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Research Article

Review Analysis of the Intermodulation Distortion (IMD) on The Instrument Landing System (ILS)

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ABSTRACT

Our study analyzes electromagnetic interference (EMI) from various sources (sporadic E, aircraft electronics, wireless attack, FM radio broadcasting) affecting instrument landing systems (ILS). Since the compatibility between the FM broadcasting frequency plan and the aeronautical radionavigation service frequency plan has not been fully studied. [1] The paper analytically describes the transmission of CSB (Carrier-Sideband) and SBO (Sideband-Only) signals from the instrument landing system transmitter and how to generate of third-order intermodulation products, can cause phase and amplitude distortion of navigation tone signals (90 Hz, 150 Hz), resulting in incorrect navigation instructions being displayed on the aircraft's course deviation indicator (CDI). Due to this problem, at the end of the paper we have a suggestion on how to increase the immunity of an ILS receiver. In this paper, we present only analytical results that deal only with interference from FM radio transmitters. The research is still ongoing and experimental results will be presented in future studies.

Keywords: Instrument Landing System (ILS), CSB (Carrier and Sideband) and SBO (Sideband-Only), Difference in Depth of Modulation (DDM), Course Deviation Indicator (CDI), FM Broadcasting, Intermodulation distortion (IMD).

INTRODUCTION

Interference from FM broadcasting service to instrument landing system (ILS) localizer is a widely recognized problem for many years and has been described by both the ITU and ICAO [2,3]. FM broadcasting stations operate with high-powers levels of up to 250kW erp, whereas aeronautical facilities in the adjacent band operate with power levels in the range of 0.02-6kW erp. FM broadcasting stations, due to their high power levels, transmit significant spurious emissions. In addition, some ILS receivers have a high susceptibility to FM interference. Although ICAO introduced new immunity standards in 1998, not all states have adopted There is no guard band between the highest assignable frequency for FM broadcasting (107.9 MHz) and the lowest assignable radionavigation frequency (108.0 MHz), which increases the risk of intermodulation. [1,4] Since 1 January 2001, VHF (very high frequency / 30 - 300 MHz) broadcasting stations in Europe have been allowed to operate with reduced restrictions and increased transmitter power levels. This has a significant impact on VHF radio navigation receivers, especially ILS radio receivers located on aircraft. For safety reasons, ILS systems on aircraft require the use of radio receivers with better immunity to interference from FM broadcasting transmitters. [5, 6]. Instrument landing system (ILS) require additional protection against interference by modifying current equipment to allow for frequency modulation. Despite this being a known issue, it is not yet common practice Intermodulation distortion (IMD) is a significant problem for ILS receivers, as it can cause false readings by creating unwanted frequency components in the ILS band. High-power VHF signals can produce IMD products at harmonic or intermodulation frequencies, where the third-order products ($2f2 - f1$, $2f1 - f2$) are particularly complex signals and cause the receiver to enter a nonlinear environment. Therefore, it is necessary to implement effective filtering to attenuate these interfering signal frequencies and preserve the navigation signal in order to maintain accurate signal reception.

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INTRUMENT LANDING SYSTEM

Brief Overview of the ILS System

The Instrument Landing System (ILS) is a precision radio navigation system used to guide aircraft to and from the centerline of a runway in all weather conditions. The first commercial aircraft landing using ILS occurred in 1938, and it was adopted as an international standard by ICAO in 1949 and is the system we have today. ILS is still the most common radio-guided landing system in use worldwide and will remain so for the foreseeable future. It is probable that over the next decade GNSS-guided approaches will begin to become the norm in operational practice, but ILS will have to remain in place as a local backup. [7] The transmitter of the instrument landing system, located on the ground, transmits amplitude-modulated navigation tone signals (90 and 150 Hz) into space, which are received by the radio navigation receiver located on the aircraft. The receiver first demodulates the incoming signal to extract the 90 Hz and 150 Hz navigation tone signals. These tones are sent to a detector, where the magnitudes of the tone signals are compared. [8] Based on this comparison, an electrical voltage is generated in the receiver, which controls the amount of deflection of the needle of the course deviation indicator (CDI). The key factor that determines the position of an aircraft relative to the runway centerline is the Difference in Depth of Modulation (DDM). DDM is the difference between the modulation depths of the 150 and 90 Hz signals. When the aircraft is aligned with the runway centerline, DDM is zero, indicating that no correction is required. [8] The ground transmitters of the Instrument Landing System (ILS) use amplitude modulation DSB-SC CSB and SBO; CSB (Carrier and Sidebands) and SBO (Sidebands Only) modulation techniques to guide the aircraft safely during landing. The system transmits signals that are received by the aircraft's onboard radio navigation receiver.

Definition of CSB (Carrier-Sideband) and SBO (Sideband-Only) Modulation in ILS

The instrument landing system (ILS) uses the CSB (Carrier and Sidebands) and SBO (Sidebands Only) techniques to help aircraft land safely. CSB (Carrier-Sideband) Signal is an amplitude-modulated (AM) signal carrying the 90 Hz and 150 Hz navigation tones. These tones create a difference in modulation depth on either side of the runway centerline, CSB signal can be written as:

$$S_{CSB}(t) = A_c[1 + m_1\cos(2\pi f_{90}t) + m_2\cos(2\pi f_{150}t)]\cos(2\pi f_c t) \quad (1)$$

A_c is the carrier amplitude. m_1 and m_2 are modulation indices for the two modulating signals. f_{90} and f_{150} are the frequencies of the modulating signals. f_c is the carrier frequency.

SBO (Sideband-Only) Signal is a double-sideband suppressed-carrier (DSB-SC) signal. It contains only the 90 Hz and 150 Hz tones modulated onto sidebands, without the carrier. The mathematical expression for the SBO DSB-SC signal can be written as:

$$S_{SBO}(t) = A_s[m_1\cos(2\pi f_{90}t) + m_2\cos(2\pi f_{150}t)]\cos(2\pi f_c t) \quad (2)$$

A_s is the carrier amplitude. m_1 and m_2 are modulation indices for the two modulating signals. f_{90} and f_{150} are the frequencies of the modulating signals. f_c is the carrier frequency.

Total Signal (CSB + SBO) The combined signal received by the aircraft is the sum of the CSB and SBO signals:

$$s_{total}(t) = s_{CSB}(t) + s_{SBO}(t)$$

$$s_{\text{total}}(t) = \begin{bmatrix}(A_{CSB1} + A_{SBO1})\cos(2\pi \cdot 90t) + \\ (A_{CSB2} + A_{SBO2})\cos(2\pi \cdot 150t)\end{bmatrix} \cdot \cos(2\pi f_c t) \quad (3)$$

Sum-and-Difference Technique

The receiver locates itself using a sum-and-difference technique, analyzing the 90 Hz and 150 Hz sine wave tones. The CSB signal combines these tones, while the SBO signal uses them out of phase, inverting the 150 Hz signal. The

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localizer signal's centerline shows the difference between CSB and SBO signals, generating a stronger 150 Hz signal above and a dominant 90 Hz tone below.[8]

The DDM is calculated as the difference between the modulation depths of the 90 Hz and 150 Hz tones:

$$DDM = \frac{U_{90\text{ Hz}} - U_{150\text{ Hz}}}{U_{90\text{ Hz}} + U_{150\text{ Hz}}} \quad (4)$$

$A_{90} = A_{CSB1} + A_{SBO1}$, the combined amplitude of the 90 Hz tone. and $A_{150} = A_{CSB2} + A_{SBO2}$, the combined amplitude of the 150 Hz tone.

When DDM ≠ 0 :

DDM ≠ 0 occurs when the aircraft is off-course.

If DDM > 0, the 90 Hz tone is stronger, indicating the aircraft is to one side (e.g., to the left of the runway centerline for the localizer).

If DDM < 0, the 150 Hz tone is stronger, indicating the aircraft is to the opposite side (e.g., to the right of the centerline).

INTERMODULATION DISTORTION (IMD) IN AERONAUTICAL RADIO RECEIVERS

Intermodulation distortion (IMD) occurs when several signals interfere in a nonlinear system, producing unwanted frequencies. In the instrument landing system (ILS) band (108-112 MHz), the most serious problem is third-order intermodulation products, as they can cause interference in the ILS frequency range where third-order intermodulation products increase by 3 dB for every 1 dB increase in the desired input signal, which increases their impact on precision navigation. Therefore, third-order intermodulation interference can degrade ILS signals and cause incorrect navigation information to be provided or a malfunction flag to be activated on the course deviation indicator [9 ,10].

Nonlinear systems produce harmonic components. Therefore, if the input signal from a nonlinear system has a frequency fa, then the output signal will contain multiples of the input frequency. (2fa, 3fa, 4fa, ……). Intermodulation occurs when the input signal to a nonlinear system contains two or more frequencies, for example if the input signal contains three frequency components fa, fb and fc. This can be expressed as a formula:

$$x(t) = M_a \sin(2\pi f_a t + \varphi_a) + M_b \sin(2\pi f_b t + \varphi_b) + M_c \sin(2\pi f_c t + \varphi_c) \,, \quad (5)$$

M_a $M_b M_c$ are the amplitudes for each component. They determine the power of the signal. f_a $f_b f_c$ are the frequencies of the signals, each component has its own unique frequency. φ_a φ_b φ_c are phase angles that determine where each signal begins in time. The order of the intermodulation products, O, is determined by the sum of the absolute values of the coefficients:

$$O = |k_a| + |k_b| + \cdots + |k_N| \quad (6)$$

if $|k_a| + |k_b| = 2$this is a second-order intermodulation product, if $|k_a| + |k_b| = 3$ this is a third-order product. third-order intermodulation products appear if the following conditions are met:

$$\begin{gathered} |k_a| + |k_b| + |k_c| = 3 \\ (f_a + f_b - f_c), (f_a + f_c - f_b), (f_b + f_c - f_a) \\ (2f_a - f_b), (2f_a - f_c), (2f_b - f_a), (2f_b - f_c), (2f_c - f_a), \end{gathered} \quad (7)$$

Impact of IMD on CSB and SBO signals

Interference caused by intermodulation distortion (IMD) in the vicinity of the instrument landing system carrier frequency (108.1 MHz) can cause disruptions in CSB transmissions, affecting the accuracy of heading guidance. The magnitude of IMD on the CSB signal can be represented as:

$$S_{CSB}(t) = \left(A_c + \varepsilon' \cos(2\pi f_{IMD} t)\right)[1 + m_1 \cos(2\pi f_{90} t) + m_2 \cos(2\pi f_{150} t)] \cos(2\pi f_c t) \quad (8)$$

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ϵ′ epsilon represents the amplitude of the IMD product at f_{IMD}. This introduces a modulation term at the frequency f_{IMD}, which could interfere with the desired 90 Hz/150 Hz modulation tones. Ac is the carrier amplitude. f_{IMD} is the frequency related to intermodulation distortion. m_1 and m_2 are modulation indices for signals with frequencies f_{90} and f_{150}. f_c is the carrier frequency.

Impact on SBO Signals

Because SBO signals are suppressed carrier signals, they are more sensitive to IMD products generated by adjacent channels. The IMD effect on SBO signals is given by:

$$S_{SBO}(t) = \left(A_s + \varepsilon' \cos(2\pi f_{IMD} t)\right)[m_1 \cos(2\pi f_{90} t) + m_2 \cos(2\pi f_{150} t)]\cos(2\pi f_c t) \quad (9)$$

Where ϵ′ is the amplitude of the IMD product in the SBO signal. In the case of SBO signals, since there is no carrier, the IMD affects the modulation balance between the 90 Hz and 150 Hz tones directly, which in turn can lead to distortion of the spatial modulation. A_s Amplitude of the main SBO signal component (constant). $m_1 \cos\left(2\pi f_{90} t\right)$ represents a modulating signal at frequency f_{90} (typically around 90 Hz), which is used for ILS modulation in the Localizer or Glide Slope system. $m_2 \cos\left(2\pi f_{150} t\right)$ represents another modulating signal at frequency f_{150} (typically around 150 Hz), another key modulating frequency in ILS signals. f_c Carrier frequency, which is the frequency of the localizer or glide slope signal (e.g., for the localizer, between 108.1 MHz and 111.95 MHz; for the glide slope, between 329.15 MHz and 335 MHz). [8]

ROLE OF FILTERS IN MITIGATING IMD

Third-order intermodulation distortion (IMD3) introduces unwanted frequency components near the desired signal band, which can degrade signal quality. A well-designed filter addresses this issue by providing a steep roll-off and sharp attenuation in the stopband, while preserving the integrity of the desired signal, such as the ILS signal. IMD3 products often fall within the filter's stopband, making it necessary for the filter to have a sharp roll-off to effectively attenuate these unwanted frequencies. Filters with steep transitions, such as Elliptic filters, are particularly effective at suppressing out-of-band interference, including IMD3. Their sharp roll-off enables them to reject signals outside the desired frequency range, including the IMD3 products that may occur just outside the passband. In contrast, Butterworth filters provide a smoother passband response that minimizes distortion but is less effective at rejecting IMD. While Butterworth filters maintain signal quality, they require higher orders to achieve the same level of IMD rejection as Elliptic filters.

IMD Rejection with Butterworth Filters

Butterworth filters have a gradual roll off, that is they reduce the signals outside the band slowly. Even though their pass band is quite smooth it causes least distortion and for good IMD rejection they may have to be of higher order (4th or 5th order). It has minimal ripple which makes it suitable for use inILS where the signal quality has to be maintained to the utmost. But for strong IMD suppression they are bad at rejecting them because of their slow attenuation of interference. [11,12]

IMD Rejection with Elliptic (Cauer) Filters

Elliptic (Cauer) filters have the sharpest roll off and at lower orders can roll off nearby IMD products more effectively than Butterworth filters. They are very effective at rejecting VHF broadcast interference with that sharp cutoff though, and their passband and stopband ripples may cause slight distortions. Nonetheless, their better rejection deserves attention for situations where interference suppression is critical, e.g., ILS receivers that are subjected to very strong external signals [11].

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Butterworth vs. Elliptic Filters for IMD Rejection in ILS Receivers

Whether Butterworth or elliptic filters are used is determined by the system requirements. Butterworth filters are designed for signal integrity and have a smooth passband; however, their gradual roll-off makes them less effective against strong interference. Elliptic filters offer superior IMD rejection. With only small fluctuations of the signal, they are not suitable for weak signals. Elliptic filters are recommended for ILS receivers with strong VHF interference by attenuating IMD3 products. Butterworth filters are best for signal purity but are not very effective against third-order intermodulation products. The process by which an elliptical filter changes the amplitude and phase of signals at different frequencies is mathematically represented by its transfer function. An elliptic filter's poles and zeros, which are positioned carefully to produce the steepest roll-off and the intended ripple characteristics in the passband and stopband, can be used to calculate the filter's transfer function [12]. An n-th order elliptic filter's transfer function H(s) is commonly represented as a ratio of two polynomials in the complex frequency variable s, where s=jω, where ω is the angular frequency. The form of the transfer function is:

$$H(s) = \frac{B(s)}{A(s)} \tag{10}$$

A(s) is the denominator polynomial related to the poles of the filter, and B(s) is the numerator polynomial related to the zeros of the filter. The general structure of the polynomial coefficients in A(s) and B(s) depends on the specific design parameters of the filter, such as the passband ripple ϵ, the stopband attenuation A(s), the cutoff frequency ωc, and the filter's order n.

Poles and Zeros:

Poles: The poles of an elliptical filter are located in the left half-plane of the complex s-plane (for low-pass filter design). Which improves the sharp cutoff characteristics and is designed to achieve the steepest transition from band to stop. Nulls: Nulls are placed at specific points in the s-plane to shape the frequency response to achieve the desired wave behavior in both the passband and stopband. The filter design places the poles and zeros in a way that minimizes the maximum deviation from the ideal frequency response, providing the desired amount of passband gain and stopband attenuation.

Transfer Function Expression:

Mathematically, for an elliptic low-pass filter, the transfer function can be written as:

$$H(s) = \frac{1}{\sqrt{1+\epsilon^2 \prod_{k=1}^{n} \frac{(s-p_k)}{(s-z_k)}}} \tag{11}$$

ϵ is the ripple factor in the passband (determining how much ripple is tolerated), p_k are the poles of the filter, z_k are the zeros of the filter, and n is the order of the filter. This is a general representation, but it should be noted that the specific values of p_k and z_k depend on the desired characteristics of the filter, such as the passband ripple and the stopband attenuation [11].

Frequency Response and Normalized Frequency Response:

The frequency response $H(j\omega)$ of the filter is obtained by substituting s=jω into the transfer function, where ω is the angular frequency of the signal being processed:

$$H(j\omega) = \frac{B(j\omega)}{A(j\omega)} \tag{12}$$

The frequency response of an Elliptic filter is a flat passband with a ripple, and then a sharp transition from passband to stopband. Furthermore, it has a steep roll off in the stopband thus rejecting unwanted frequencies and intermodulation products.

For practical filter design, the transfer function is usually normalized by bringing the frequency response to the desired cutoff frequency. The normalized transfer function $H_{\text{norm}}(j\omega)$ of a low-pass Elliptic filter is usually written in the following form: This formulation is convenient for design because it ensures that the filter's passband ripple is minimized while still achieving the desired rate of transition from passband to stopband. The frequency ω is normalized to the desired cutoff frequency.

$$H_{\text{norm}}(j\omega) = \frac{1}{\sqrt{1+\epsilon^2 \prod_{k=1}^{n} \frac{(j\omega - p_k)}{(j\omega - z_k)}}} \quad (13)$$

The Bode plot of an Elliptic filter is characterized by a frequency response with a small ripple, and a flat passband. It has a sharp transition to the stopband as frequency increases. The attenuation increases rapidly in the stopband, and there is very little signal leakage [12].

CONCLUSION:

From the analysis of the intermodulation distortion (IMD) caused by FM broadcasting service on the instrument landing system (ILS). This type of intermodulation product is a source of interference at the operating frequencies of aeronautical systems and causes distortion of the ILS localizer navigation signal in it, leading to amplitude and phase shifts, which, in turn, result in incorrect navigation indications on the course deviation indicator (CDI) or the activation of a malfunction alarm. Our view is that further research is needed to address this problem, both in FM broadcast transmitters and in aircraft navigation systems, stronger immunity to third-order intermodulation rejection is needed. In particular, the regulations for navigation systems, especially for ILS receivers, should be reviewed, and the FM transmitter power levels should be adjusted to meet the requirements of radio navigation systems. It should be noted that since intermodulation distortion (IMD) has a large impact on the course deviation indicator (CDI), it would be advisable to increase the receiver immunity by using Butterworth and Elliptic filters. Studying this and conducting an experiment is the next stage of our research.

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