FREQUENCY SYNTHESIS TYPE AIRBORNE TRANSMITTERS

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SUMMARY

After a brief glimpse of the composition of a modern airborne transmitter, a reminder is given of how the choice of a servoed carrier scheme after frequency division on a quartz crystal reference, favoring transmissions at high data speed, has opened up the way to a whole generation of frequency synthesis transmitters covering the 2.1 - 2.7 GHz band in sub-bands of 150 MHz with a pitch of 0.5 MHz.

The advantages of frequency synthesis from the quadruple aspect of maintenance, availability “on the shelf”, flexible use in a congested frequency plan and discretion, are then commented on.

Finally, in a last section - more theoretical than the previous ones - the technical difficulties which arise from the “spirit” of frequency synthesis are referred to.

1. INTRODUCTION

A frequency modulation type airborne telemetering transmitter is the result of a compromise between numerous electrical or mechanical requirements which are often contradictory, the most striking ones being referred to below:

- good stability in temperature of the carrier transmitted
- high spectral purity (noise and harmonic lines)
- wide base band
- notable power transmitted
- small size and weight
- generally good performances in a difficult environment - thermal - electro-magnetic and vibratory
- reliability.

During the past few years a new requirement has become increasingly frequently expressed: this is the frequency synthesis demanded to satisfy different motivations felt by the users:

- simple use of an increasingly congested frequency plan
- easy maintenance when the telecommunication system operates several channels in the same plan
- availability: on the shelf
- discretion obtained through frequency agility.

In a few special cases frequency diversity operating is required without any addition of complex “black boxes”.

So as to meet these different requirements there are two modern solutions to the problem arising:

- transposition through mixing and filtering
- phased-in servoing of the carrier to a reference after frequency division.

These basic schemes will be examined and criticized in paragraph 2 from the dual aspect of the capacity to accept high base bands and the possibility of frequency synthesis.

Paragraph 3 contains explanations. of INTERTECHNIQUE’s choice and the way in which its concepts have been perceived on the French market.

As a conclusion paragraph 4 details the technical difficulties arising from the concept of a frequency synthesis transmitter where the very idea of frequency programming imposes a study of very wide pass band circuits.

2. OUTLINE OF THE MAIN BASIC SCHEMES

Although in the past direct multiplication transmitters firstly of high level, then low level with final application later were produced, and are still used in the realm of satellites where data speeds are very low (1 to 2 Kbit/s) at the present time only the two following types are used:

- transposition through mixing and filtering
- phased-in servoing of the carrier to a reference after frequency division.

2.1 Transposition through Mixing and Filtering

Figure 1 illustrates this scheme in the case in which a passive filter eliminates the undesirable residue from mixing.

2.1.1 Advantages

This type of generation offers the following advantages:

- easy passage of the continuous component in the base band
- very low noise in the vicinity of the carrier
- small volume of the “modulated carrier generation” section if medium spectral purity is sufficient.

2.1.2 Drawbacks

2.1.2.1 Limited Modulation Band

First of all, with medium complexity of the modulator in FI, the ratio of the highest fm modulation frequency to the value of the FI must not be over 10%.

Moreover, still on the assumption of a simple modulator construction, a relative thermal drift of 10^{-3} in a 100° range is a not easily accessible limit. If a 10^{-5} stability of the frequency transmitted fs is the object aimed at, the drift of the quartz crystal OL (of around 10^{-6}) being assumed negligible, the dual inequality can be written as follows

$$10\ fm \leq FI \leq \frac{fs}{100}$$

which shows in particular that if fs = 2400 MHz, fm $\leq$ 2.4 MHz and this value is insufficient for a high quality TV transmission.

2.1.2.2 Harmonic Purity

The elimination of the spurious frequencies generated in the mixture deserves great attention inview of the fact that the volume generally allocated is low and therefore does not provide for the use of highly overstrained cavities.

In fact, drawing (C) in Figure 1 shows the undesirable frequency defined by the double sequence $|pfo - qFI|$ the couple (p, q) consisting of natural integers, possibly nul.

It is not easy to eliminate these frequencies in the general case; nevertheless, when operating at fixed frequency, the phenomenon can be remedied by a judicious choice of the different parameters. The problem arises differently in the case in which the output frequency is to be progammed with a low pitch (0.5 MHz for example).

2.1.2.3 Programming Difficulty

Although in principle the programming seems to be easy, given that it suffices to make LO synthesizable, good spectral purity on output (see 2.1.2.2) can only be validly obtained at the cost of using a programmable output passband filter ("LO follower").

2.1.2.4 Operating of Two Transmitters on Frequency Diversity

Owing to the difficulty of programming with a guarantee of good spectral purity, it is impossible to use a couple of transmitters on frequency diversity, programmed on two distinct frequencies synchronized on the same reference.

The customary synchronization scheme is shown in Figure 2.

The construction of the synchronizer is relatively complex, certain incompatibilities between the diversity pitch and the data rate can even occur.

2.1.3 Alternative Version of the Basic Scheme with Active Filtering

The defects indicated can be remedied by employing phase seroving in hyper-frequency to perform the filtering. This version is detailed in Figure 3. It offers the following advantages over the basic scheme:

- good harmonic purity
- easy programming of the output frequency (making the OL synthesizable); the servo loop acts as LO follower filter eliminating the $|pfo - qFI|$ combinations (see 2.1.2.2).

It has however the following defects as compared to the basic scheme:

- highly complex involved with the servoing of a free micro-wave oscillator on a reference that is itself micro-wave
- difficulty in stabilizing the servo loop whose band must be practically equal to the modulation band
- high volume of the "modulated carrier generation" section.

2.2 Phased-In Servoing of Carrier to a Reference After Frequency Division

If it is observed that in most of the uses encountered (TV or telemetering), the passage of the continuous component is not required, the principle of operating illustrated in Figure 4 can be adopted.

The theoretical study of this scheme - especially its performance versus noise will be indicated in detail in paragraph 4.

2.2.1 Advantages

- Excellent harmonic purity, the modulated signal being generated directly at the output frequency.
- Large modulation passband and large frequency excusion, both permitted by the application of the modulation to a micro-wave VCO
- Easy programmming of the output frequency.
- Simple operating in frequency diversity in accordance with the scheme in Figure 5.
- Reliability

2.2.2 Drawbacks

2.2.2.1 Frequency Noise

The deviation of the spurious frequency is practically (see 4.1) that of the micro-wave VCO and hence - theoretically - multiplied by $\frac{Fs}{FI}$ (= 100) as compared to the scheme in paragraph 2.1.

The customary value found for the effective spurious frequency deviation is 1 kHz to 2300 MHz. In fact this limitation will only be felt in the case of modulations at very low rate as used in satellite - earth links. In cases of high data speeds, as encountered in telemetering on board aircraft or missiles, the signal/noise ratio on transmission is still 56 dB for a numeric speed of 1 Mbit/s and 78 dB for an image transmitted according to the CCIR notifications.

It must moreover be stressed that the coherence between the waves - mutliples of a common driver- generated for frequency diversity, is only obtained the cost of a 1 KHz uncertainty, which is a limit to the gain of any predetection type frequency diversity receiving system.

2.2.2.2 High Volume

In conventional technologies - hybrid micro-electronics over 300 MHz, single layer printed circuits below 300 MHz - the volume of two monofrequency transmitters delivering the same power (0.5 W) can be compared, one built according to the transposition and passive filtering technique, the other by phase servoing after frequency division: the figures are respectively 80 cm^3 and 130 cm^3. Thus to construct low power monofrequency transmitters, the frequency division scheme is penalizing, unless harmonic purity higher than that normally required (- 25 dBm) is desired.

2.2.2.3 Non-transmission of the Continuous Component

Servoing ensures stability of the carrier versus slow drifts (temperature or ageing of components other than the quartz crystal driver); it therefore erases the low components of the modulation. As a general rule the low break in the modulation is obtained at 10 Hz and to date we have not yet encountered uses liable to be impeded by this break.

It can be observed that, by replacing the quartz crystal driver in Figure 4 by a VCXO, the present drawback can be eliminated. Figure 5 illustrates this principle. It should be indicated that in this case, the frequency excursion permitted is limited by the VCXO to a maximum of 10^{-3} of the output frequency, which is sufficient for telemetering transmissions but too low for quality television. Moreover the frequency stability in temperature becomes critical.

3. CHOICE CRITERIA

3.1 Comparative Table

The table below summarizes the previous analysis.

Striking Characteristics	Transposition and Filtering	Phased-in Servoing of the Carrier to a Reference After Frequency Division
• Passband	Limited	Very large
• Transmission of the continuous component	Easy	Complex: limits the frequency excusion
• Harmonic purity	Medium	Excellent

• Noise near the carrier	Reduced	Intense: limits the use to high data speeds (> 100 kbit/s)
• Frequency synthesis	Complex: requires the use of a programmable follow-up filter	Easy: results from the principle of frequency division
• Operating on synchronized frequency diversity	Delicate: requires a complex external synchronizer	Easy
• Volume, weight	Reduced	Medium
• Potential reliability	Good	Excellent

3.2 INTERTECHNIQUE's Choice

As shown in Table 3.1 the choiceof a basic scheme is the result of a compromise according to the characteristics to be favored:

- for fixed frequency applications, limited to a 1.5 MHz base band, the transposition and passive filtering scheme is sufficient
- in application where a larger base band (up to 10 MHz is required) or the possibility of frequency programming, the frequency division scheme is essential.

Because they initially sought for a large modulation band, INTERTECHNIQUE adopted this second scheme in 1974 and made it programmable as of 1977 by defining the following specifications:

- output frequency programmable in ranges of 150 MHz in the 2100 - 2700 MHz band
- programming pitch: 0.5 MHz
- frequency control: by pre-wired plug
- passband: from 10 Hz to 10 MHz
- frequency excursion: up to 5 MHz
- power: f rom 5 to 20 W.

The photos below show a number of products satisfying this definition: (HE 2308 MP, X 4863, HE 2520 VP).

3.3 Reception on the French Market

Looking back in time it is a good thing to examine how this choice was perceived by the French market.

For aircraft flight tests, frequency synthesis transmitters very soon superceded fixed frequency transmitters: here the operating flexibility of the frequency plan prevailed, whereas the band allocated to telemetering is narrow (2300 - 2350 MHz).

For the debugging of missiles - and although some 50 telemetering channels are available between 2200 and 2300 MHz - the frequency programming requirement has never appeared to be essential.

The services which have adopted frequency synthesis transmitters have rather more remembered the following advantages:

- simplified maintenance: one single transmitter can back up all the equipment in the 2200 - 2300 MHz telemetering band
- possible availability of the equipment “on the shelf”.

One of the aspects which could appear essential at a time when much reference is made to discrete transmissions, has never claimed attention: this is frequency agility. Nevertheless the possibility of exploring a 150 MHz frequency range only devoting 10 to 20 microseconds to channel allocation, is indeed an imperfect means but sufficiently dissuasive versus an intruder.

3.4 Advantage of Frequency Synthesis

This explanation of the market situation of telemetering transmitters in France has highlighted the advantages offered by frequency synthesis:

- flexible use of the frequency plan
- management of a maintenance depot facilitated
- availability “on the shelf”
- discretion.

This analysis cannot be concluded without saying a few words of a characteristic resulting from frequency synthesis: reliability.

In fact, in order to be frequency programmable on a relatively broad range, a transmitter must consist of very wide band circuits (VCO and micro-wave amplifiers, seroving) which by nature

- are not critical in debugging phase
- are not sensitive to the effects of ageing.

Here the qualities required to obtain high reliability can be recognized. In the “Ariane” launchers program the CNES has appreciated this quality.

4. TECHNICAL DIFFICULTIES ENCOUNTERED

The main characteristics defining the specifications of a frequency synthesis type airborne telemetering transmitter were summarized in paragraph 3.

In the lines below the main technical difficulties encountered in the concept of a frequency synthesis transmitter observing the technical clauses listed, are indicated.

4.1 Analysis of the Phase Noise on Output

The following figure shows the characteristic parameters.

with the following notations:

p = Laplace variable

K_φ = phase detector volt gain per radian

K_f = gain of the VCO (Hertz per volt)

$F(p)$ = transfer function of loop filter = $\dfrac{1+\tau_2 p}{1+\tau_1 p}$

τ_1, τ_2 = time constants

D = loop division rank

$m(p)$ = modulating message

$\bar{n}(p)$ = noise voltage producing output phase fluctuation

$\varphi_s(p)$ = output phase fluctuation.

The transfer function, in closed chain, of the local transmitter is provided by:

$$G(p) = \frac{\overline{\varphi_s}}{\frac{K_f}{p}\left[m(p) + \bar{n}(p)\right]} = \frac{p}{p + \frac{K_f K_\varphi}{D} F(p)} = \frac{p\left(p + \frac{\omega_n^2 D}{K_f K_\varphi}\right)}{p^2 + 2\xi\omega_n p + \omega_n^2} \tag{1}$$

where

$$\begin{cases} \omega_n^2 = \dfrac{K_f K_\varphi}{D} \dfrac{1}{\tau_1} \\ 2\xi\omega_n = \dfrac{1}{\tau_1}\left(1 + \dfrac{K_f K_\varphi}{D} \tau_2\right) \end{cases} \tag{2}$$

Being concerned with the carrier noise in the absence of modulation, we subsequently shall assume that m(p) = 0.

The functional relation between the input phase noise (due to $\bar{n}$) and the output phase noise $\overline{\varphi_s}$ is given by:

$$\overline{\varphi_s}(\omega) = \left|G(j\omega)\right|^2 \overline{\varphi_e}(\omega) \tag{3}$$

We shall then consider a conventional form of the signal/noise ratio of the spectral power density of a free oscillator, i.e.:

$$\overline{\varphi_e}(\omega) = \frac{1}{\omega_\varphi\left[1 + \left(\frac{\omega}{\omega_\varphi}\right)^2\right]} \quad \text{where} \quad \int_{-\infty}^{+\infty} \overline{\varphi_e}(\omega)\, d\omega = 1 \tag{4}$$

and where ω_φ is a 3 dB break pulse (generally measured experimentally).

By substituting 4 and 3 in 1, we find:

$$\overline{\varphi_s}(\omega) = \frac{(\omega/\omega_n)^4}{\left(\omega^2/\omega_n^2 - 1\right)^2 + 4\xi^2 \frac{\omega^2}{\omega_n^2}} \times \frac{1}{1 + \gamma^2 \frac{\omega^2}{\omega_n^2}} \times \frac{2}{\omega_\varphi}$$

where

$$\gamma = \frac{\omega_n}{\omega_\varphi}$$

Noting that it is current practice to use $\xi = 1/\sqrt{2}$ we can write:

$$\overline{\varphi_s(\omega)} = \frac{(\omega/\omega_n)^4}{(\omega/\omega_n)^4+1} \times \frac{1}{1+\gamma^2\left(\frac{\omega}{\omega_n}\right)^2} \times \frac{2}{\omega_\varphi}$$

$$\gamma = \frac{\omega_n}{\omega_\varphi}$$

The curve representing $\overline{\varphi_s(\omega)}$ has a maximum value provided by:

$$\mathrm{Max}\left\{\overline{\varphi_s(\omega)}\right\} = \frac{1}{(1+\gamma)^2} \times \frac{2}{\omega_\varphi}$$

$$\text{at} \quad \omega_M = \frac{\omega_n}{\sqrt{\gamma}}$$

Numeric Example

$$\omega_n = 2\pi . 10 \ \text{rad/sec}$$

$$\omega_\varphi = 2\pi . 0{,}5 . 10^3 \ \text{rad/sec}$$ value measured

$$\xi = 1/\sqrt{2}$$

We find:

$$\gamma = \frac{\omega_n}{\omega_\varphi} = 0{,}02$$

$$\omega_M = 2\pi . 70{,}7 \ \text{rad/sec}$$

$$\mathrm{Max}\left\{\overline{\varphi_s}\right\} = 6.10^{-4}$$

At w_M, the free oscillator will have a spectral signal noise ratio at 3.10^{-4}. Servoing, owing to the fact that its break frequency is low so as not to disturb the modulation, doubles the signal/spectral noise ratio near the carrier.

NB.: the value $f_\varphi = \omega_\varphi / 2\pi$ = 500 Hz must not be confused with the effective spurious frequency deviation which, in an analysis band ($[0, f_m]$) is defined by:

$\overline{\Delta f_{eff}^2} = f_m \int_0^{f_m} \overline{\varphi_s(\omega)} \cdot d\omega$ whose value is practically 1 KHz to 2.3 GHz.

4.2 Modulation Nonlinearity

It is relatively easy to conceive a linear VCO on a range of ± 10% of its neutral frequency when it is loaded on a suitable impedance. Unfortunately, in a frequency synthesis transmitter the VCO is followed by an amplification chain feeding an antenna often ill-adapted in the total programming band.

When the reflection coefficient seen by the VCO is not identically null in the useful band, it produces a distortion resulting from the drive effect of the oscillator through its load (pulling); the nonlinear distortion produced generates the differential phase on the TV image or the incorrect restoration of the binary rate in a numeric signal.

The notation are as follows:

f_0 = central frequency of the VCO
P_{inc} = oscillator power of available
$r(f)$ = reflection coefficient of the load to the frequency f
P_{ref} = $|r(f)|^2 P_{inc}$ = power reflected by the load
Q_c = oscillator overvoltage load.

In the oscillator output plane where the $r(f)$ is measured, and incident and reflected wave are superposed. The power oscillator P_{inc} is subjected to an injection power P_{ref} which - in accordance with Adler's theory - will vary its frequency f by value $\Delta(f)$ so that:

$$\Delta(f) = \frac{f_0}{Q_c}\sqrt{\frac{P_{ref}}{P_{inc}}} = \frac{f_0}{Q_c}|r(f)| \tag{1}$$

In a narrow interval (df) of the band occupied by the modulated wave (1-5 MHz for a numeric signal and 1 Mbit/s or 24 MHz for a TV signal), the differential frequency variation is provided by:

$$\frac{\Delta(f)}{df} = \frac{f_0}{Q_c}\,\frac{d\tau}{df} \qquad (2)$$

Moreover, if Δf_0 represents the frequency excursion of the modulated signal in the absence of any disturbance, the value $\Delta F'$ observed in the presence of energy reflected by the load is expressed by the relation:

$$\Delta F' = \Delta F_0 \left\{ 1 + \frac{f_0}{Q_c}\,\frac{d\tau}{df} \right\} \qquad (3)$$

A numeric application shows the criticality of the load adaptation. To respect the specifications indicated above, the characteristics values to be obtained are the following:

- $\frac{f_0}{Q_c} = 0{,}1$
- $\frac{\Delta(f)}{df} = \frac{\Delta F' - \Delta F_0}{\Delta F_0} = 10^{-2}$

These values are satisfied if: $\frac{d\tau}{df} = 4 \cdot 10^{-5}$

In the case of a fixed frequency application, the value $f_0/Q_c = 0{,}01$ would be sufficient making the slope regularity of the reflection coefficient less critical ($\frac{d\tau}{df} = 4 \cdot 10^{-4}$ in this case).