

## Transistor Effect in the Cochlear Amplifier

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The paper presents a new electromechanical amplifying device i.e., an electromechanical biological transistor. This device is located in the outer hair cell (OHC), and constitutes a part of the Cochlear amplifier. The physical principle of operation of this new amplifying device is based on the phenomenon of forward mechano-electrical transduction that occurs in the OHC's stereocilia. Operation of this device is similar to that of classical electronic Field Effect Transistor (FET). In the considered electromechanical transistor the input signal is a mechanical (acoustic) signal. Whereas the output signal is an electric signal. It has been shown that the proposed electromechanical transistor can play a role of the active electromechanical controlled element that has the ability to amplify the power of input AC signals. The power required to amplify the input signals is extracted from a battery of DC voltage. In the considered electromechanical transistor, that operates in the amplifier circuit, mechanical input signal controls the flow of electric energy in the output circuit, from a battery of DC voltage to the load resistance. Small signal equivalent electrical circuit of the electromechanical transistor is developed. Numerical values of the electrical parameters of the equivalent circuit were evaluated. The range, which covers the levels of input signals (force and velocity) and output signals (voltage, current) was determined. The obtained data are consistent with physiological data. Exemplary numerical values of currents, voltages, forces, vibrational velocities and power gain (for the assumed input power levels below 1 picowatt ( $10^{-12}$  W)), were given. This new electromechanical active device (transistor) can be responsible for power amplification in the cochlear amplifier in the inner ear.

**Keywords:** cochlear amplifier, acoustoelectric transducers, electromechanical transistor, equivalent circuits, field effect transistors, ion currents.

### 1. Introduction

The purpose of this paper is to present the physical model (electrical equivalent circuit) of a new amplifying device, i.e., an electromechanical biological transistor that is present in the human hearing organ, i.e., in Cochlea. The physical principle of operation of the proposed by the authors a new electromechanical amplifying device is based on the phenomenon of forward mechano-electrical transduction, that is generated by the movement of stereocilia at the top (apical part) of the outer hair cell (OHC).

Many physical phenomena occurring in biological systems can be explained quantitatively by using the idea of electromechanical and electronic transistor. In fact, during our studies on electrical signals in Cochlea, the authors were able to explain quantitatively by using the concept of an electromechanical transistor,

such important phenomenon as power amplification (KIEŁCZYŃSKI, 2013). To the best of our knowledge, this idea of an electromechanical transistor was not presented as yet in the scientific literature.

The entire tract of gain process in the cochlear amplifier includes: basilar membrane (BM), OHC, tectorial membrane (TM) and inner hair cell (IHC's) afferent innervation. IHC operates as a sensor, while the OHC acts as the sensor (mechano-electrical transducer) and actuator (electromechanical transducer). OHCs play a key role in the process of active amplification and sharpening the frequency characteristic (selectivity enhancement) in the cochlear amplifier (LIAO *et al.*, 2005). Therefore, in this work the authors have restricted their attention to the OHC. In this paper we do not consider the operation of the entire cochlear amplifier. We do not investigate also operation of the entire OHC. We analyze only the work of the OHC as

a mechano-electrical transducer. We examine only phenomenon of power amplification occurring in the electromechanical transistor being a part of the OHC. We do not consider either the phenomenon of frequency selectivity enhancement, which also occurs in the OHC, or the piezoelectric effect (electromotility).

OHC stereocilia form the mechanical input circuit of the electromechanical transistor. The electric output circuit of the electromechanical transistor amplifier are not neurons (afferent nerves) in the OHC, but is the non-linear OHC transmembrane capacitance consisting of fixed charges located on the opposite sides of the cell membrane. The electric current of  $K^+$  ions, that is generated by the movement of OHC stereocilia and flowing in the output circuit, is sensitive to the input mechanical signal changes (i.e., velocity and/or force on OHC's stereocilia).

Electrical signal amplified by the electromechanical transistor is employed as the pumping signal in the parametric OHC amplifier, in which the nonlinear capacitance plays a key role (KIEŁCZYŃSKI, 2013). The role of the OHC-parametric amplifier is to sharpen the frequency characteristic (increase in selectivity). Subsequently, the electrical signal with enhanced power and sharpened frequency characteristic transforms to the mechanical side (domain), where it performs useful work on TM. In a further step, TM transfers mechanical energy to the IHC (through its stereocilia). IHC receives the amplified mechanical signal and converts it into an electrical signal, which finally stimulates the neurons (afferent nerve endings).

The amplifying elements are characterized by their ability to amplify signal power (SHOCKLEY, 1956). The principle of power gain relies on the use a low power to control the flow of high power, from the source of the power to the load, where the power is dissipated performing useful work (SHOCKLEY, 1962).

Device for controlling the flow of electrical energy from the source of potential energy to the load is called a transistor. It plays also a role of the controlled valve, and consequently a role of the controlled time-varying resistor (GOLDE, 1974). In a classical electronic amplifier, electrical input signal acting in the input circuit of the transistor, controls the amount of electrical energy flowing from a DC battery to the load resistance in the output circuit.

Amplifier, in which one type of energy (i.e., mechanical energy) controls the flow of the second kind of energy (i.e., electrical energy) is called electromechanical amplifier. A characteristic feature of an electromechanical amplifier is the presence of moving parts. In the considered in this article electromechanical transistor, stereocilia are moving parts, which deflection controls the flow of ionic channel currents in the structure of outer hair cells (OHCs) in Cochlea. Stereocilia are part of each single OHC and are located on its top. As we will see later, electromechanical biological tran-

sistor operates on a principle similar to the principle of operation of unipolar field effect transistor (FET).

In order the effect of power amplification occurs: three elements are necessary:

1. A source of potential energy;
2. A device (active controlled element, i.e., transistor) for controlling the flow of energy from a power source to the load;
3. An active controlled element should have the input and output circuits. Input signal is applied to the input control circuit. Output signal is connected to the controlled output circuit.

In proposed by the authors electromechanical amplifying device (i.e., electromechanical transistor), input circuit is a mechanical circuit. The input signal is the velocity and/or force on the stereocilia. Deviation of stereocilia causes modulation of the ion channel current of potassium ions  $K^+$  flowing in the structure of an outer hair cell (OHC). In this way, alternating channel current (AC) produces an alternating voltage (AC) in the output circuit across the load resistance. The output circuit is a closed electrical circuit. The output signal is the voltage and/or current signal.

An active controlled element (i.e., electromechanical transistor) can be regarded as a variable in time channel resistance  $R(t)$  that is controlled by the mechanical input signal. This new device can play a very important role in the cochlear amplifier, providing the power required to amplify the power of input acoustic signals. Thus, the electromechanical biological transistor powers the cochlear amplifier in the inner ear (KIEŁCZYŃSKI, 2013). The idea of this new amplifying device can be also helpful in explanation of the "cochlear microphonics" effect generated by the organ of Corti.

The developed up to date models of the Cochlear amplifier were presented in numerous papers (GOLD, 1948; DAVIS, 1983; EGUILUZ *et al.*, 2000; COHEN, FURST, 2004; RAMAMOORTHY, DEO, 2007; KEENER, SNEYD, 2009; ASHMORE *et al.*, 2010). The proposed models are phenomenological models, rather than physical ones. It should be noted that in these works the power amplification effect of the input signal has not been considered.

Presented in this paper electromechanical transistor is only a part of the Cochlear amplifier. Transistor amplifier provides power (generates a pump signal) to the OHC parametric amplifier. Transistor amplifier alone does not provide either tuning or selectivity. On the other hand, parametric amplifier based on nonlinear OHC capacitance described in the previous work (KIEŁCZYŃSKI, 2013) provides necessary tuning and selectivity.

In this paper a small signal equivalent circuit of the electromechanical transistor for AC signals is given. The numerical values of equivalent circuit elements were determined.

In this work, the orders of magnitude for the mechanical quantities (force and velocity) and electrical quantities (voltage and current), in the considered electro-mechanical transistor are given. Estimated are levels of mechanical input power and electrical output power for a number of driving levels of input acoustic signal.

Similarly like in the classical electronic transistor amplifier, also in the proposed by the authors electromechanical transistor amplifier, energy is extracted from a DC voltage source. This DC source reflects the electrochemical potential energy between the endolymph and perilymph. Mechanical signal in the input circuit controls continuously the power flow in the output circuit, from a DC battery to the load resistance. Considered electromechanical transistor is a transducer that allows active conversion of electrical energy stored in the source of DC constant voltage.

Considered in this work electromechanical transistor is an amplifying device which is characterized by a lack of reverse interaction of the output electric circuit on the input mechanical circuit. This is a feature desirable for amplifying devices.

Plan of the article is as follows. Section 2 introduces the concept of Electromechanical Controlled Element (EMCE), which is very helpful in understanding the principles of operation of the proposed electromechanical transistor. Section 3 presents the physical model of the device. Section 4 shows the small-signal electrical equivalent circuit of the electromechanical transistor. Section 5 describes the power gain of the electromechanical transistor. Section 6 contains the conclusions.

## 2. Electromechanical controlled element

Introducing the idea of an electromechanical controlled element (EMCE) is very helpful in understanding the physical foundations of the operation of the electromechanical biological transistor, proposed by the authors. In this element the flow of electric power in the output circuit is controlled by the mechanical energy changes in the input circuit.

Electromechanical controlled element can be regarded as a variable resistance (or conductance) controlled continuously by the input signal, i.e., one can denote  $EMCE \equiv R(t)$ . The mechanical input signal (force and/or velocity) controls the electric charge flowing through the amplifying element (i.e., electromechanical transistor), and consequently producing the appropriately amplified output signal (voltage and/or current) on the load resistance in the output circuit.

To explain the operation of the EMCE, let us consider the electrical circuits in Figs. 1 and 2. To cause an alternating current flow through the load resistor  $R_L$  in Fig. 1, one should apply an AC voltage source, see the circuit in Fig. 1.

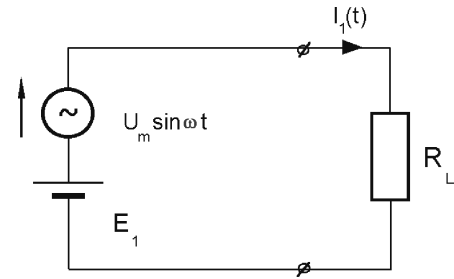


Fig. 1. Circuit including an AC sinusoidal voltage source  $U_m \sin \omega t$  along with a DC voltage source  $E_1$ , which are used to produce an AC voltage across the resistance  $R_L$ .

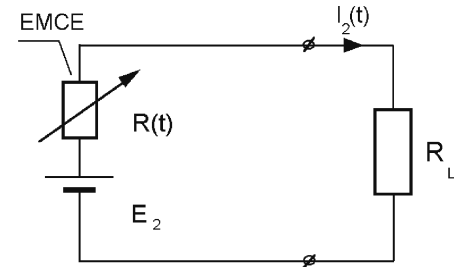


Fig. 2. Diagram of the circuit that includes the EMCE (i.e., a variable in time resistance  $R(t)$ ), which is equivalent (with respect to the signals occurring at the resistance  $R_L$ ) to the circuit with an AC voltage source from Fig. 1. The value of the resistance  $R(t)$  is controlled mechanically by the input force and/or velocity signal.

Current  $I_1(t)$  flowing through the resistor  $R_L$  in Fig. 1 is:  $I_1(t) = (E_1 + U_m \cdot \sin \omega t) / R_L$ . The same value of the electric alternating current (AC) in the resistor  $R_L$  also can be realized in a different way, without the use of a source of alternating voltage (AC). To this end, it suffices to replace the AC voltage source ( $U_m \sin \omega t + E_1$ ) via serial connection of another DC voltage source  $E_2$  with the EMCE, see Fig. 2. Changes of current in the circuit of Fig. 2 are caused by operation of the EMCE that is  $R(t)$ . AC current  $I_2(t)$  flowing through the resistance  $R_L$  in Fig. 2 is:  $I_2(t) = E_2 / (R_L + R(t))$ . The EMCE resistance varies according to a new function of time. It can be determined from the condition of equivalence of the circuits in Figs. 1 and 2 in respect to electrical waveforms occurring across the resistor  $R_L$ . Namely, from the condition  $I_1(t) = I_2(t)$ , we obtain:

$$R(t) = R_L \cdot \left( \frac{E_2}{U_m \sin \omega t + E_1} - 1 \right). \quad (1)$$

Since generally, the condition  $U_m \ll E_1$  is fulfilled, therefore Eq. (1) can be written as:  $R(t) = R_L \cdot \{E_2/E_1 \cdot (1 - U_m/E_1 \cdot \sin \omega t) - 1\}$ . Thus, the resistance  $R(t)$  in Fig. 2, as well as an AC voltage source in Fig. 1, can vary sinusoidally with time.

The above analysis shows that the electromechanical controlled element extracts power from the battery of DC voltage (endocochlear potential), and trans-

forms it into an alternating current (AC) power, which may be then dissipated as useful output power on the load resistance  $R_L$ . Electromechanical controlled element has a separate input mechanical circuit and separate output electric circuit. Electromechanical controlled element plays a dual role: first, produces the source of an AC electric voltage (from a DC voltage battery), second it can be used to amplify the mechanical input power. The ability of the EMCE to amplify the power of the input mechanical signal results from the fact that, in general, the input mechanical power necessary to control the value of the resistance  $R(t)$  is lower than the output electric power dissipated on the load resistance  $R_L$ .

### 3. Description of the device

Consider the structure of a single OHC, see Fig. 3a. Presented electromechanical active device constitutes only the initial part of the OHC and the entire amplifying tract of the cochlear amplifier, that begins with BM deflection and terminates in IHC, where the amplified mechanical signal is transformed into an electrical signal, which stimulates the afferent nerves.

Electromechanical amplifying device considered in this work, is a mechano-electrical transducer that can convert mechanical input signals into electrical output signals. The proposed amplifying device is an electromechanical active element that enables active conversion of the electrical energy stored in the battery of DC voltage (endocochlear potential). The structure of the proposed amplifying device is illustrated in Fig. 3a. The physical circuit model of the considered device is presented in Fig. 3b.

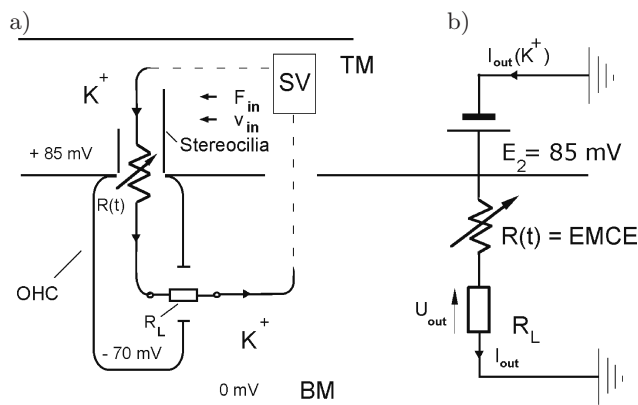


Fig. 3. a) Structure of an electromechanical biological transistor, being part of a single OHC. Arrows indicate the flow of  $K^+$  electric current in the electromechanical amplifier,  $R(t)$  is a time-varying channel resistance, that represents the EMCE, and  $R_L$  is a load resistor. BM is basilar membrane, TM is tectorial membrane, and SV denotes Stria Vascularis, b) electrical equivalent circuit of an OHC's electromechanical transistor model, electromotive force  $E_2 = 85$  mV represents the endocochlear potential.

Figure 3a presents a schematic sectional view of the single OHC, that can play a role of an electromechanical amplifier. To illustrate the principle of operation of the new amplifying device, channels at the upper (apical) part and in the lower (basolateral) part of the OHC are shown in Figure 3a greatly enlarged. Operation of the channels in the apical part is modeled by one resultant channel. We proceed similarly in the case of channels in the basolateral part of the OHC. Their operation is also modeled by one resultant (effective) channel. The flow of potassium ions is mainly responsible for electrical phenomena occurring in the OHC. The ionic  $K^+$  current flowing in the structure of an OHC (from the top-left to the right-down), is displayed. The top (apical) channels play a role of a controlled (time-varying) resistance. The bottom (basolateral) channels are modeled as a load resistance, see Fig. 3a. Figure 3b shows a physical circuit model of a presented in Fig. 3a electromechanical amplifying device. In this circuit model we can observe a source of potential energy (a DC battery), an active control element that is represented by a controlled (time-varying) resistance  $R(t)$ , and a load resistance  $R_L$ . The physical basis of the operation of a considered electromechanical transistor is the phenomenon of forward mechano-electrical transduction taking place in the OHC's stereocilia.

The input circuit of a new electromechanical transistor is a mechanical circuit consisting of stereocilia. Input control signal is the velocity and/or the force applied to stereocilia. The output circuit is an electrical circuit, see Fig. 3b. Electrical output controlled signal is the current and/or the voltage across the resistance  $R_L$ . The electric circuit in Fig. 3a,b closes through the structures lying outside the OHC (stria vascularis).

#### 3.1. Controlled time-variable resistance

The mechanism for opening and closing of mechanically gated ion channels at the apical part of the OHC can be compared to operation of continuously controlled hydraulic valves. Each of these ion channels can therefore be represented by a variable in time resistance.

Mechanically gated ion channels situated at the top part of the OHC are mechano-electrical transduction (MET) channels, which carries out transformation of the mechanical signal into an electrical signal. The degree of opening of these channels is controlled by changing the mechanical input control signal that is the mechanical displacement, velocity and/or force acting on the stereocilia. According to the level of the input signal (velocity and/or force) the cross-section of the channels varies and modulation of a resistance (conductance) of these channels occurs, for the potassium ion current  $K^+$ , which flows through these chan-

nels. Therefore, sinusoidal motion of stereocilia produces corresponding sinusoidal variation in the resistance of these ionic channels. The overall effect of all of these channels can be modeled in terms of circuit theory by one effective channel with variable in time resistance (conductance)  $R(t)$ , that is controlled by a mechanical input signal (velocity and/or force).

Here, we can see a direct analogy of this effective MET channel to the channel in the semiconductor FET transistor, where the channel resistance is modulated by changing the cross-section of the channel and its conductivity, caused by the operation of the electrical input signal (gate voltage). In the proposed electromechanical transistor similarly as in the field effect transistor (FET), in the current conduction process involved are carriers of only one type (sign). For this reason, the electromechanical transistor as well as the classical electronic FET, are unipolar transistors.

Ion channels located at the basolateral part of the OHC are controlled electrically (i.e., by changing the transmembrane voltage). In our model, the overall operation of these channels is modeled by an individual resistance of a constant value, which is identified with the load resistance  $R_L$ . At this resistance useful output power is dissipated, that is the output power in the proposed by the authors the active amplifying device. The flow of ionic current  $K^+$  is driven by the electromotive force (DC voltage source)  $E_2$ . This electromotive force is the source of energy for amplifying processes occurring in Cochlea. The electrical circuit of  $K^+$  ion current flowing through the structure of the OHC, closes on the outside of the OHC. The ion current ( $K^+$ ) is flowing outside the OHC body through the adjacent to the OHC structures of Cochlea, back and forth to the Stria Vascularis (MISTRİK *et al.*, 2008). The ion current ( $K^+$ ) circuit constitutes a closed electric circuit.

This electric current produces in the circuit (across the resistance  $R_L$ ) an AC electric potential, that time course follows the mechanical movement of the BM and stereocilia. Maximum receptor current in a single OHC (i.e.,  $I_2$  in Fig. 3b) depends on the level of the input driving acoustic signal. For example, for a driving level of an input acoustic signal equal to 30 dB SLP, maximum receptor current equals about 1.5 nA (RAMAMOORTHY, DEO, 2007). Hence, the resistance  $R_L$  can be estimated in this case to be of the order of:  $R_L = 85 \text{ mV}/1.5 \text{ nA} = 56.67 \text{ M}\Omega$ , (i.e.,  $G_L = 1/R_L = 17.64 \text{ nS}$ ).

Taking into account the results of Sec. 2 (see, Figs. 1 and 2) and those described above in Sec. 3 (see, Fig. 3ab), we can see a direct correspondence between the amplifying device of Fig. 3b, and electromechanical controlled element of Fig. 2. Therefore, proposed by the authors the new electromechanical amplifying device of Fig. 3a,b (based on the use of a single OHC) acts as an electromechanical transistor amplifier.

Electromechanical amplifying system of Fig. 3a,b satisfies three necessary conditions of power gain, namely:

1. There is a source of potential energy (voltage source  $E_2$ );
2. There is a device (electromechanical controlled element) to control the flow of energy from the voltage source  $E_2$  to the load resistance  $R_L$ , i.e., EMCE =  $R(t)$ . The value of the resistance  $R(t)$  is controlled by the input mechanical signal (velocity and/or force);
3. There is a mechanical control input circuit and an electric controlled output circuit.

Thus, this electromechanical controlled element EMCE =  $R(t)$  can represent an electromechanical transistor. This transistor is an analog of an electronic unipolar Field Effect Transistor (FET).

## 4. Electrical equivalent circuit

### 4.1. Small-signal electric equivalent circuit.

Matrix  $[h]$

Small signal equivalent circuit of the electromechanical transistor for small values of both: output AC electric signals (voltage and current), and input mechanical signals (velocity and force on stereocilla) is given in Fig. 4.

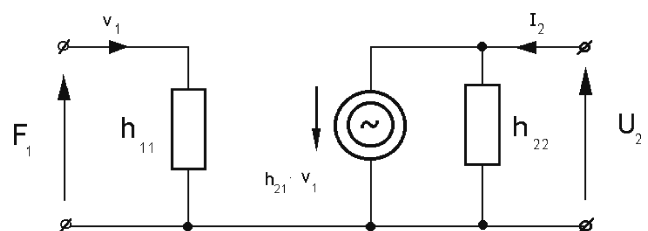


Fig. 4. Linearized small signal equivalent circuit illustrating the operation of an electromechanical transistor. Forward mechano-electrical transduction equivalent circuit.

The output circuit has the properties of the controlled current source. Output current  $I_2$  is generated by the controlled current source  $h_{21}v_1$ , which depends linearly on the input velocity.

Small signal equivalent circuit for electromechanical unipolar transistor (Fig. 4) can be presented in the matrix form by using the concept of a hybrid matrix  $[h]$ . The output electrical circuit of the device does not load the mechanical input circuit. Therefore, we can assume that  $h_{12} = 0$  (no reverse interaction), which means that the considered two-port network in Fig. 4 is unilateral. The hybrid matrix  $[h]$  of the electromechanical transistor is as follows:

$$\begin{bmatrix} F_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ U_2 \end{bmatrix} = \begin{bmatrix} Z_{in} & 0 \\ g_{em} & g_{22} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ U_2 \end{bmatrix}. \quad (2)$$

Elements of the matrix  $[h]$  have the following physical interpretation:  $h_{11} = Z_{\text{in}}$  is a mechanical input impedance,  $h_{22} = g_{22}$  is an electrical output conductance,  $h_{21} = g_{\text{em}}$  is an electromechanical transconductance (transduction coefficient).

Equations (2) form constitutive equations of the considered active element treated as an electromechanical transducer.

Parameter that describes the amplifying properties (e.g., power gain) of the electromechanical transistor is an electromechanical transconductance (transduction coefficient), that relates the changes in electrical output current ( $I_{\text{out}}$ ) with the changes in the mechanical input signal (force and/or velocity). We choose the definition of this electromechanical transconductance in the following form:

$$g_{\text{em}} = \frac{\partial I_{\text{out}}}{\partial v_{\text{in}}}. \quad (3)$$

As shown in Eq. (2), the AC component of the output current  $I_2$  is proportional to the input velocity  $v_1$ , i.e.,  $I_2 \approx h_{21}v_1$ . The value of the output current  $I_2$  is of the order of several hundreds of pA ( $10^{-12}$  A).

Typical numerical values, that can be assigned to the matrix elements  $[h]$  for the electromechanical transistor are as follows:

$$[h] = \begin{bmatrix} 10^{-6} \frac{\text{N}}{\text{m/s}} & 0 \\ 10^{-6} \frac{\text{A}}{\text{m/s}} & 10^{-8} \text{ S} \end{bmatrix}. \quad (4)$$

In the considered amplifying device shown in Fig. 4, the electrical output power is not extracted from the input driving circuit, hence a reverse interaction of the electrical output circuit on the mechanical input circuit does not occur. This is an advantage of the proposed electromechanical transistor, which is hereby an unilateral amplifying device.

Given above numerical values can be used to assess the amplifying ability of two-port network from Fig. 4. Namely, it can be shown that the maximum power gain (under the matching conditions in the input and output circuits) is equal to:

$$k_{ps \text{ max}} = \frac{h_{21}^2}{h_{11} \cdot h_{22}}. \quad (5)$$

Substituting the data from Eq. (4) to Eq. (5) we obtain  $k_{ps \text{ max}} = 100$ . The above example shows that the electromechanical two-port network from Fig. 4 has the ability to amplify the active power of the input signal.

## 5. Power amplification in an electromechanical biological transistor

Mechanical movement of stereocilia in the input circuit controls the flow of alternating electrical current

in the output circuit. Hence, stereocilia act as an electromechanical controlled (adjustable) valve.

From biological investigations results that mechanical power delivered to stereocilia of a single OHC and corresponding to low levels of the input driving signal  $< 40$  dB SPL (Sound Pressure Level), is small (of the order of  $10^{-14}$  W) (RAMAMOORTHY, NUTTAL, 2012). On the other hand, this low level of the input power may correspond to a relatively high power level of the output electrical signal, e.g., of the order of  $10^{-12}$  W.

Mechanical (acoustic) active power of input signal is given by:

$$P_{\text{in}} = \frac{1}{2} F_{\text{in}} \cdot v_{\text{in}}, \quad (6)$$

where  $F_{\text{in}}$  represents the force amplitude of the mechanical input signal, and  $v_{\text{in}}$  is the velocity amplitude of the mechanical input signal.

An effective active power of output electrical signal is determined by the relationship:

$$P_{\text{out}} = \frac{1}{2} U_{\text{out}} \cdot i_{\text{out}}, \quad (7)$$

where  $U_{\text{out}}$  is the voltage amplitude of the output electrical signal, and  $i_{\text{out}}$  is the current amplitude of the output electrical signal.

Thus, the power gain can be written as:

$$k_p = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{U_{\text{out}} \cdot i_{\text{out}}}{F_{\text{in}} \cdot v_{\text{in}}}. \quad (8)$$

Applying physiologically relevant experimental data we can determine the ranges of variation, in which the levels of the input mechanical signals, (force and velocity) and the electrical output signals (voltage and current) are contained, for specified levels of given driving input acoustic signals. Namely, for a moderate driving levels of the input signal, equal to e.g., 60 dB and for a frequency  $f = 1$  kHz, we can write:

$$P_{\text{in}} = \frac{1}{2} 100 \text{ pN} \cdot 10^{-4} \text{ m/s} = 0.5 \cdot 10^{-14} \text{ W}, \quad (9)$$

$$P_{\text{out}} = \frac{1}{2} 4 \text{ mV} \cdot 250 \text{ pA} = 0.5 \cdot 10^{-12} \text{ W}. \quad (10)$$

Substituting Eqs. (9) and (10) into Eq. (8) we get  $k_p = 100$ . Thus, the achieved power gain is 100. The values used in Eqs. (9) and (10) are biologically justified. They are in accordance with the experimental (literature) physiological data presented in (RAMAMOORTHY, NUTTAL, 2012; FETTIPLACE, 2006; NIN *et al.*, 2012; CHAN *et al.*, 2007). Results for power gain and the levels of input mechanical signals, and output electrical signals for several different driving levels of input acoustic signal are given in Table 1.

As can be seen from Table 1, for small driving levels of input signal, power gain is the highest and decreases gradually with increasing of driving level. For large values of driving levels, the power gain is low

Table 1. Exemplary values of power gain, input force, input velocity, output voltage and output electric current for several driving levels of input acoustical signal.

Driving level [dB]	Force $F_{in}$ [pN]	Velocity $v_{in} \times 10^{-4}$ [m/s]	Voltage $U_{out}$ [mV]	Current $i_{out}$ [pA]	Power gain $k_p$
30	30	0.1	1	150	500
60	100	1	4	300	120
80	250	4	5	400	20

(about a dozen). This is consistent with the dependence of gain on the driving level, which is observed in actual Cochlea (compression).

The performed analysis shows that the considered in this work the electromechanical active device (i.e., electromechanical transistor) can be used to amplify the power of an AC input signal. This is the key property of active amplifying devices.

## 6. Conclusions

In this paper, the authors presented a new type of amplifying device i.e., an electromechanical biological transistor. This device is located in the OHC and constitutes a part of the whole Cochlear amplifier. The main feature of this new electromechanical transistor is its ability to amplify power of input mechanical signals. To the authors knowledge, the considered electromechanical amplifying device (electromechanical transistor) is a novelty.

In this new active device, the mechanical input stimulus causes controlled release of electric potential energy stored in the battery of direct voltage (DC) (endochochlear potential), and consequently, the flow of this energy in the output circuit to the load resistance, where it performs useful work.

The authors developed the physical model of a new electromechanical active device along with its small-signal electrical equivalent circuit, and the constitutive equations of the device. The principle of operation of the new active amplifying device is based on the forward mechano-electrical transduction phenomenon, that occurs at the top (apical) part of the OHC.

The operation of this new electromechanical amplifying device is analogous to the operation of the classical unipolar field effect transistor (FET). In the case of the electromechanical transistor, the applied input signal is a mechanical (acoustic) signal. Whereas, the output signal is an electrical signal. Mechanical input control signal continuously modulates the overall channel resistance  $R(t)$  of the top (apical) part of an OHC, producing in this way an amplified electrical signal (e.g., the voltage across the load resistance) in the output circuit located in the basolateral part of the

OHC membrane. Hence, the electromechanical transistor is essentially a time-varying resistance  $R(t)$ , the value of which is controlled by the input mechanical signal (force and/or velocity).

The developed model of an electromechanical transistor can be helpful in explanation of the phenomenon of power amplification in the Cochlear amplifier, and can also be applied to clarify the “cochlear microphonics” effect that is produced by the OHCs in the Cochlea.

Generated by the electromechanical transistor (AC) voltage source is employed as a driving pumping signal in an OHC’s cochlear parametric amplifier presented in the paper (KIELCZYŃSKI, 2013).

This paper presents the small-signal equivalent circuit of the electromechanical biological transistor for alternating signals. Electromechanical transistor under consideration is characterized by the absence of reverse interaction of output electrical circuit on the input mechanical circuit, what is an advantage.

It has been shown that the proposed new device i.e., an electromechanical transistor has the ability to amplify the power of alternating input signals (AC). Power gain levels typical for this new amplifying device have been estimated. It was determined the range within which the levels of input signals (force and velocity) and output signals (voltage and current) are contained. These data are consistent with physiological data. Exemplary numerical values of current, voltage, force and velocity (for the assumed input power levels below 1 picowatt ( $< 10^{-12}$  W)), were specified.

The transfer of electronic concepts into biology can contribute to a more complete description of complex biological systems (MEAD, 1989; SHAKESPEAR, 2010; PIERCE, DAVID, 1958; GALBRAITH, 2008; WEITZEL *et al.*, 2003; RATTAY *et al.*, 1988; RAMAMOORTHY, DEO, 2007; RAMAMOORTHY, NUTTAL, 2012; CHAN *et al.*, 2007; MANDAL, SHAKESPEAR, 2011; EISENBERG, 2012; LETAW, BARDEEN, 1954). The developed in the work the new electromechanical amplifying device (i.e., electromechanical transistor) can result in the development of new applications of electronic methods in the interdisciplinary field of bioelectronics.

## References

1. ASHMORE J., AVAN P., BROWNELL W.E., DALLOS P., DIERKES K., FETTIPLACE R., GROSH K., HACKNEY C.M., HUDSPETH A.J., JULICHER F., LINDNER B., MEAUD J., PETIT C., SANTOS SACCHI J.R., CANLON C. (2010), *The remarkable cochlear amplifier*, Hearing Research, **266**, 1–17.
2. CHAN V., LIU S.C., VAN SCHALK A. (2007), *AER EAR: A matched silicon cochlea pair event representation interface*, IEEE Trans on Circuits and Systems I, **54**, 1, 48–59.

3. COHEN A., FURST M. (2004), *Integration of outer hair cell activity in one-dimensional cochlear model*, Journal of the Acoustical Society of America, **115**, 5, 2185–2192.
4. DAVIS H. (1983), *An active process in cochlear mechanics*, Hearing Research, **9**, 1, 79–90.
5. EISENBERG B. (2012), *Ions in fluctuating channels: Transistors alive*, Fluctuation and Noise Letters, **11**, 2, 00076 (20 pages).
6. EGUILUZ V.M., OSPECK M., CHOE Y., HUDSPETH A.J., MAGNASCO M.O. (2000), *Essential nonlinearities in hearing*, Physical Review Letters, **84**, 5232–5235.
7. FETTIPLACE R. (2006), *Active hair cell movement in auditory hair cells*, Journal of Physiology, **576**, 29–36.
8. GALBRAITH C.J. (2008), *Cochlea-based RF channelizing filters*, IEEE Trans on Circuits and Systems I, **55**, 4, 969–979.
9. GOLD T. (1948), *Hearing. II. The physical basis of the action of the cochlea*, Proc. R. Soc. London B. Biol. Sci., **135**, 492–498.
10. GOLDE W. (1976), *Electronic Systems* [in Polish], Vol. II, Chap. 5, WNT, Warsaw.
11. KEENER J., SNEYD J. (2009), *Mathematical Physiology. II: Systems Physiology*, Springer, Ch. 20.
12. KIELCZYŃSKI P. (2013), *Power amplification and selectivity in the cochlear amplifier*, Archives of Acoustics, **38**, 1, 83–92.
13. LETAW H., BARDEEN J. (1954), *Electrolytic analog transistor*, Journal of Applied Physics, **25**, 5, 600–606.
14. LIAO Z., POPEL A., BROWNELL W.E., SPECTOR A.A. (2005), *Effect of voltage-dependent membrane properties on active force generation in cochlear outer hair cell*, Journal of the Acoustical Society of America, **118**, 6, 3737–3746.
15. MANDAL S., SHAKESPEAR R. (2011), *A bio-inspired cochlear heterodyning architecture for an RF cochlea*, IEEE Trans on Circuits and Systems I, **58**, 7, 1647–1660.
16. MEAD C. (1989), *Analog VLSI and neural systems*, Addison-Wesley, Boston, New York.
17. MISTRİK P., MULLANEY C., MAMMANO F., ASHMORE J. (2009), *Three-dimensional current flow in a large-scale model of the cochlea and the mechanism of amplification of sound*, Journal of Royal Society Interface, **6**, 32, 279–291.
18. NIN F., REINCHENBACH T., FISHER J.A.N., HUDSPETH A.J. (2012), *Contribution of active hair-bundle motility to nonlinear amplification in the mammalian cochlea*, PNAS, **109**, 51, 21076–21080.
19. PIERCE J.R., DAVID E.E. (1958), *Man's world of sound*, Doubleday&Company, New York.
20. RAMAMOORTHY S., DEO N.V. (2007), *A mechano-electro-acoustical model for the cochlea: Response to acoustic stimuli*, Journal of the Acoustical Society of America, **121**, 5, 2758–2773.
21. RAMAMOORTHY S., NUTTAL A.L. (2012), *Outer hair cell somatic electromotility in vivo and power transfer to the organ of Corti*, Biophysical Journal, **102**, 2, 388–398.
22. RATTAY R., GEBESHUBER I.C., GITTER A.H. (1998), *The mammalian auditory hair cell: A simple electric circuit model*, Journal of the Acoustical Society of America, **103**, 3, 1558–1565.
23. SHAKESPEAR R. (2010), *Ultra low power bioelectronics*, Cambridge University Press, New York.
24. SHOCKLEY W. (1956), *Electron and holes in semiconductors with applications to transistor electronics*, R.E. Krieger Pub. Co, New York.
25. SHOCKLEY W. (1962), *Transistors*, [in:] The age of Electronics, C.F.J. Overhage [Ed.], McGraw-Hill, New York.
26. WEITZEL E.K., TASKER R., BROWNELL W.E. (2003), *Outer hair cell piezoelectricity: Frequency response enhancement and resonance behavior*, Journal of the Acoustical Society of America, **114**, 3, 1462–1466.