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The Impact of Intermodulation Distortion (IMD) on Aeronautical ILS Radio Navigation Receivers

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The present research is based on the test procedures for measuring aeronautical navigation receiver characteristics used to determine intermodulation distortion (IMD), coming from the sound-broadcasting service in the band of about 87-108 MHz and the aeronautical ILS service in the band 108-118 MHz. The aviation sector is currently experiencing a significant increase in air traffic, with over 5,000 flights airborne at any given moment. One of the most crucial stages of a flight is the final approach and landing. Nowadays, the majority of airports are equipped with the instrument landing system (ILS). Two VHF AM transmitters are fed from the same drive sourses, the two radio beams from a coherent transmission bat with the modulation depth of the two navigation tones varing depending on where the aircraft is in relation to the ranway centerline. This is the so-called space modulation. It offers the most accurate guidance for both horizontal and vertical positions during an aircraft's approach in all weather conditions to ensure the pilot's landing safely. Electromagnetic interference (EMI) addressed to the ILS localizers is a well-known issue in the aviation industry. Interference with civil aviation frequencies is an increasing concern. Intermodulation distortion is a type of interference that happens when multiple signals combine in a non-linear device, impacting aircraft navigation receivers. This situation can result in ILS receiver's problems like the overload and desensitization of low-noise amplifiers, mixers, and various circuits. It may also cause reciprocal mixing effects because the receiver can not restore an ideal navigation tones for proper received signal conversion. *© 2024 Bull. Georg. Natl. Acad. Sci.*

electromagnetic interference, intermodulation distortion, instrument landing system, Difference in the depth of modulation

According to the 55th edition of Boeing, statistical summary of commercial jet airplain accidents, 43% of fatal jet accidents occur during final approach and landing [1]. The Instrument Landing System (ILS) is a precise radio navigation system that guides aircraft during the critical final approach and landing phases, regardless of weather conditions. The system transmits signals, which are received by the aircraft's onboard radio navigation receiver. The receiver first demodulates the incoming signal to extract the 90 Hz and 150 Hz navigation tones. These tones are sent to a detector for further processing, where their magnitudes are compared [2]. The system generates an electrical voltage based on this comparison, which controls the deflection of the CDI needle, guiding the pilot toward the runway.

A key factor in determining the aircraft's position relative to the runway centerline is the difference in depth of modulation (DDM). DDM represents the difference in modulation depths of the two tones (90 Hz and 150 Hz). When the aircraft is perfectly aligned with the runway centerline, the DDM is zero, indicating that no correction is necessary [3,4] (Fig. 1.).

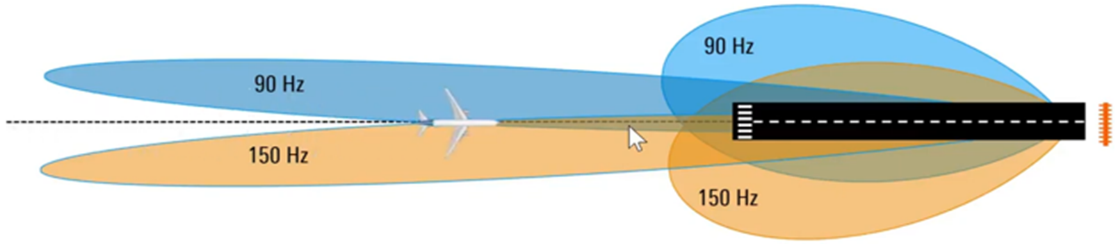

Fig. 1. 150 Hz and 90 Hz navigation tone signals are sent from the localizer transmitter.

A Conceptual modelof ILS localizer system. Instrument Landing System (ILS) terrestrial transmitters use amplitude modulation DSB-SC- Double Sideband Suppressed Carrier, CSB and SBO, CSB (Carrier and Sidebands) and SBO (Sidebands Only) techniques to guide aircraft safely during landing. The system transmits signals, which 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:

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

where 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

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

where 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:

$$\begin{gathered} s_{\text{total}}(t) = s_{CSB}(t) + s_{SBO}(t) \\ s_{\text{total}}(t) = \left[\left(A_{CSB1} + A_{SBO1}\right)\cos(2\pi\cdot 90t) + \left(A_{CSB2} + A_{SBO2}\right)\cos(2\pi\cdot 150t)\right]\cdot\cos\left(2\pi f_c t\right) \end{gathered} \quad (3)$$

Only the CSB signal is present along the centerline with equal energy for the 90 Hz and 150 Hz tones. The LOC indicator will be positioned in the center. The SBO power is reduced at center antennas to establish a prominent CSB area along the centerline. On the left side, the 150 Hz modulation in the SBO signal is shifted by 180° and is also 180° out of phase relative to the CSB at the antenna level. As a result, the 150 Hz modulation in phase for both CSB and SBO is causing the sideband energies to add. Conversely, the energy for the 90 Hz modulation is reduced because the 90 Hz modulations in CSB and SBO are out of phase. This results in greater energy for the 150 Hz signal, indicats a larger depth of modulation. This effect intensifies as we move away from the centerline. On the right side, where the 150 Hz modulation is out of phase for CSB and SBO, the energy for the 150 Hz signal is reduced compared to the energy for the 90 Hz signal in the sidebands. This difference becomes more significant as we move away from the centerline [5].

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

$$\begin{gathered}\text{CSB} = \text{ Carrier and Sidebands} \\ (\text{Modulation} = 90Hz + 150Hz \text{ tone}) \\ \text{SBO} = \text{ Sidebands Only} \\ (\text{ Modulation} = 90Hz - 150Hz \text{ tone}).\end{gathered} \tag{4}$$

F1 and F2 are tones of 90 and 150 Hertz, generating sinusoidal signals at the ILS antenna. The CSB signal is m (f1 + f2), and the SBO signal is n(f1 + f2). m and n depend on transmitter power and antenna gain. Combining CSB and SBO signals allows us to group f1 and f2 terms. Since f1 is larger, the 90 Hz signal is stronger at this location.

$$\begin{aligned}&CSB = m\left(f1 + f2\right) SBO = n\left(f1 - f2\right) \\ &SUM \\ &CSB + SBO = m\left(f1 + f2\right) + n\left(f1 - f2\right) \\ &CSB + SBO = mf1 + mf2 + nf1 - nf2 \\ &CSB + SBO = \left(m + n\right) f1 + \left(m - n\right) f2 \\ &f1 \; is \; stronger \; f1 > f2 \, .\end{aligned} \tag{5}$$

The process for the difference shows that f1 is less than f2, indicating a stronger 150 Hz signal at that point.

$$\begin{aligned}&CSB = m\left(f_1 + f_2\right) SBO = n\left(f_1 - f_2\right) \\ &\qquad \text{DIFFERENCE} \\ &CSB - SBO = \quad m\left(f_1 + f_2\right) - n\left(f_1 - f_2\right) \\ &CSB - SBO = \quad mf_1 + mf_2 - nf_1 + nf_2 \\ &\mathbf{CSB - SBO} = \quad (m-n) f_1 + (m+n) f_2 \\ &\qquad \mathbf{f_1 < f_2} \quad \mathbf{f_2} \text{ is stronger.}\end{aligned} \tag{6}$$

The localizer signal centerline shows the difference between CSB and SBO signals, generating a stronger 150 Hz signal above and a dominant 90 Hz tone below.

Three scenarios without interference:

DDM Calculation:

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

$$DDM = \frac{U_{90\,\mathrm{Hz}} - U_{150\,\mathrm{Hz}}}{U_{90\,\mathrm{Hz}} + U_{150\,\mathrm{Hz}}}, \qquad (7)$$

where $A_{90} = A_{CSB1} + A_{SBO1}$, the combined amplitude of the 90 Hz tone, $A_{150} = A_{CSB2} + A_{SBO2}$, 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) (Fig.2).

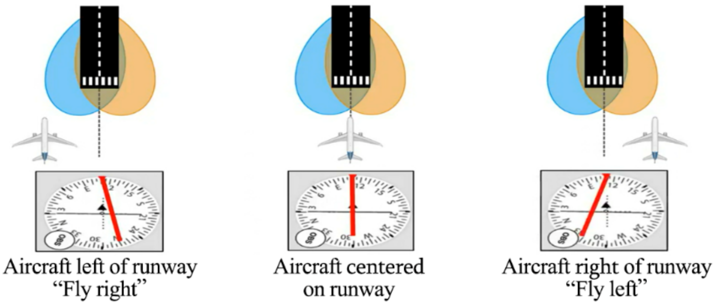

Fig. 2. Navigation information is provided to the pilot on the CDI.

Intermodulation Distortion (IMD) in the Aeronautical Receiver

Intermodulation Distortion (IMD) is a form of nonlinear distortion that occurs when multiple signals of different frequencies mix within a nonlinear system, producing unwanted signals at new, often unpredictable, frequencies. In an aeronautical receiver, IMD can be triggered by the signals from outside the aeronautical band causing the receiver to behave non-linearly. For IMD to occur, at least two broadcasting signals must be present. These signals must have a specific frequency relationship that allows for the creation of intermodulation products within the RF channel used by the aeronautical receiver. One of the signals needs to have a sufficient amplitude to push the receiver into a nonlinear operating region, but interference can still result even if the other signal is of significantly lower amplitude [6,7,]. In the ILS band (108–112 MHz), third-order intermodulation distortion is a primary concern. Third-order IMD is particularly problematic because the resulting intermodulation products can land close to critical ILS frequencies, making it difficult to filter them out.

Third-order intermodulation distortion (IMD). Third-order IMD is especially troublesome because its products increase at a faster rate compared to the input signals. Specifically, if desired input signal is increased in 1 dB the, the unwanted third-order products increase by 3 dB. (Fig. 3.) This characteristic makes it a significant source of interference for precision systems like ILS. For example, if two VHF radio transmitters operate on nearby frequencies, their third-order product could fall within the ILS frequency range. This interference can cause the onboard ILS receiver to pick up incorrect information, potentially resulting in errorous glide slope or localizer data. Such a deviation in navigation data could lead to a hazardous landing situation due to the third-order intermodulation products [6-9]:

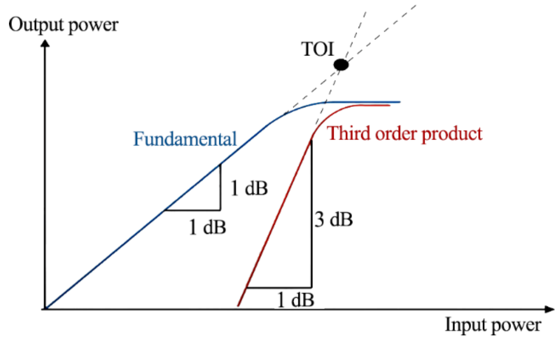

Fig. 3. The third-order intermodulation products increase in amplitude by 3 dB.

$$f_{IMD3} = 2f_1 - f_2$$
$$\text{and } f_{IMD3} = 2f_2 - f_1, \tag{8}$$

where f_1 and f_2 are the frequencies of the two input signals.

The power of the third-order intermodulation product can be expressed as:

$$P_{IMD3} = P_{in} - 2\cdot\left(IP3 - P_{\text{in}}\right), \tag{9}$$

where P_{IMD3} is the power of the third-order intermodulation product and P_{in} – the input power of the fundamental tones.

Analytical Derivation of IMD Effects on CSB and SBO

Impact on CSB signals. When an intermodulation distortion (IMD) product, radiated from a nearby VHF transmitter, impacts the ILS carrier frequency (108.1 MHz), it can disrupt the amplitude-modulated CSB (carrier and sideband) signal. This interference may lead to inaccurate course guidance and poor signal quality, making it hard for aircraft receivers to interpret the 90 Hz/150 Hz tones correctly.This can result in pilots straying from the centerline. If an IMD product appears close to 109 MHz, it can introduce unwanted noise or tones that disrupt the AM demodulation process, causing the aircraft's receiver produce errorous tone modulation and misleading course information. For the CSB signal, the IMD can be written as:

$$S_{CSB}(t) = \left(A_c + \varepsilon'\cos\left(2\pi f_{IMD}t\right)\right)\left[1 + m_1\cos\left(2\pi f_{90}t\right) + m_2\cos\left(2\pi f_{150}t\right)\right]\cos\left(2\pi f_c t\right), \tag{10}$$

where (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, A_c 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 (DSB-SC) signals. SBO signals are more vulnerable to interference because they rely on the suppressed carrier. Any intermodulation product that lands near the sideband frequencies could introduce noise or distortion in the 90 Hz/150 Hz sidebands. Or even distort the amplitude balance of the sidebands, confusing the receiver [10]. This could lead to inaccurate fine corrections for lateral position, which is especially critical during the final approach. For the SBO signal, the IMD can be written as:

$$S_{SBO}(t) = \left(A_s + \varepsilon' \cos\left(2\pi f_{IMD} t\right)\right)\left[m_1 \cos\left(2\pi f_{90} t\right) + m_2 \cos\left(2\pi f_{150} t\right)\right]\cos\left(2\pi f_c t\right), \quad (11)$$

where ϵ′ epsilon is the amplitude of the IMD product in the SBO signal. Since the SBO signal has no carrier, the IMD affects the modulation balance between the 90 Hz and 150 Hz tones directly, potentially distorting 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 corresponds to 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).

Phase and Amplitude Distortion

If the IMD product shifts the phase of the 90 Hz and 150 Hz tones, we can express the total signal as:

$$S_{IMD}(\mathrm{t}) = S_{CSB}(t) + S_{SBO}(t), \quad (12)$$

where the phase and amplitude distortions affect the sum and difference of the two signals.

In-phase components (on the right side of the centerline) will be affected by IMD if the spurious tones cause phase shifts. This may result in incorrect additive modulation, causing incorrect course deviation signals.

Out-of-phase components (on the left side of the centerline) could be impacted similarly, where phase shifts or amplitude distortion from IMD might prevent the signals, leading to incorrect lateral guidance.

In practice, IMD in the ILS frequency band can result in:

False deviation guidance: The aircraft may receive incorrect guidance signals, leading the pilot to believe they are on left or right of the centerline when they are not.

Erroneous flag signals: The receiver may erroneously flag a course deviation or loss of signal, even if the actual ILS signals are clear.

Conclusion

This approach helps to detect how well the navigation system can handle spurious signals across the entire frequency range in a busy airport, where multiple high-power transmitters are located. The study provides an assessment of the effects of electromagnetic interference, including intermodulation signals, in the aeronautical frequency spectrum. At busy airports, various high-power transmitters can cause intermodulation distortion from multiple sources, which can cause the aircraft become disorientated relative to the landing strip as it approaches. This approach helps to determine how well the navigation system can handle false signals, where high power transmitters can cause intermodulation distortion.

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ტელეკომუნიკაცია

ინტერმოდულაციური სიგნალების ზემოქმედების გავლენა აერონავტიკულ ILS რადიოსანავიგაციო მიმღებზე

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(წარმოდგენილია აკადემიის წევრის რ.ხუროძის მიერ)

ჩვენი კვლევა ეფუძნება სატესტო პროცედურებს საავიაციო მიმღების მახასიათებლების გასაზომად ინტერმოდულაციური დამახინჯების დადგენის მიზნით, რომელიც გენერირდება სამაუწყებლო რადიოგადამცემებიდან სიხშირულ დიაპაზონში **87-108 MHz** და წარმოქმნის ელექტრომაგნიტურ ხელშეშლებს აერონავტიკულ **ILS** სერვისებზე ზემოქმედებით, **108-118 MHz** რადიოსიხშირულ ზოლში. გაანალიზებულია, თუ როგორ გავლენას ახდენს ამ სისტემებზე ელექტრომაგნიტური ხელშეშლები, რომლებიც გენერირდება სხვადასხვა წყაროდან, მათ შორის, **FM** სამაუწყებლო რადიოსერვისიდან. ეს ხელშეშლები ქმნის ინტერმოდულაციურ პროდუქტს **ILS**-ის **(108–112 MHz)** სიხშირულ ზოლში, მესამე რიგის ინტერმოდულაციური დამახინჯების სახით, რომელმაც აღნიშნულ სიხშირულ ზოლში შეიძლება გამოიწვიოს სანავიგაციო მიმღებში ცრუ გადახრის სიგნალი. ამ ვითარებაში თვითმფრინავმა შესაძლოა მიიღოს არასწორი სახელმძღვანელო სიგნალები, რაც პილოტს აფიქრებინებს, რომ ხომალდი მდებარეობს დასაფრენი ზოლის ცენტრალური ხაზიდან მარცხნივ ან მარჯვნივ. ამ კატეგორიის სიგნალების მიღებამ შეიძლება შეცდომით მონიშნოს კურსის გადახრა ან სიგნალის სრული დაკარგვა, რაც გამოიწვევს თვითმფრინავის დეზორიენტაციას დასაფრენ ზოლთან მიმართებით. კვლევა უზრუნველყოფს ელექტრომაგნიტური ხელშეშლის, მათ შორის, ინტერმოდულაციური სიგნალის ზემოქმედების შეფასებას აერონავტიკული სიხშირის სპექტრში. დატვირთულ აეროპორტებში, სხვადასხვა მაღალი სიმძლავრის გადამცემებმა შეიძლება გამოიწვიოს ინტერმოდულაციური დამახინჯება მრავალი წყაროდან, რაც შესაძლოა გახდეს თვითმფრინავის ორიენტაციის არევის მიზეზი მისი დაფრენის დროს დასაფრენ ზოლთან მიმართებით. ეს მიდგომა გვეხმარება იმის დადგენაში, თუ რამდენად კარგად შეუძლია სანავიგაციო სისტემას გაუმკლავდეს ყალბ სიგნალებს. საიდანაც მაღალი სიმძლავრის გადამცემებმა შეიძლება გამოიწვიოს ინტერმოდულაციური დამახინჯება.

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