Modern Acoustic and Electronic Design of Studio Condenser Microphones

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Abstract
Condenser microphones have been used for more than 70 years in professional audio recording applications, due to their good frequency response, extended frequency range and wide dynamic range. If all parameters are properly designed, the microphone capsule will also have an excellent transient response. The basic design of studio microphone capsules today dates back several decades. Some capsules have been in production unchanged for 50 years or more. Nevertheless, the technical performance of microphones has been improved step by step by continued refinement of the associated electronic circuitry (e.g. tubes versus semiconductors, FET technology improvements, circuitry design aspects, etc.) Not until a few years ago did the quality of the electronics finally match that of the capsule in terms of self-noise level and dynamic range. However, the capsule design has also been improved by making use of technological advances and modern materials.

Studio microphones developed recently for high-resolution applications are capable of sensitivity corresponding to the noise level of air particles hitting the diaphragm surface due to thermal molecular movement, and at the same time have a dynamic range of 130 dB or more. This is true for both microphones using analog electronics and microphones using the most recent ADC technology.

This paper gives an overview of recent advances in the acoustic and electronic design of studio condenser microphones.

1. Introduction
Condenser microphones have been used for more than 70 years in professional audio recording applications, due to their good frequency response, extended frequency range and wide dynamic range. The basic design of studio microphone capsules today dates back several decades. Some capsules have been in production unchanged for 50 years or more. Nevertheless, the technical performance of microphones has been improved step by step by continued refinement of the associated electronic circuitry.
We will examine the individual components of a studio condenser microphone and will trace the developments over the past few decades which have led to the present level of technology.

2. Frequency response and frequency range
The era of the studio condenser microphone began in 1928. The first condenser microphone available on the market, the CMV 3, was initially constructed as a pressure transducer. Its frequency range extending to 10 kHz was a notable technological advance over the carbon granule, ribbon and dynamic microphones which had been in common use up to that time [1].

A few years later, in 1932, the legendary M7 capsule was developed. This capsule, which is still to be found in many microphones today, gives a balanced sound which is highly prized by sound engineers and performing artists [2] [3]. This development once again considerably extended the frequency range, so as to include the entire audio range.

Thus it can be seen that the key specifications of frequency range of a studio microphone had already been established 70 years ago, and had attained standards which are still recognized today.

3. Transient response
Although the transmission characteristics of condenser microphones may be affected by the electronic circuitry as well, the heart of a microphone is of course the capsule, which acts as the “acousto-electric” transducer. The capsule characteristics are usually described by a polar pattern and the frequency response at an angle of 0°. These are measurement results, where the amplitude is plotted against the frequency, for sine tone oscillations in a specific acoustic environment.
However, in real application environments, the microphone is substantially affected by transient signals [4].

Unfortunately, due to a lack of standardized measurement procedures, scarcely any published data is available in this regard, even though the transient response of a microphone is of interest and is often more informative than a frequency response in explaining the distinguishing sound characteristics.

The microphone illustrated in Fig. 1 has a capsule 22 mm in diameter, with a particularly flat, extended frequency response.
Fig. 1: Small-diaphragm microphone with its frequency response.

It exhibits an upper cutoff frequency (-3 dB) of 25 kHz. This value, together with the character of the curve, gives the microphone the transient response shown in Fig. 2.

Fig. 2: Transient response of the small-diaphragm microphone.

This microphone makes almost no change to the original sound, except for changes due to the physically determined cutoff frequency [5].

The transient response of a small microphone capsule is basically easier to control than that of a large-diaphragm microphone, since smaller vibrating masses are involved.

Here it should be noted that only around 40 % of the vibrating mass is comprised of the diaphragm itself, whereas approximately 60 % consists of the mass of the air which is moved by the diaphragm.

Figure 3 illustrates the transient response of a microphone which is very frequently used in professional studios. Its double-diaphragm capsule, with a diameter of 34 mm, was developed around 1960.

Fig. 3: Transient response of a large diaphragm microphone (1960).

It can be clearly seen that the impulse is broader and the subsequent postoscillation more pronounced and sustained than is the case with the transient response of the small-diaphragm capsule shown in Fig. 2. This is due not only to the larger diaphragm diameter and the associated larger vibrating air mass, but also to the air in the capsule system which is enclosed between the two diaphragms, which are positioned at 8 mm from one another.

The transient response of a large-diaphragm microphone constructed in the year 2003 is illustrated in Fig. 4. The capsule used here has a diameter of 33 mm and the distance between the two diaphragms is 6 mm.

Fig. 4: Transient response of a large-diaphragm microphone (2003).

The enclosed air mass in this double-diaphragm system is correspondingly smaller than the enclosed air mass in the capsule in Fig. 3, and the internal flow conditions are dimensioned more favorably. This is reflected in a considerably faster, well-controlled transient response, which is perhaps why the microphone is described as having an especially neutral sound character. Its transient response closely approaches that of the small-
diaphragm microphone illustrated in Fig. 2, and is a considerable improvement over the transient response shown in Fig. 3.

4. Equivalent self-noise level

Another studio microphone characteristic which determines the sound quality is the equivalent self-noise level. This specification gives information concerning the noise voltage at the microphone output. Here the microphone is considered as if it were noiseless and as if the noise voltage originated as a result of noise interference acting on the diaphragm. By virtue of this reference to the microphone input, the noise voltage can be regarded as equivalent to an acoustic signal and can be compared with wanted signal levels picked up by the microphone (signal-to-noise ratio).

The noise signal originates partly from the transducer, i.e. acoustic noise from the capsule, and partly from the electronics that are required for condenser microphones.

4.1. Capsule noise

Capsule noise results from the fact that the diaphragm is surrounded by air. Depending on the temperature, the air molecules hit the diaphragm stochastically due to Brownian molecular motion, causing the diaphragm to move even when the microphone is in completely quiet surroundings.

The extent of the diaphragm movement depends upon the volume of air involved as well as upon the type and magnitude of the frictional constraints associated with the internal construction of the capsule.

The mechanical dimensions of a capsule, and hence the volume of air involved, can be varied only to a limited extent, since they must be designed in accordance with acoustic conditions such as the build-up of pressure in front of the diaphragm, the sound paths within and around the capsule, etc. For this reason the capsule diameter is always approximately 21 mm for small-diaphragm studio microphones and approximately 34 mm for large-diaphragm microphones.

The frictional constraints can be reduced by decreasing the internal acoustic damping, so as to improve the interface with the sound field and increase the efficiency of the transducer. This yields more wanted signal and less noise. However, a significant decrease in damping can impair the transient response. It furthermore will necessitate electrical equalization of the capsule signal, since the frequency response will no longer be flat. Nevertheless, an improved signal-to-noise ratio results, because the boost in the signal occurs in the frequency range to which the human ear is most sensitive, whereas the boost due to electrical correction occurs at low and high frequencies to which the ear is less sensitive [6].

The “classic” capsule of a condenser microphone consists of two electrodes. One of these is a movable diaphragm and the other is a fixed electrode referred to as the “backplate”. With this type of construction, the sensitivity can be determined by the design of the backplate, the distance of the diaphragm from the backplate and the flexibility of the diaphragm. However, in a general way, the sensitivity is also determined by the level of the polarization voltage that is applied.

For several decades, no particular attention was paid to optimizing these parameters, since the signal-to-noise ratio of microphone capsules was in any case significantly better than that of the accompanying electronics. However, improvement in the noise specifications of modern circuits made it worthwhile to recenter on this aspect of capsule design.

Thus in the mid-1980s, microphones with a push-pull capsule design came onto the market. Here the diaphragm is mounted between two fixed, acoustically permeable electrodes. The diaphragm therefore generates a useful signal in both directions of motion, thus resulting in a considerably improved signal-to-noise ratio. Another advantage of this design is that independently of the direction of motion of the diaphragm, opposing changes in the air gap impedance arise on the two sides of the diaphragm. The total impedance thus remains constant, and the source of nonlinearity in transducers with a “classic design” is eliminated [7].

4.2. Circuit noise

The noise due to the electronic circuitry is essentially determined by the primary transducer stage. In the case of audio frequency circuit technology, the quality is determined by the tube or a field-effect transistor. However, other circuit details have also led to improved noise values.

Figure 5 provides an overview of the reduction in the self-noise level of audio frequency condenser microphones over the past few decades. This table compares different generations of microphones which use the same capsule, but which are equipped with enhanced circuit technologies. It can be seen that considerable improvements in noise levels have been achieved, and that both large-diaphragm and small-diaphragm microphones have benefited from these developments.

Figure 5 contains furthermore data for recently developed microphones. By means of a coordinated optimization of the capsule and circuit design, today equivalent self-noise levels of 7 dB-A or better can be achieved. With these microphone specifications a limit has been reached, since the noise level is no longer determined by the electronic circuitry, but by the capsule. It has already been pointed out that due to acoustic conditions,
the capsule noise can scarcely be reduced further without adversely affecting other capsule specifications.

<table>
<thead>
<tr>
<th>Microphone Type</th>
<th>Year of Construction</th>
<th>Capsule Type</th>
<th>Self-Noise Level db-A</th>
<th>Dynamic Range dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>KM 64</td>
<td>1964</td>
<td>single membrane</td>
<td>21</td>
<td>102</td>
</tr>
<tr>
<td>KM 184</td>
<td>1993</td>
<td>21 mm ∅</td>
<td>16</td>
<td>122</td>
</tr>
<tr>
<td>U 67</td>
<td>1960</td>
<td>double membrane</td>
<td>17</td>
<td>102</td>
</tr>
<tr>
<td>U 87A</td>
<td>1986</td>
<td>34 mm ∅</td>
<td>12</td>
<td>105</td>
</tr>
<tr>
<td>TLM 103</td>
<td>1997</td>
<td>single membrane, 34 mm ∅</td>
<td>7</td>
<td>131</td>
</tr>
<tr>
<td>D-01 (digital)</td>
<td>2003</td>
<td>double membrane, 29 mm ∅</td>
<td>7</td>
<td>130</td>
</tr>
</tbody>
</table>

Fig. 5: Historical development of the equivalent self-noise level due to inherent noise, for some condenser microphones.

The underlying circuit design essentially permits the molecular noise of the air to be heard at the microphone output. This means that in the case of a ‘typical’ capsule with a distance of 30 µm between the diaphragm and the backplate, a polarization voltage of 60 V and an unweighted noise voltage of 3 µV at the microphone output, a diaphragm displacement of $1.5 \times 10^{-12}$ m would cause a signal to be transmitted.

As a comparison, it should be noted that this diaphragm displacement is 500,000 times smaller than the wavelength of red light, which is 700 nm!

5. Dynamic range

As shown in the right-hand column of Fig. 5, new generations of circuitry permitted the extension of the microphone dynamic range. Whereas the dynamic range was previously approximately 100 dB, modern microphones can transmit 130 dB or more without distortion. (‘dynamic range’ definition: Maximum sound pressure level for THD less than 0.5 % minus self-noise level weighted to DIN/IEC 651. THD of the microphone amplifier when an input level equivalent to the capsule output at the specified SPL is applied).

6. Summary

It has been shown that due to progress in circuitry technology, the quality of the electronics finally matches the quality of the capsule in terms of self-noise level and dynamic range. However, the capsule design has also been improved by making use of technological advances and modern materials.

Studio microphones developed recently for high-resolution applications are capable of sensitivity corresponding to the noise level of air particles hitting the diaphragm surface due to thermal molecular movement, and at the same time have a dynamic range of 130 dB or more. This is true for both microphones using analog electronics and microphones using the most recent ADC technology [8].

In capturing sounds for recordings, the studio microphone constitutes the first link in the chain, and should therefore also be the strongest link. The developments described in this paper illustrate how in the case of microphone capsules, and particularly in the case of microphone circuitry, many individual steps have been taken so as to guarantee that modern studio microphones can continue to fulfill this role.

7. Acknowledgements

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8. Bibliography