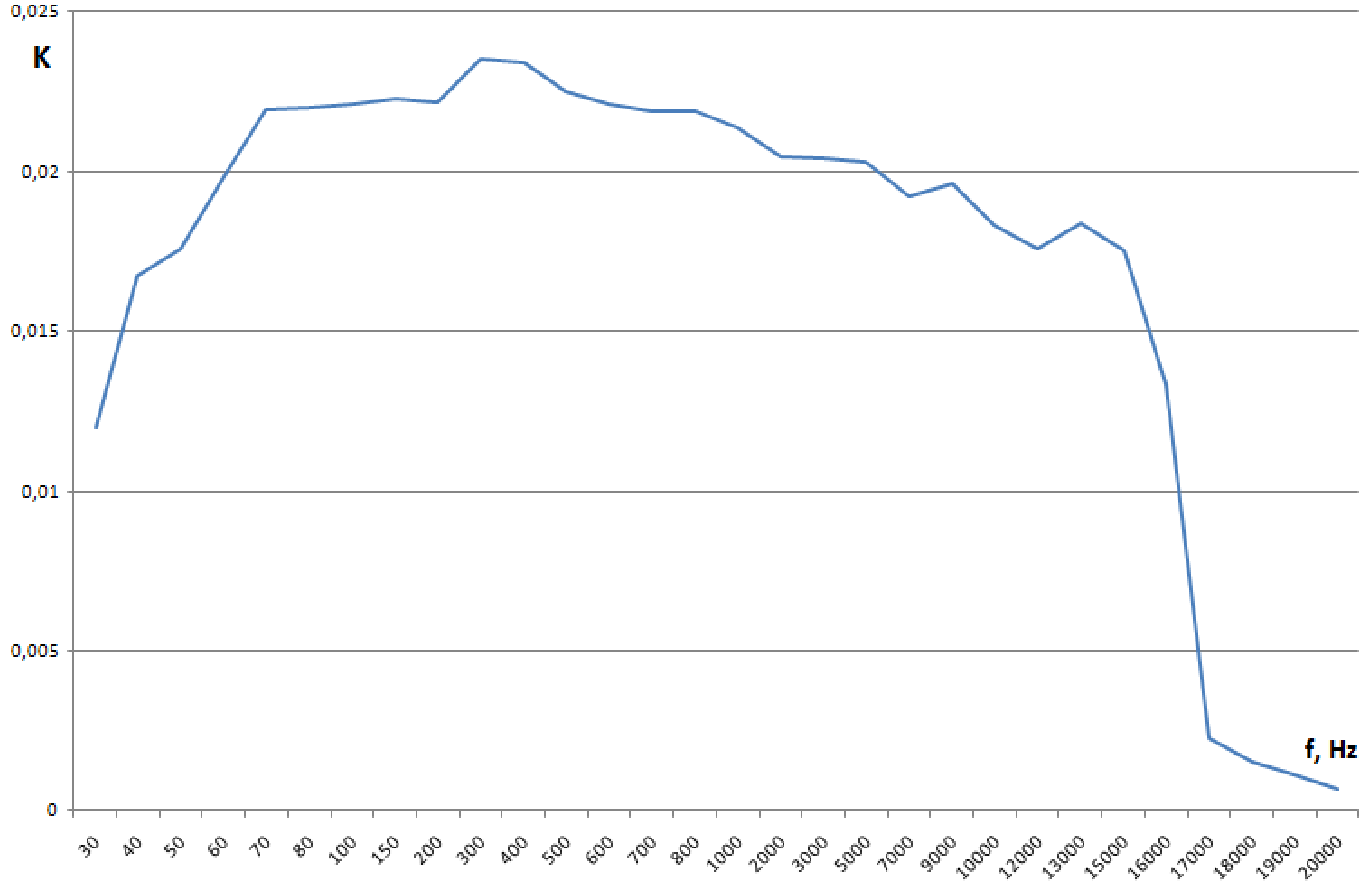

Fig. 5. Amplitude-frequency characteristics of audio output transformer

According to fig.5, we concluded that the best performance of the transformer was achieved in the frequency range of 40 Hz to 18 kHz.

To measure the electromagnetic field, an ELF Sensor [4] was used. The instrument consists of the following parts: 1. Sensor and Electronic Circuit; 2. Indicator. The parts were connected with a cable (0.9 m long). Instrument accuracy was 5% for measurement results and 5% for frequency range (45 to 600 Hz).

Measurements were made in a three axis system (fig. 6). We began with the measurement of the magnetic induction on axis “X” (fig. 7). The sensor to transformer distance was increased from 15 mm to 200 mm.

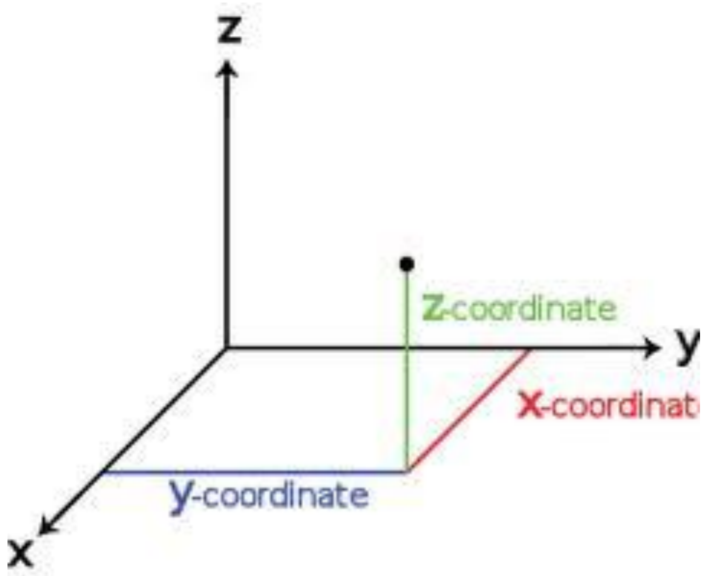

Fig. 6. Three axis system for experiment

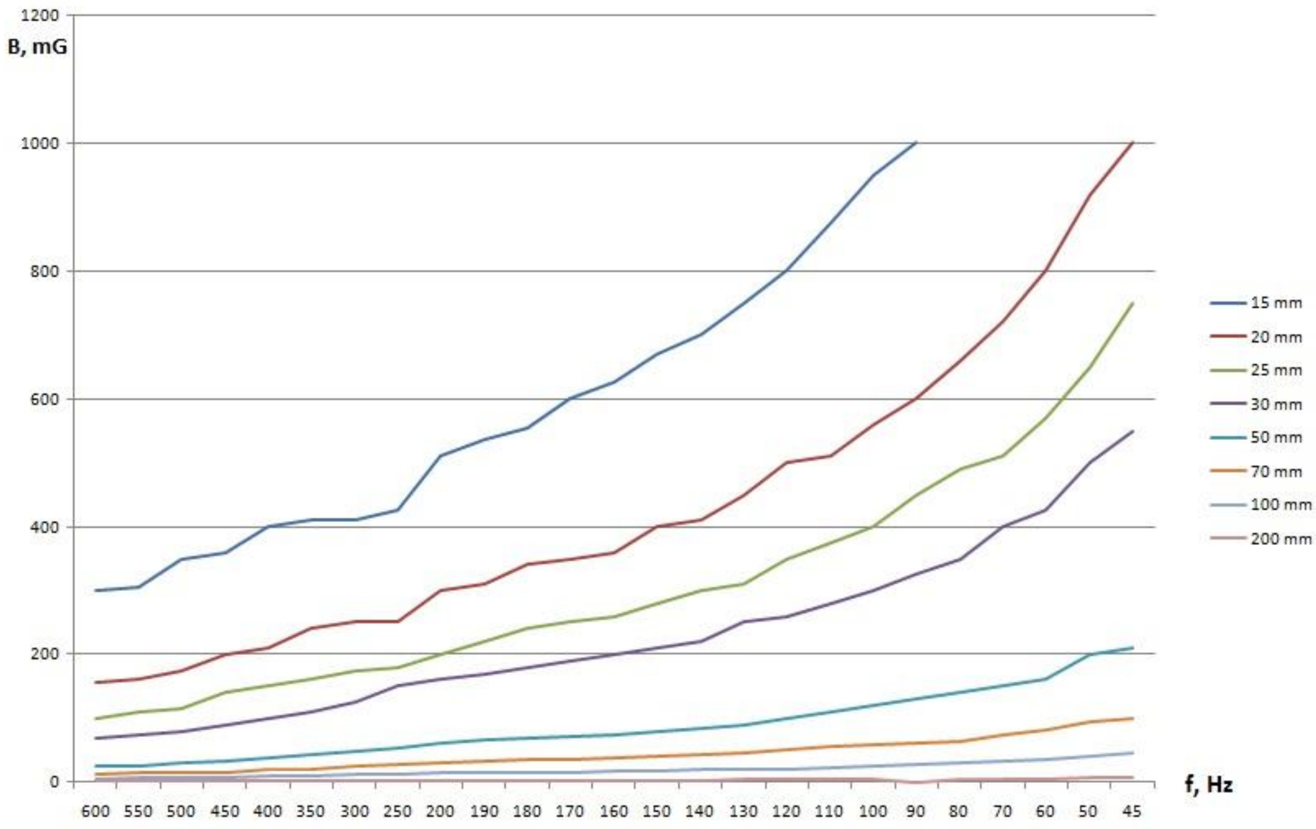

Fig. 7. “X” axis measurement results

The same measurements were made for “Y” and “Z” axes (fig. 8-9).

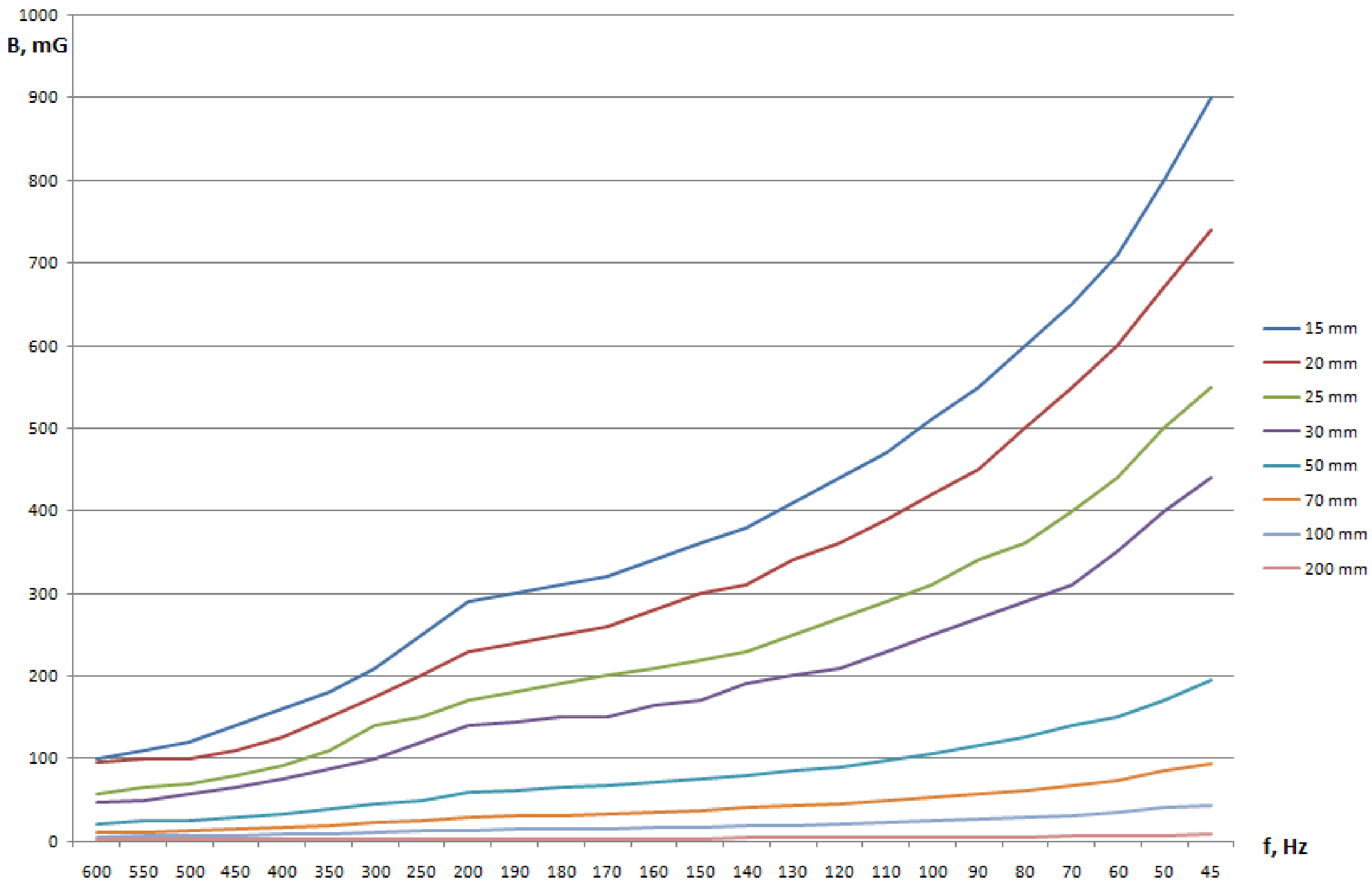

Fig. 8. "Y" axis measurement results

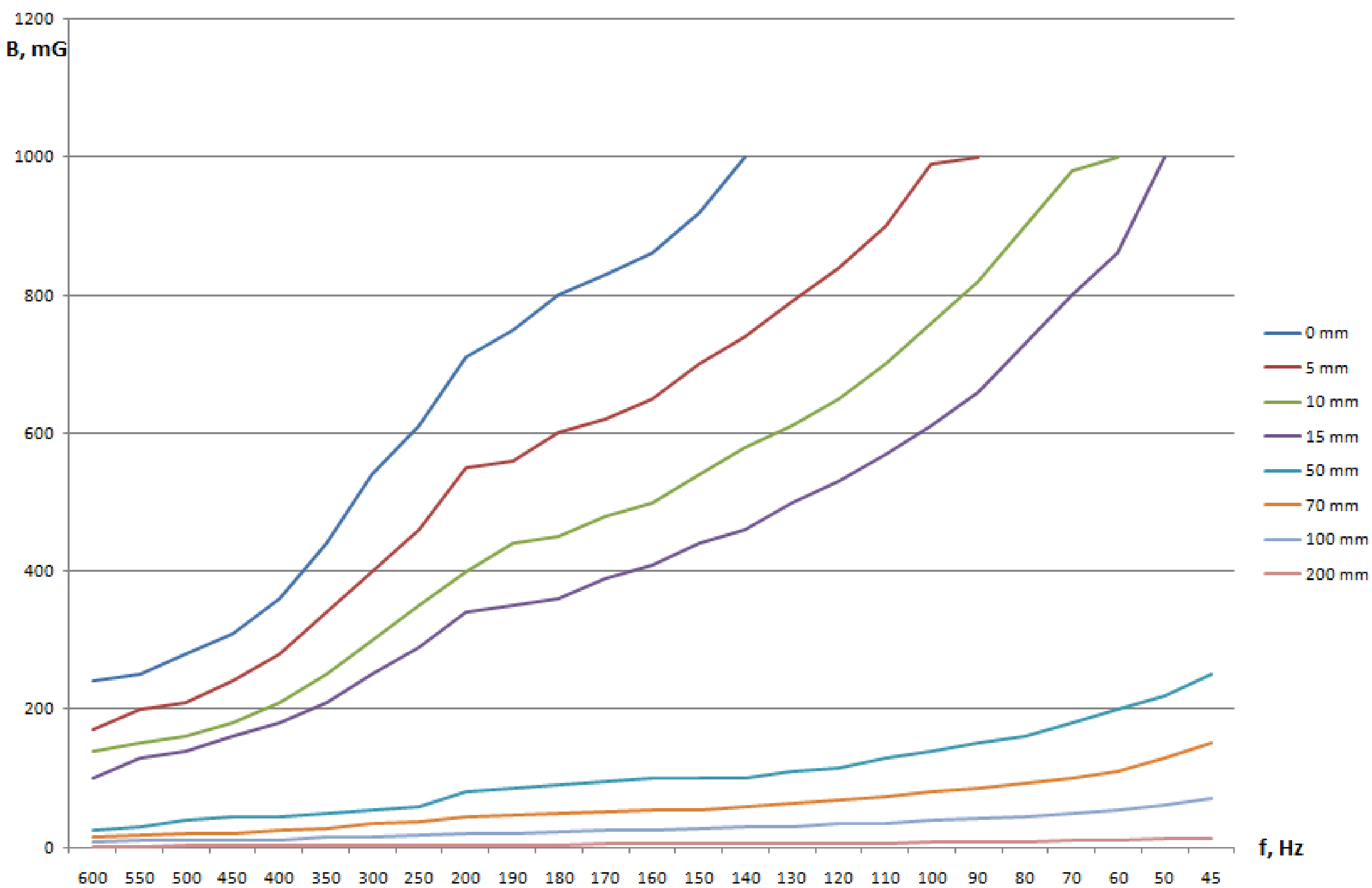

Fig. 9. "Z" axis measurement results

According to Table 2, the measurement results did not exceed the exposure limits (1 G = 0.0001 T).

CONCLUSION

An output transformer for a single-ended tube amplifier was designed meeting the requirements of IEEE C95.3.1-2010 standard, 4210-2003 National Standard of Ukraine and IEEE C95.6-2002 standard. All standards are available at no charge.

The transformer design was a balance between cost, quality and compliance standards, the frequency range of the transformer was between 40 Hz and 18 kHz.. The tube chosen for the output amplifier was a Russian 6p1p tetrode tube of 3.5 W output power sufficient to achieve an adequate sound quality.

Transformer magnetic field measurements were made by an ELF Sensor that complied with the requirements of IEEE C95.3.1-2010 standard and 4210-2003 National Standard of Ukraine.

The transformer was analyzed within the range 45 kHz and 600 Hz, and exposure levels remained within the exposure levels for brain and heart. The transformer designed therefore did not exceed the magnetic field exposure limits for brain and heart. Magnetic field induction level measurement results complied with the requirements of IEEE C95.6-2002 standard.

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