Analysis and measurement of anti-reciprocal systems

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Nov 7, 2014
Thesis objective:

- Provide a clear insight into “Anti-reciprocal” systems such as electromagnetic systems
Major updates after my preliminary exam....
1. Using a conceptual BAR model, I linked all subtopics of my thesis into one place to strengthen and organize my thesis structure
Projecting thesis topics onto the transducer model

Electrical part

Mechanical part

Acoustical part

True KCL, KVL

True gyrator

ECE ILLINOIS
Thesis contents

1. INTRODUCTION
2. THEORETICAL METHODS
3. EXPERIMENTAL METHODS
4. RESULTS
5. CONCLUSIONS

Major updates after my preliminary exam:
1. Using a conceptual BAR model, I linked all subtopics of my thesis into one place to strengthen and organize my thesis structure
2. I added more experimental work and result, such as hearing measurement probe manufacturing procedure.
I. Theoretical part

- We take a Balanced Armature Receiver (BAR, a speaker used in hearing-aids) as a specific example of the “Anti-reciprocal” system to demonstrate the system’s operational principle

II. Experimental part

- We introduce
  - Experiments to support (verify) our theory
  - An example to make use of the BAR; the hearing measurement probe manufacturing
I. Theoretical part

- An answer for the question: how does the BAR work?
  - Introduction of BAR
  - Overview of BAR’s operational principle
  - Case study I=0 and I≠0 (Eddy-currents)
  - Force on the armature ($F_m$) with Hysteresis effect
Balanced Armature Receiver (BAR)

• The oldest telephone receiver was invented by A. G. Bell in 1876

• Attraction and release of the armature are controlled by the current from the coils, which generates electromagnetic fields

• It has evolved into the modern hearing-aid devices
An example of the modern style BAR, Knowles ED7045

Cross section of Knowles ED receiver

Inside of the BAR without case and diaphragm
Overview of the BAR’s operation
The AC magnetic (solenoid) field’s direction is perpendicular to the current.
Hysteresis loss (the energy required to rotate the domains of magnetic dipoles) will occur when the induced magnetic field affects the armature.
An eddy current is generated in the opposite direction of the conducting current. This phenomenon is independent of the permanent magnet.
Due to the polarity between the permanent (DC) magnetic field and the generated AC magnetic field, the armature feels a force.
Due to the polarity between the permanent (DC) magnetic field and the generated AC magnetic field, the armature feels a force. Magnetic force, $F_m$: Force between two nearby magnetized surfaces to create a magnetic image.
The BAR’s behavior:
\[ I = 0 \text{ and } I \neq 0 \text{ (Eddy-currents)} \]
- Polarity of magnetic dipoles, net magnetic density $B=0$
- Magnetic poles always come in pairs (N and S)
The magnetic dipoles are lined up from N to S.
The armature behaves as a magnet with magnetic flux density $B_0$ (Tesla=Wb/m²)
Polarity of magnetic dipoles, net magnetic density $B = 0$.
The armature is balanced

\[ \psi_{DC\_upper} + \psi_{DC\_lower} = 0 \] (the net flux)
\( I > 0 \)

\[ \psi_{AC} \]

\[ \psi_{up} > \psi_{low} \]

\[ \psi_{up} = \psi_{DC_{upper}} + \psi_{AC} \]

\[ \psi_{low} = \psi_{DC_{lower}} - \psi_{AC} \]

\[ \psi_{UPgap} \]

\[ \psi_{LOWgap} \]
\[ \Psi_{\text{UPgap}} = (\Psi_{\text{up}} - \Psi_{\text{low}}) + \Psi_{\text{LOWgap}} \]

Going up

\( F_{\text{UPgap}} > F_{\text{LOWgap}} \), so the armature goes up
A gyrator swaps the generalized flow and force (Impedance matrix)

\[
\begin{bmatrix}
\Phi(\omega) \\
F(\omega)
\end{bmatrix} =
\begin{bmatrix}
0 & -B_0 l \\
B_0 l & 0
\end{bmatrix}
\begin{bmatrix}
I(\omega) \\
U(\omega)
\end{bmatrix}
\]

Eq. 1

\[
\Phi(\omega) = -B_0 l U(\omega) \quad \text{and} \quad F(\omega) = B_0 l I(\omega)
\]

Eq. 2

Two Eqs. for an Ideal gyrator
\[ I > 0 \]
\[ \nabla \times H_z = J_{c\phi} + \dot{D} \approx J_{c\phi} = \sigma E_\phi \quad (1. \text{Ampere’s law}) \]
\[ \nabla \times E_\phi = -\dot{B}_z \quad (2. \text{Faraday’s law}) \]
\[ \nabla \times (\nabla \times H) = \nabla \left( \nabla \cdot H \right) - \nabla^2 H \quad (3. \text{Vector identity}) \]

\[ \nabla \times (\nabla \times H_z) = -\nabla^2 H_z \quad \vdash 3 \]
\[ \nabla \times (\sigma E_\phi) = -\nabla^2 H_z \quad \vdash 1 \]
\[ \sigma \nabla \times E_\phi = -\sigma \dot{B}_z \quad \vdash 2 \]

Finally, \[ \nabla^2 H_z = \sigma \mu_a \frac{dH_z}{dt} \]

In the frequency domain \[(jk)^2 = \sigma \mu_a j\omega \]
\[ k_\rho = \pm \sqrt{\sigma \mu_a \omega} e^{-\angle 45^\circ} \quad \text{(diffusion)} \]

\[ 2H_z(\rho, t) = 2H_0 e^{j\omega t - k\rho} \]
Eddy current

\[ \mu_0 \ll \mu_a \]

Manipulating the Faraday’s law,

\[ emf = \int E_\Phi \cdot dl = \int \nabla \times E_\Phi \cdot dA \]

\[ = - \int B_z \cdot dA = -\Psi_a \]

where, \( dA \) is the cross sectional area of the armature core.

- Emf is Thevenin voltage (true KVL)
Force on the armature and hysteresis
• Force on the armature \( (F_m) \) exists for two opposing poles across an air gap
  – Opposite poles attract and like poles repel
• **Hysteresis** can be explained by describing the $F_m$.

• Assumption: Core is initially not magnetized

  1. Electrical energy: $W = \int v(t)i(t)dt \ [J=N\cdot m]$

  2. $W_d = \int \frac{HlAdB}{lA} = \int \mathbf{HdB} = \frac{1}{\mu} \int \mathbf{BdB} = \frac{B^2}{2\mu} \left[ \frac{J}{m^3} = \frac{N}{m^2} \right]$

  3. Therefore $F_m = WdA$

     $F_m = \frac{AB^2}{2\mu} = \frac{AgB_g^2}{2\mu_0} = \frac{\Psi_g^2}{2\mu_0 A_g} \ [N]$
The green formula can be related to the famous hysteresis loop graph

- x-axis and y-axis represent H and B
- Hysteresis loss: subtraction of two regions
- A typical hysteresis phenomenon of Ferro-magnetic material

We are interested in BAR’s operational region
• Hunt 1954, Ch. 7, Moving armature transducer systems

• BAR type receivers are operating in a lens shaped region
  – The region can be linearly approximated
  – Centered at $\Psi_0$ (due to the permanent magnet)
  – Alternating $\Psi_i$

$$F_m = \frac{\Psi_g^2}{2\mu_0 A_g} = \frac{(\Psi_0 + \Psi_i)^2}{2\mu_0 A_g} = \frac{\Psi_0^2 + 2\Psi_0 \Psi_i + \Psi_i^2}{2\mu_0 A_g}$$

– If $\Psi_i = \Psi_I \cos \omega t$, then

$$\Psi_i^2 = \frac{1}{2} \Psi_I^2 (1 + \cos 2\omega t)$$
Electrical input impedance $Z_{in}$, Unblocked

$|Z_{in}| \text{ [Ω]}$

Frequency (Hz)

$Z_{\phi}[\text{rad/rad}]$

Frequency (Hz)

$\approx 3.5\text{kHz}$

$\approx 7\text{kHz}$
Quasi-static (QS) and delay

- Let’s discuss this topic at the end of this presentation 😊
Sub conclusion from theory part

• Principles of the BAR's operation include the Eddy-current effect, hysteresis loss, and force on the two magnets

• This work will provide a fundamental, clearer insight into this type of BAR system
II. Experimental part

- Experiments to support (verify) our theory
  - Electrical input impedance measurements
  - Laser vacuum measurements
  - Pressure measurements

- Hearing measurement probe manufacturing
  - Existing probe study
  - Manufacturing and evaluation
Experiments to support our theory
Electrical input impedance measurements

- Used for the Hunt parameter calculation

\[ Z_{in} = \frac{\Phi_A - \Phi_B}{I} = \frac{\Phi_A - \Phi_B}{\Phi_B/R} = R \left( \frac{\Phi_A}{\Phi_B} - 1 \right). \]
Laser vacuum measurements

- A portion of the transducer’s case was carefully removed
- Then a thin plastic window was glued on, to reseal the case

Pressure measurements

- The circled ‘M’ means an input from the ER7C microphone
Hearing measurement probe manufacturing
Existing probe study: ER10C (Etymotic Research)

- Otoacoustic emission (OAE, sounds given off by the inner ear when the cochlea is stimulated by a sound) measurement device
- Two speakers and microphones are separated internally across the PCB circuit, microphones are placed ahead of the receivers
The microphones are firmly attached to the chamber.

The speakers are attached to steel tubes via a soft rubber tubes, floated in the air. The air is a best damper, vibrational crosstalk from the speakers can be reduced.
ED27045 speaker’s thin steel tube holder

EK23133 microphone port holder

The microphone’s sound path is cylindrical ‘T’ shape

ER10C New design, #2972
Gap, no glue, the white jammed thing is putty

ER10C Old design, #465
The middle part fits well to the case of ER10C. RTV could be applied to the edge area

Looking down from the ER10C probe front with its case
Issues with ER10C

- The small number of competitors in the market, users have not had many alternatives to the system
- The size of the probe is too big for infants
- Handling it without extreme caution may lead to malfunction of the probe (delicate device)
- The result of the measurement depends too much on the condition of the foam tip that is inserted in the subject’s ear canal
- Above 6 kHz, calibration (always) fails (the most critical problem)
Problem: above 6 kHz, calibration fails

**OLD ER10C**
- Brass material for the middle tube holder part
- RTV is used to block the holder’s side hole
- Calibration passes up to 9-10kHz
- ER10C with 3 digits serial number

**New Good ER10C**
- Aluminum material for the middle tube holder part
- RTV is not used to block the holder’s side hole, but some of black material seals the side hole fortunately
- Calibration passes up to 6kHz
- ER10C with 4 digits serial number

**New Bad ER10C**
- Aluminum material for the middle tube holder part
- None of material seals the holder’s side hole, a portion of the hole could be sealed randomly.
- Calibration totally fails or sometimes it passes but is unstable usually above 4kHz
- ER10C with 4 digits serial number
- We blocked the microphone hole on the ER10C foam tip to decouple the microphone sound path to the ER10C
Observation: Crosstalk in the system

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Observation: Crosstalk in the system

- We blocked the microphone hole on the ER10C foam tip to decouple the microphone sound path to the ER10C
- Any signal that is shown on the right side of this figure (blue) can be assumed as the internal crosstalk (20dB/Oct)
Hypothesis, approach, and expectation

- The long wire attached to the ER10C probe contributes to the electrical crosstalk (capacitive coupling) in high frequency.
- To lower the electrical crosstalk, we attached an external amplifier (close to the probe head).
- The available calibrating frequency range will be extended above 6 kHz.
Results: the calibration frequency range has been extended to 11kHz
Gamma in each cavity

1. Theoretical, length based: \( \Gamma_k^L = e^{-2L_k \kappa(f)} \) (dashed line)
2. Experimental:
   \( \Gamma_k^{4c} = \frac{1 - Y_k^{4c}}{1 + Y_k^{4c}} \) (solid line) where
   \( Y_k^{4c} = \frac{U_s}{P_k - Y_s} \)

Pressure null (\( c_0/4L_k \approx 45/L_k \))

1. Theoretical (green circle):
   \( P_k^L = \frac{P_s}{Y_s + Y_k^L} \)
   where \( Y_k^L = \frac{1 - \Gamma_k^L}{1 + \Gamma_k^L} \)
2. Experimental (pink circle):
   \( P_k^{4c} = \frac{P_s}{Y_s + Y_k^{4c}} \)
Probe manufacturing and evaluation

- Learning from lots of trials (and errors)

**MA 12-4**
- Receivers
  - GQ 30710 (37 ohm at 1 kHz)
  - GQ 30783 (90 ohm at 1 kHz)
- Microphone
  - EK23133 (ER10C microphone)
- Physical structure looking at the electrical terminal end of the probe

**MA 13-2 June 2013**
- These probes use TWFK 60173 receivers
- Stable and continuous 4-cavity calibration pass

**MA 15-1**
- Microphone (1): FG-23652
- Receivers (2): TWFK 60173
- 2.2k ohm (red) acoustic resistors (2) for receivers (Knowles BF 1021)
- Casing: 2 pieces, front and back
- Soft material compared to other MA15 series due to the manufacturing setting (not high resolution)
- Silicon glue, super glue, and liquid electrical tape

**Future direction**
- The receivers are generating sound behind the microphone
- Key idea
  - PCB board
  - An amp is attached in probe's body (not shown in this picture)

**MA12-1**
- OUT: Knowles TWFK 60173 (2) receivers
- In: Knowles EM23346 (1) microphone
- ILO's coupler

**MA16 current design**
- But in MA16 current design, the position of the microphone is ahead of the receivers without considering the steel tube length.
## Sensitivity factors ($\approx 0.8\text{cc cavity}$)

<table>
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<th>MA12-3</th>
<th>ILO-TE</th>
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<th>MA 12-2</th>
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<td>Microphone sensitivity [volt peak/Pa]</td>
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<tr>
<td>Receiver sensitivity [Pa/volt peak]</td>
<td>2.1e4</td>
<td>1.65</td>
<td>6 e3</td>
<td>456</td>
<td>7.5e4</td>
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</tbody>
</table>

### Design Option

#### a: Without acoustic resistors

- **Code: D1a**
  - Case (SLA, clear)
  - Front part (tip): D1a-01
  - Back part: D1a-02
  - Middle part: Black rubber: D1a-03

#### b: With acoustic resistors (●)

- **Code: D1b**
  - Case (SLA, clear)
  - Front part (tip): D1b-01
  - Back part: D1b-02
  - Middle part: Black rubber: D1b-03

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- MA16 & MA17 simulator

- **Microphone rubber tube**
  - Nearly centered
  - 1 or 2 mm ahead of the small square, inner board

- **Cotton piece**
  - Remove speaker distortions
  - Packing the space between the speaker and microphone to support to make the cylindrical structure (cavity)

- **Steel tube** 22mm

- **Acoustic resistor**

- **Microphone**

- **Receivers**

- **Speaker** 10mm
| Gamma | in each cavity

1. Theoretical, length based: \( \Gamma_k^L = e^{-2L_k \kappa(t)} \) (dashed line)

2. Experimental:
\( \Gamma_k^{4c} = \frac{(1 - Y_k^{4c})}{(1 + Y_k^{4c})} \) (solid line) where
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1. Theoretical (green circle):
\( P_k^L = \frac{P_s}{(Y_s + Y_k^L)} \)
where \( Y_k^L = \frac{1 - \Gamma_k^L}{1 + \Gamma_k^L} \)

2. Experimental (pink circle)
\( P_k^{4c} = \frac{P_s}{(Y_s + Y_k^{4c})} \)
1. Frequency responses of both microphone and speaker should be as flat as possible
   - especially within the frequency range of human hearing (ideally up to 20kHz for the microphone and up to 16kHz for the speaker)

2. Thevenin parameters must be stable over time
   - This can be evaluated via source calibration (i.e., 4 cavity calibration, Allen (1986))

3. Output levels for loudspeakers should be higher
   - especially for measuring hearing impaired ears. (i.e., 85dB SPL desirable)

4. Dynamic range as large as possible
   - Dynamic range is defined as the difference between the first harmonic level and the total harmonic level at each frequency (i.e., 50-60dB is acceptable)
5. Linearity superior to current probes
   – Dynamic range should be linear across the frequency range of interest

6. Impulse response should be short and exact
   – The duration of impulse ringing should be less than 1 ms. This result is critical to TEOAE measurement

7. Crosstalk issues including all noise sources must be addressed - microphone, loudspeaker...

8. Good seal and stability in the ear canal
   – This needs good earplug design to fit a range of adult ear-canal sizes and shapes easily

9. The size of the probe is an especially critical factor in the clinic for measurements of infant ears, due to their very small ear canals.

   These must take into account in the probe design !!
Sub conclusion from Experimental part

• We have solved the crosstalk problem in the ER10C which has kept users from calibrating the probe above 6 kHz
  – Now the system can pass 4C calibration above 10 kHz
• The MA16 and MA17, prototype probes, have comparable performance characteristics
• This study shows that crosstalk may be a general problem for OAE hearing probe devices which needs to be carefully addressed in the design process
Quasi-static delay

- When we deal with a physical system, such as ear canal, transmission line representation is simpler and intuitive way to model the system
  - Lumped element can mimic the system almost identically, but needs more element than a single transmission line
  - We don’t have to worry about the band limitation of the system
  - We need a transmission line to accurately model for our system
\( Z = \frac{1 + \Gamma}{1 - \Gamma} \) where the reflectance \( \Gamma = e^{-\frac{S}{c}} \).

\( \tau = \frac{l}{c} \) represents a pure delay.

The \( l, c \) stand for the length of the ear canal and speed of sound.

When \( \Gamma = \pm 1 \), poles and zeros appear in impedance domain (magnitude), respectively.

The reflection of the wave relates to the standing wave.
CONCLUSIONS AND EXPECTED CONTRIBUTIONS

1. The uniqueness of our BAR model
   - Extends anti-reciprocal networks using a gyrator
   - Includes a semi-inductor in the network
   - Represents non quasi-static networks by means of transmission line

2. The $Z_{\text{mot}}$ is not a physically realizable PR impedance supported by
   - PR property, it’s not a driving point impedance
   - A simplified electro-mechanic model simulation
   (Physical explanation about the negative $Z_{\text{mot}}$ real parts: Eddy-currents loss)

3. A generalization of the ABCD matrix cascading method
   - Characterized by the Möbius transformation
   - Found isomorphic relation between two methods
4. In-depth investigation of the BAR’s operational principles
   – Reinterpreting the gyrator including the AC magnetic flux along with DC flux
   – Apply and investigate the classic theories to the specific BAR case, such as KCL, KVL, and the diffusive wave equation dynamic (or non-QS) terms

5. Providing technical understanding of not only ER10C system but also hearing measurement devices in general

Summary of contributions:
This analysis puts “the anti-reciprocal electro-magnetic” transducer’s theory and application on a firm basis
‘s’ or ‘ω’

- Proper frequency domains for signals and systems
  - Signals (i.e., φ, I) and systems (i.e., power and impedance)
- System: Laplace frequency $s = \sigma + j\omega$
  - Indicate Positive-Real (PR) system
    - strictly non negative on the right half of the Laplace plane (passive condition)
  - In Laplace frequency plane, the abscissa (x-axis) is for a real part (σ referring to any loss in a system) while the ordinate (y-axis) is for an imaginary part ($j\omega$ where ω is an angular frequency or a Fourier frequency)
- Signals: They do not need to obey the PR property
  - Angular Fourier frequency ω is used
    - i.e., $\phi(\omega)$ and $I(\omega)$ are complex quantities
- For example, one can use Fourier transform to convert a voltage in the time domain to a voltage in the frequency domain. But to convert power from one domain to the other, the Laplace transform must be applied
False in general vs. True always

- But there is the danger in this process that before we get to see the complete story, the incomplete truths learned on the way may become ingrained and taken as the whole truth—that what is true and what is only sometimes true will become confused......
The Table 15–1 separates those which are true in general from those which are true for statics, but false for dynamics.

The equations we started with are the true equations.

- The electromagnetic force (often called the Lorentz force) $F = q(E + v \times B)$ is true. It is only Coulomb’s law that is false, to be used only for statics.

- The four Maxwell equations for $E$ and $B$ are also true. The equations we took for statics are false, of course, because we left off all terms with time derivatives (true KCL, KVL).
It will be great, if this point can be emphasized at the beginning not to mislead students.

A different view to see one problem. But it is important to have view of diversity 😊
References


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THANK YOU 😊