LINEARISATION OF POWER AMPLIFIERS, USING MINIMAL CONTROL SYNTHESIS

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Abstract: This report is centred on the development of a novel control algorithm for the adaptive linearisation of mobile radio frequency (RF) communications amplifiers, in order to significantly improve their distortion characteristics. The proposed adaptive linearisation methodology achieves optimal efficiency with minimal distortion. Research objectives also include the synthesis of RF amplifier dynamic models, which are generated by Saleh`s model, and the design and test of physical test systems incorporating the new forms of control.

Keywords: Model reference adaptive control, power amplifiers, linearization, nonlinear modelling.

1. INTRODUCTION

With the evolution of existing and new standards for mobile communication systems and wireless multimedia services, such as modern cellular telephones and base stations, the quantity and complexity of the signals to be transmitted from a given location is increasing. However, the amount of the spectrum available has not increased by the same extent, which leads to an increasing demand for more spectrally efficient formats of transmission, such as multi-channel modulation formats. It is also desired that the signals are transmitted without significant distortion. Therefore, efficiency and fidelity become two critical issues in modern communication systems.

As important components in the transmission of signals, power amplifiers are required to perform relatively linearly with low energy consumption. Thus, there is a growing need for highly linear amplifiers with relatively high efficiency, which generate signals without adding any significant distortion. However, in current open-loop design practice, there is always a trade-off between distortion performance and efficiency, since efficient amplifier systems are highly nonlinear devices. Generally, linearity could be achieved by one of the following two strategies: either a linearly designed amplifier with high efficiency is backed off from its saturation region, or a non-linear amplifier is employed with linearisation techniques to compensate the effects of the non-linearities. The former strategy is difficult to achieve and is often compromised by the increased power dissipation. Therefore, linearisation of the power amplifiers is the preferred option.

1.1 Linearisation techniques

Different control techniques have been introduced and developed, such as Cartesian feedback (Briffa and Faulkner, 1996), feed-forward (Cavers, 1995), and pre-distortion (Faulkner, *et al*., 1990).

Cartesian loop feedback divides the modulation into I (in-phase) and Q (quadrature) parts rather than amplitude and phase characteristics, and has proven to be an effective method. Although the method can tolerate environmental changes, it has possible instabilities because of its sensitivity to the stability margins. Similar to other feedback methods, Cartesian feedback requires a trade-off between spectral growth and loss of amplitude (Meier and DeSwardt, 1998).

Feed-forward is open-loop and inherently stable. However, it is sensitive to the environmental changes and delay mismatch. It also requires the addition of amplitude and phase controllers, which can have adaptation schemes to achieve linear performance.

Pre-distortion is also an open-loop and unconditionally stable method, which is simple and suited to weak non-linearities. The feedback techniques can be regarded as a form of pre-distortion with continuous adaptation via the feedback path. However, the method can not tolerate external changes. Thus, to improve the linearisation performance, a digital processor is usually used, which causes some loss of efficiency. The speed of adaptation is a critical problem in pre-distortion since the learning time in traditional methods can be long, especially when encountering strong non-linearities.

Hence, existing methods show limitations in practice and yet the incorporation of more advanced control strategies is still scarce (Zozaya and Bertran, 2004).

A novel error-based feedback adaptive control will now be presented as a new linearisation technique, which is called the minimal control synthesis (MCS) algorithm. Thus, the principal aim of this research is to use adaptive feedback control to linearise the RF amplifiers, despite unknown and/or time-varying characteristics within the devices.

1.2 Theory of Minimal Control Synthesis (MCS)

The adaptive minimal control synthesis (MCS) algorithm was introduced by Stoten (1989) and, subsequent to the first publication, various extensions of the algorithm have been presented. In addition, the algorithm has been implemented in numerous practical engineering situations.

The basic MCS algorithm starts with an assumed state-space equation of the plant to be controlled as (1) shows below

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + n(t) \tag{1}$$

where $A(t)$ is the plant matrix, $B(t)$ is the input matrix, both of which contain unknown and time-varying parameters, $x(t)$ is the plant state vector, $u(t)$ is the control signal and $n(t)$ is the unknown disturbance. The basic structure of the closed-loop system is as follows:

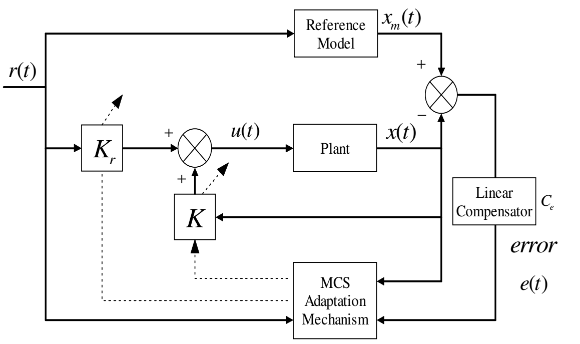

Fig. 1. MCS block diagram

The chosen adaptation law, MCS, has the form:

$$K_r(t) = \int_0^t \alpha e(\tau) r(t)^T d\tau + \beta e(t) r(t)^T + K_r(0) \tag{2}$$

$$K(t) = \int_0^t \alpha e(\tau) y(t)^T d\tau + \beta e(t) y(t)^T + K(0) \tag{3}$$

$K_r(0)$ and $K(0)$ are initial conditions that are usually set to be zero, $r(t)$ is the reference signal, $d(t)$ and $y(t)$ are the desired and actual power amplifier output respectively (see (5) below), and $x_m(t)$ is the reference model state vector. The error $e(t)$ between $d(t)$ and $y(t)$ feeds the adaptation mechanism. Stability and robustness proofs for MCS have been developed via a combination of hyperstability and Lyapunov techniques (eg. Stoten and Hodgson, 1994).

The MCS control signal is then given by:

$$u(t) = K_r(t) r(t) + K(t) y(t) \tag{4}$$

The output error signal is:

$$e(t) = d(t) - y(t) \tag{5}$$

where the desired and actual outputs are $d(t) = C_e x_m(t)$ and $y(t) = C_e x(t)$ respectively, while C_e is the output error matrix used to impose the strictly positive real (SPR) condition on the error dynamics, which is also called linear compensator. Thus,

$$e(t) = C_e\left(x_m(t) - x(t)\right) = C_e x_e(t) \tag{6}$$

Finally, we have

$$C_e = \textit{ even row of } (P) \tag{7}$$

where P is the solution to the Lyapunov equation:

$$PA_m + A_m^T P = -Q \tag{8}$$

A_m is the reference model matrix and Q is a strictly positive real (SPR) matrix. In practice, we could choose a pragmatic solution that ensures pole/zero cancellation in the error dynamics in order to satisfy the SPR condition (and satisfy the Lyapunov equation too). For the first order MCS, for example, we have the settling time t_s and can set

$$C_e = [4/t_s] \tag{9}$$

2. CONFIGURATION AND MODELLING

2.1 Configuration

Consider the basic structure of a model reference adaptive system with a general power amplifier:

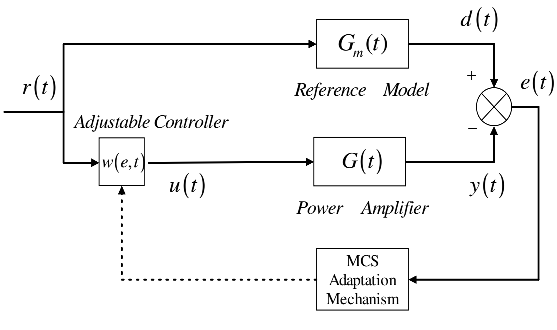

Fig. 2. Typical model reference adaptive system structure for linearisation of power amplifiers

In a similar way to Fig. 1, $G_m(t)$ represents the reference gain (reference model) in Fig. 2; $w(e,t)$ is the adjustable parameter, which is introduced by the adaptation mechanism; $u(t)$ is the control signal; $G(t)>0$ models the behaviour of the power amplifier. The error $e(t)$ between the desired and actual output feeds the adaptation mechanism, which is used to calculate the adjustable parameter $w(e,t)$. To estimate the performance, define the error:

$$e(t) = G_m(t)r(t) - w(e,t)G(t)r(t) \qquad (10)$$

To achieve asymptotic convergence of the system, we must ensure that

$$\lim_{t\to\infty} e(t) = 0 \qquad (11)$$

When the error-based MCS controller is implemented, the adjustable parameters $w(e,t)$ has the form shown in (2) and (3), where α and β are weighting parameters on the adaptive effort, both of which are scalars and usually chosen empirically. Typically, we might have $\{\alpha, \beta\}$ = {0.1, 0.01}, {1, 0.1}, {10, 1}, {100. 10}, etc. The equivalent architecture of the proposed lineariser is as follows:

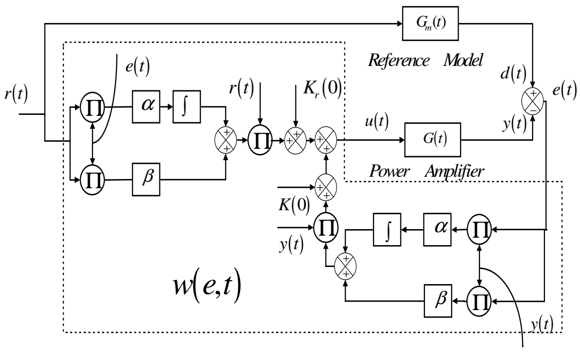

Fig. 3. Adaptation mechanism

In Fig. 3, the dashed frame contains the adjustable parameter $w(e,t)$, which multiplies the reference input $r(t)$, thus, giving the control signal or the PA input $u(t)$.

2.2 Non-linear modelling, based on real model

In this section, we use Saleh`s method to model the non-linearities of a power amplifier based on the AM/AM and AM/PM conversion characteristics (Saleh, 1981).

Consider an input signal with amplitude and phase modulation:

$$r(t) = \underbrace{x(t)}_{\substack{Amplitude\\Modulation}} \cos\left(w_0(t) + \underbrace{\phi(t)}_{\substack{Phase\\Modulation}} \right) \qquad (12)$$

The corresponding output with memory-less non-linearities:

$$y(t) = \underbrace{A\left[x(t)\right]}_{\substack{AM/AM\\Conversion}} \cos\left(w_0(t) + \phi(t) + \underbrace{\Phi\left[x(t)\right]}_{\substack{AM/PM\\Conversion}} \right) \qquad (13)$$

Based on the curve, or the experimental data of the non-linearities of the power amplifiers, Saleh suggests that simple two-parameter formulae can be used to approximate the non-linearities of the power amplifier. In turn, this can be represented by the following expressions with two parameters:

$$A(x) = \frac{\lambda_a x}{\left(1+\mu_a x^2\right)} \qquad (14)$$

$$\Phi(x) = \frac{\lambda_\phi x^2}{\left(1+\mu_\phi x^2\right)} \qquad (15)$$

Thus, we have the general form:

$$z(x) = \frac{\lambda x^n}{\left(1+\mu x^2\right)^v} \qquad (16)$$

The required parameters, λ and μ in the equation (16), are calculated by means of a minimal mean-square-error curve-fitting procedure, using the measured data of the AM/AM (or AM/PM) characteristics. In Fig. 4, we only concentrate on AM/AM characteristics since AM/AM and AM/PM have the same form as (16).

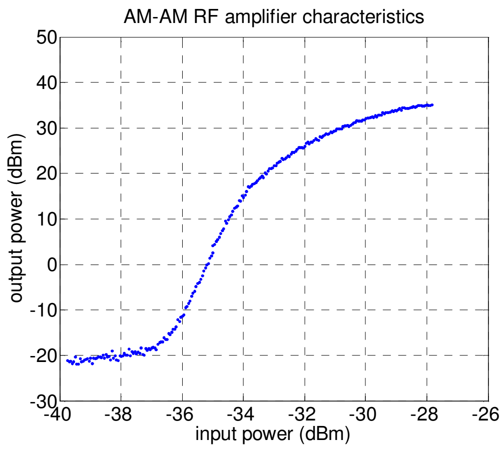

Fig. 4. AM/AM characteristics of the given amplifier

Fig. 4 shows the AM/AM conversion characteristics of a Class C amplifier in dBm, where dBm is an abbreviation for the power ratio in decibel (dB) of the measured power referenced to one milliwatt (mW). 240 data samples were used, and a range of values of n and v were selected for curve-fitting. Taking n=5 and v=4 yields λ=1.2874×10^{24} and μ=1.9806×10^8. The AM/AM data and fitted curve are shown in Fig. 5, with input and output now expressed in volts rather than dBm.

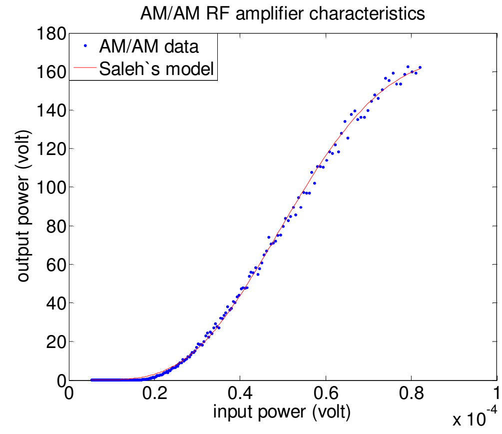

Fig. 5. Saleh`s model,generated by experimental data

3. SIMULATION AND RESULTS

The simulation results of the described algorithm, based on the structure shown in Fig. 3, are shown below.

When the MCS controller is implemented, an ideal reference model is required since the MCS algorithm is a form of model-reference adaptive control. We choose an appropriate characteristic of a piecewise linear saturation function as the reference model, which is generated from Fig. 5, as shown in Fig. 6:

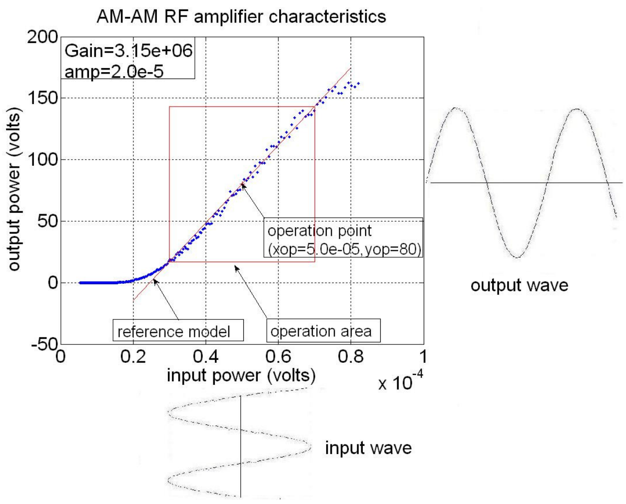

Fig. 6. Reference model (ideal amplifier)

Arbitrarily, we choose an operation point (with the coordinates *xop* and *yop*) on the curve in Fig. 6 and a corresponding operation area, which is determined by the variable *amp*. Then, as in Fig. 3, the simulation was as follows: a sine wave was input into the system, whose amplitude range was determined by the operational envelope in Fig. 6. The error between the ideal model (*Gain*) and the test model (Saleh `s model) was fed back to the MCS controller, whilst $\alpha=10^{-13}$ and $\beta=10^{-14}$. The result is shown as follows:

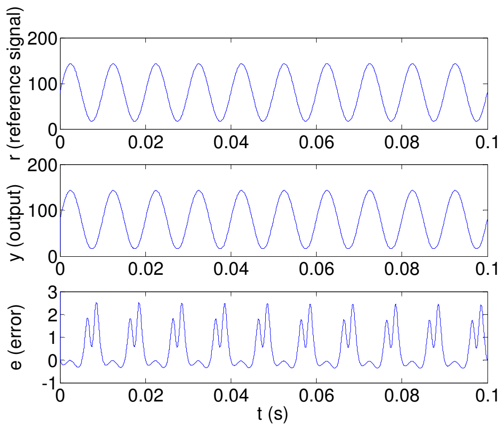

Fig. 7. Comparison between the actual and expected output

From Fig. 7, the output response is smooth and the error between the reference signal and output is relatively small.

For more practical cases, we can set up a look-up table which is established by the experimental data expressed in dBm and repeat the same procedure as described above, i.e. choose an arbitrary operation point (*xop*, *yop*) and a corresponding operation area (determined by *amp*), based on which generate a reference model. This time, we have $\alpha=10^{-6}$, $\beta=10^{-7}$ and *Gain*=6.

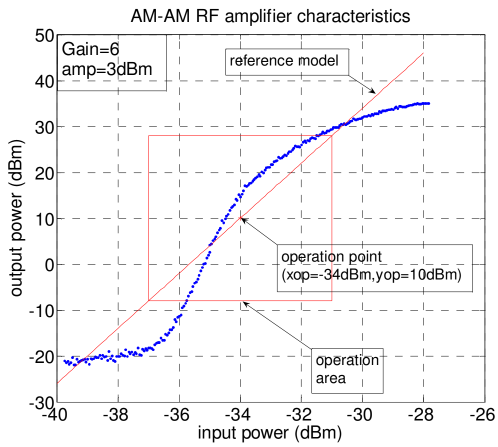

Fig. 8. Reference model (ideal amplifier)

In Fig. 8, the dots represent the noisy data. Then, putting the reference model and the data look-up table into the system configuration as given by Fig. 3, yields the results shown in Fig. 9 and Fig. 10.

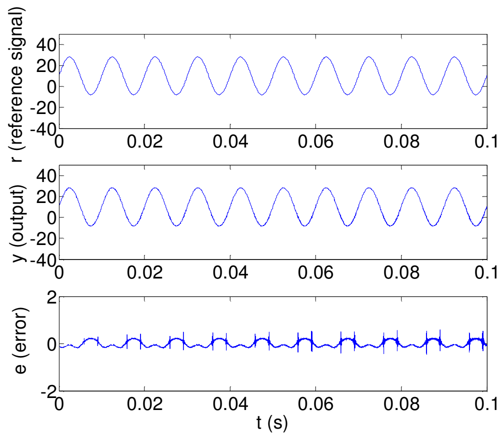

Fig. 9. Comparison between the actual and expected output

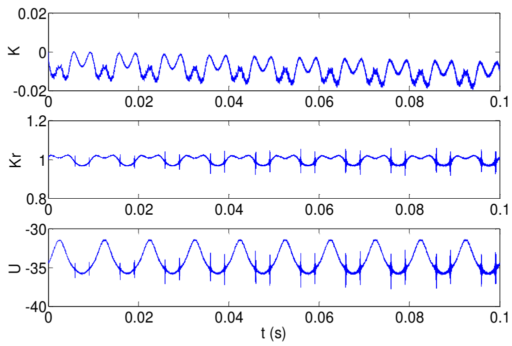

Fig. 10. K, K_r, u are feed-forward, feedback parameter and control signal respectively

From Fig. 9, we can see that the system performance is very satisfactory and the output has very low noise. In addition, the error between the reference signal and the output is small and is bounded. In Fig. 10, Parameters K and K_r are noisy as a result of the original data, but are also bounded.

4. CONCLUSION

A new application of the minimal control synthesis (MCS) algorithm has been presented for the linearisation of mobile radio frequency (RF) communication amplifiers. Simulation studies successfully demonstrated that the new structured lineariser is capable of linearizing a power amplifier which exhibits AM/AM and AM/PM distortions, and significantly improve their distortion characteristics.

The proposed method does not rely on the main amplifier`s gain for linearisation, which is a distinct advantage when compared to the classic feedback lineariser method. Moreover, compared to feed-forward implementations, optimal efficiency can be achieved with minimal distortion.

Future work will concentrate on the analysis and physical tests in the frequency domain. Theoretical stability proofs based on hyperstability theory will be investigated. The MCS algorithm will also be considered for use in the pre-distortion linearisation method.

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