SIMULATOR OF DVOR NAVIGATION SYSTEM

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Summary. The article describes a new concept of teaching aid (hardware simulator of DVOR system) for aircraft navigation system DVOR. Principles of simulator function are closely similar to real ground station of DVOR system used in navigation. Principles of DVOR are based on Doppler shift on electromagnetic waves and using different types of modulation at same time. DVOR system and its principles are quite complicated for student to understand. This was the main reason to design this teaching aid. The article is divided to two main parts. First part describes basic principles of real-life VOR and DVOR system. This part provides a theoretical background for design of simulator. Second part is focused on design and basic equations of simulator. Simulator is recommended to use in subjects focused on navigation systems because it should help to understand how this system works in real life.

Keywords: Doppler shift, simulator, aircraft, navigation, omnidirectional, beacon

1. INTRODUCTION

Navigation of all aircraft is based on satellite navigation and communication system. It is a modern, more accurate and a very reliable system. This type of navigation is available on entire planet at any time. Accuracy is many times better than navigation based on ground station. Navigation based on satellites may be connected with satellite communications and data link and together create one service call CPLDC. This service allows ATC to monitor all air traffic closely. Satellite navigation is the primary navigation system and older types of navigation act only as backup. Older, ground station based navigation systems –beacons, use transmitting of electromagnetic waves. One of the basic navigation systems based on ground stations is VOR. System VOR has limitations in where can it be placed because terrain causes loss of accuracy and system can be inaccessible. System VOR was updated to system DVOR. DVOR system is not affected by the terrain and is more accurate as well. Function of DVOR is based on Doppler shift which affects electromagnetic waves. VOR and DVOR systems are completely compatible and are both using the same instruments and display instruments on aircraft deck.

2. PRINCIPLES OF DVOR SYSTEM

Because the VOR system's operation is affected by surrounding terrain, this system has been modified. The modified system uses the Doppler effect, which gives it the name Doppler VOR or D-VOR. This system is approximately three times more accurate than VOR and it can be used in terrain, where VOR beacon's serviceability would be limited or impossible. System's resistance to terrain obstacles is achieved by removing the rotation radiation pattern. D-VOR system uses a set of non-directional antennas instead of two pairs of directional antennas, thereby eliminating distortion caused by multiple signals spreading. Signal from D-VOR system can be received on board by the same device as from VOR system in spite of differences in signal processing and emitting.

D-VOR beacon uses the same frequencies as VOR system, therefore works in range of 108-112 MHz, additional signal frequency is 9960Hz, frequency deviation of frequency modulation is 480Hz and non-directional antennas switch at 30Hz. Therefore, to maintain compatibility between D-VOR and VOR, the frequency range of D-VOR is the same as of VOR.[1][2]

In contrast with VOR, D-VOR uses at least 32 non-directional antennas set on circle and one antenna in the middle. The non-directional antenna in the middle emits sinusoidal, amplitude modulated reference signal of 30Hz. Antennas on circle emit frequency modulated signal with secondary carrier frequency of 9960Hz and frequency of 30Hz. Signal for side antennas is generated in generators of upper and lower sideband, what provides modulation of carrier frequency of 108-112MHz and with the help of secondary 9960Hzcarrier frequency a phase shift of 0° and 90°. Frequency modulation of 30Hz is created by antenna rotation in place where signal is received. It would be impossible to use one antenna, mechanically rotating at 30Hz, so the antenna rotation is replaced by electronically switching the antennas on circle. Spectrum of DVOR signal is illustrated on Figure 1. Switching control signal is formed in the switching signal generator. The direction of antennas switching rotation is counterclockwise, while in VOR, the radiation pattern rotation is clockwise. The change in a rotation ensures the compatibility between D-VOR and VOR. After demodulation of both signals, same phase relations are created in place where signal is received. The phase shift of demodulated signals corresponds with radial. [1][2]

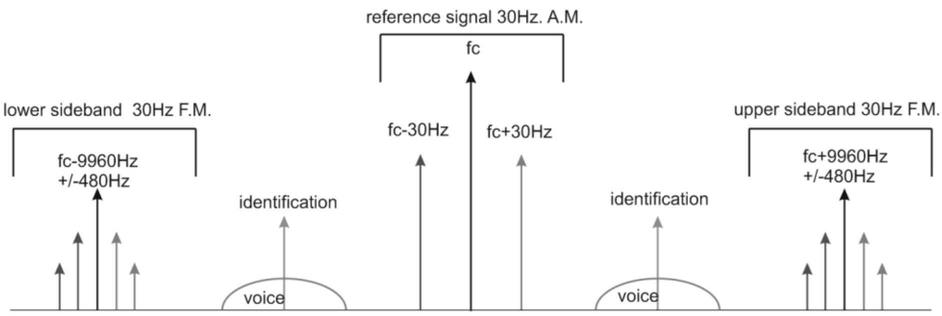

Figure 1 Illustration of DVOR signal spectrum

3. EFFECT OF DOPPLER SHIFT AT DVOR

Doppler effect marks frequency changes of acoustic or electromagnetic waves according to object's movement towards or away from the observer. Moving towards the observer increases the frequency, moving away from the observer decreases it. [2] If a distance of an aircraft is large, angular velocity of antennas when observed from the aircraft is:

$$V_x = V * \sin\phi \tag{1}$$

Where V_x resembles angular velocity towards the aircraft, V resembles angular velocity of a moving antenna and ϕ angle resembles angle relative to the x axis. For Doppler frequency shift for the sources moving at slower speed than the speed of light, we use [2]:

$$\Delta f = \frac{V_x}{\lambda} = \frac{V_x * F_U}{c} = \frac{V * F_U}{c} * sin\varphi \tag{2}$$

In this case, Δf resembles Doppler frequency shift, λ is an emitted frequency wavelenght and c resembles the speed of light. According to this equation, frequency received is modulated by sinusoidal frequency. If the sinusoidal frequency has a period of 1/30 of a second, the signal is modulated by a frequency of 30 Hz. However, ground system D-VOR transmits with two opposite antennas. One antenna runs at F_U=fc+9960Hz signal and the opposite antenna at F_L=fc-9960Hz. Doppler shift received from this antenna is also modulated by sinusoidal signal, but phase-shifted by 180°. When one antenna reaches the maximum negative value of amplitude – the peak, the other one reaches the maximum positive value.[1][4] For the second antenna, we use:

$$\Delta f = \frac{V_x}{\lambda} = -\frac{V * F_L}{c} * \sin(\phi) \tag{3}$$

Received signal is modulated by frequency of 30 Hz. This means that antennas need to fully rotate 30 times per second. If R stands for radius, the angular velocity of turning antennas is:

$$V = 60 * \pi * R \tag{4}$$

Frequency deviation is set to 480 Hz, therefore:

$$\Delta f = \frac{f_c * V}{c} = 480 = 60 * \pi * R * \frac{f_c}{c} \tag{5}$$

wheref_c is carrier frequency. For the radius, we get:

$$R = \frac{8 * c}{\pi * f_c} \tag{6}$$

4. EQUATIONS FOR SIMULATOR

One of the first things when designing was to transform basic equations of Doppler effect of DVOR system to acoustic environment. Derived equations are valid for signal source moving in a circle. If the signal source is radio waves, it is necessary to use the speed of light in vacuum c = 299 792 458m/s. Acoustic waves, i.e. mechanical vibration, has significantly lower speed, so it is necessary to use the speed of sound v_s = 340m/s in equations. Acoustic transmitter will operate on the same principle as DVOR system, i.e. it will have electronically switched acoustic transducers placed in circle. Switching speed of transducers is calculated from the equation for rotational speed of the mass point in a circle:

$$v = 2\pi f_o r \tag{7}$$

Where f_0 is transducers switching frequency and r is a radius of a circle where transducers are placed. Substituting into the equation (5) to calculate the frequency deviation we get:

$$\Delta f = \frac{f_c * v}{v_s} = \frac{2\pi r f_o f_c}{v_s} \tag{8}$$

Where v_s is the speed of sound and f_c is transmission frequency. Frequency deviation – the Doppler frequency depends on three parameters: switching frequency of transducers in circle, radius of the circle and frequency transmitted by transducers. For best demonstration of Doppler effect in DVOR system, it is practical to change every parameter, so different conditions can be simulated and we can point out how does change of any of the parameters influence final frequency deviation. For verification, tables were calculated using MATLAB. One of them is illustrated as Table.1 They show the dependence of the Doppler frequency on rotation speed, radius and transmitted frequency.

		Radius (m)												
		0,3	**0,4**	**0,5**	**0,6**	**0,7**	**0,8**	**0,9**	**1**	**1,1**	**1,2**	**1,3**	**1,4**	**1,5**
Frequency of switching (Hz)	**1**	1.66	2.22	2.77	3.33	3.88	4.44	4.99	5.54	6.10	6.65	7.21	7.76	8.32
	1,5	2.49	3.33	4.16	4.99	5.82	6.65	7.48	8.32	9.15	9.98	10.81	11.64	12.47
	2	3.33	4.44	5.54	6.65	7.76	8.87	9.98	11.9	12.20	13.31	14.41	15.52	16.63
	2,5	4.16	5.54	6.93	8.32	9.70	11.9	12.47	13.86	15.25	16.63	18.2	19.40	20.79
	3	4.99	6.65	8.32	9.98	11.64	13.31	14.97	16.63	18.30	19.96	21.62	23.28	24.95
	3,5	5.82	7.76	9.70	11.64	13.58	15.52	17.46	19.40	21.34	23.28	25.23	27.17	29.11
	4	6.65	8.87	11.9	13.31	15.52	17.74	19.96	22.18	24.39	26.61	28.83	31.5	33.26
	4,5	7.48	9.98	12.47	14.97	17.46	19.96	22.45	24.95	27.44	29.94	32.43	34.93	37.42
	5	8.32	11.9	13.86	16.63	19.40	22.18	24.95	27.72	30.49	33.26	36.04	38.81	41.58
	5,5	9.15	12.20	15.25	18.30	21.34	24.39	27.44	30.49	33.54	36.59	39.64	42.69	45.74
	6	9.98	13.31	16.63	19.96	23.28	26.61	29.94	33.26	36.59	39.92	43.24	46.57	49.90
	6,5	10.81	14.41	18.2	21.62	25.23	28.83	32.43	36.04	39.64	43.24	46.85	50.45	54.05
	7	11.64	15.52	19.40	23.28	27.17	31.5	34.93	38.81	42.69	46.57	50.45	54.33	58.21
		Frequency shift (Hz)												

Table 1 Doppler shift frequency table

For simulate signal of real DVOR system must include one non direction stransmitter – speaker. This speaker will be used for transmitting amplitude modulated acoustic signal. The exact frequency is unknow and will be set by experiment. Frequency of modulating signal must by coupled with swithing of speakers. In one period of modulating frequency must by switched all sixteen speakers. Time of transmitting from one speaker is :

$$t_v = \frac{T}{n} \tag{9}$$

Where T is period of modulating frequency and n is number of speakers.

5. SIMULATOR PREVIEW

The basic requirements are important for designing model of simulator. System may produce signal with directional information and use principles of DVOR system. We must be able to find direction to transmitter from recieved signal similary to DVOR. For teaching aid is the best use audio frequency from 20Hz to 20kHz. In this case, is not possible use radio frequency antennas but we need audio speakers. This few points is basic requiremets for starting design :

- Frequency cant be agressive
- Transmitted signal must keep the principles of DVOR system
- Doppler shift must be hearable
- Many of parameters which affect to Doppler shift must be variable
- Small mechanical dimension – interier use only
- User friendly interface

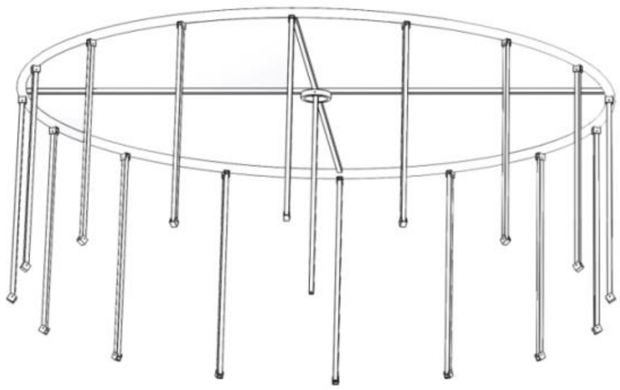

Figure 2 Basic 3D model of mechanical part

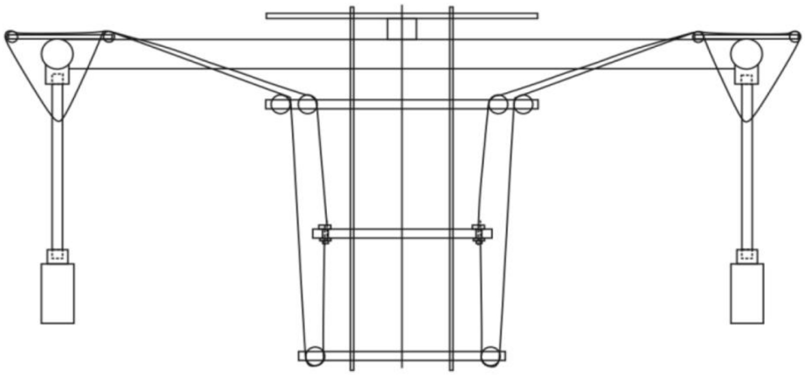

Figure 3 2D Side view of mechanical part

For best results we decided use system with variable radius. This function allow to confirm mathematical results for Doppler shift. When we have constant frequency of „rotation" and we change the radius, we will hear difference in speed of „rotation" and this will result in changed Doppler shift. In this way we can show to students, why ground station has a exact radius and what will happen when we change it.

How the radius affect the value of Doppler shif show Table 1. The mechanical dimensions are based on this table. The dimensions of mechanical part was limited by dimensions of teaching room, avaible lenghts of material and prices.

6. ELECTRONIC PART DESCRIPTION

Electronics parts are responsible for generation all spectrum of signals and overall control of simulator. These parts must provide:

- Generate all frequencies
    - Modulating frequency for AM
    - Carrie frequency for AM
    - AM this two frequencies which represented reference signal
    - Variable signal
    - Synchronized “rotation” with modulating frequency of AM signal
- Power amplification of all transmitted signal for speakers
- User input interface – buttons and rotary encoders
- Display interface
- Motor control for changing radius
- Power supply for all electronic parts

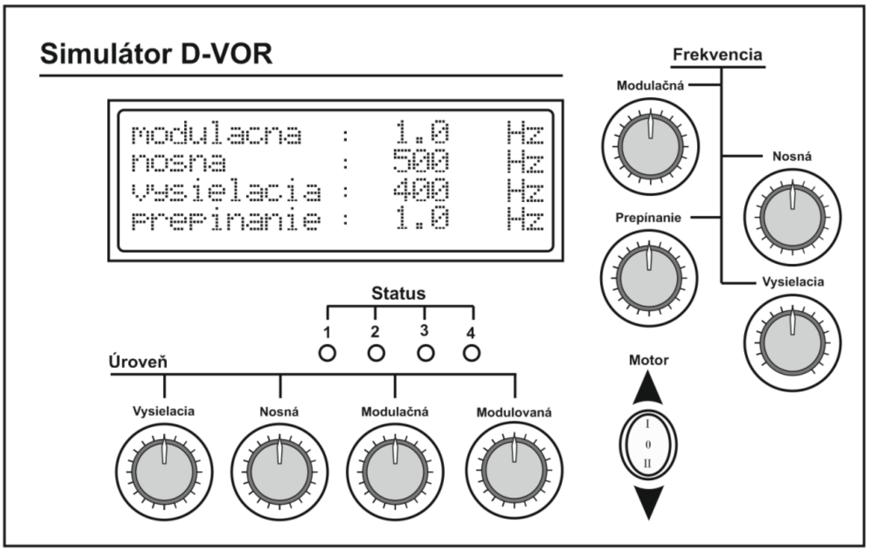

Figure 4 Front preview on control interface

The basic block circuit shows the structure of electronic parts.

1. Microcontroller -Receives input signals from control elements and generates frequencies based on requirements. Integrated DAC transducers are used to generate signals. Data for transducer are generated on the principle of direct digital synthesis – table and a control word. At the same time, the microcontroller controls the multiplex switching synchronously with the modulation frequency.
2. Control elements – allows the user to change the parameters. It is advised to use rotation encoders and buttons to ensure simple control.
3. LCD display – allows displaying of set parameters.
4. AM modulator – ensures amplitude modulation for the speaker in the centre of the device, which simulates non-directional antenna.
5. Generator 1 – circuit ensuring creation of requested transmission frequency working on the principle of direct digital synthesis.

6. MUX – digitally controlled analog multiplex which ensures electronic signal switching for power amplifiers. Transmission frequency generator is connected to the common input and individual outputs are connected to the inputs of power amplifiers.
7. Power amplifier – provides the necessary power on inputs to speaker excitation.
8. Speaker – transforms the electric energy from power amplifiers into sound waves.
9. Power supply – provides the necessary voltages with sufficient margin for each individual circuit. 3.3V voltage is required for all digital circuits, 12V sub-circuit supplies power amplifiers and amplitude modulator, 5V voltage with large current capacity is used to power the engine.
10. Motor control - control with reversing rotation by switches and relays
11. Motor – two-directional motor providing arm lifting.

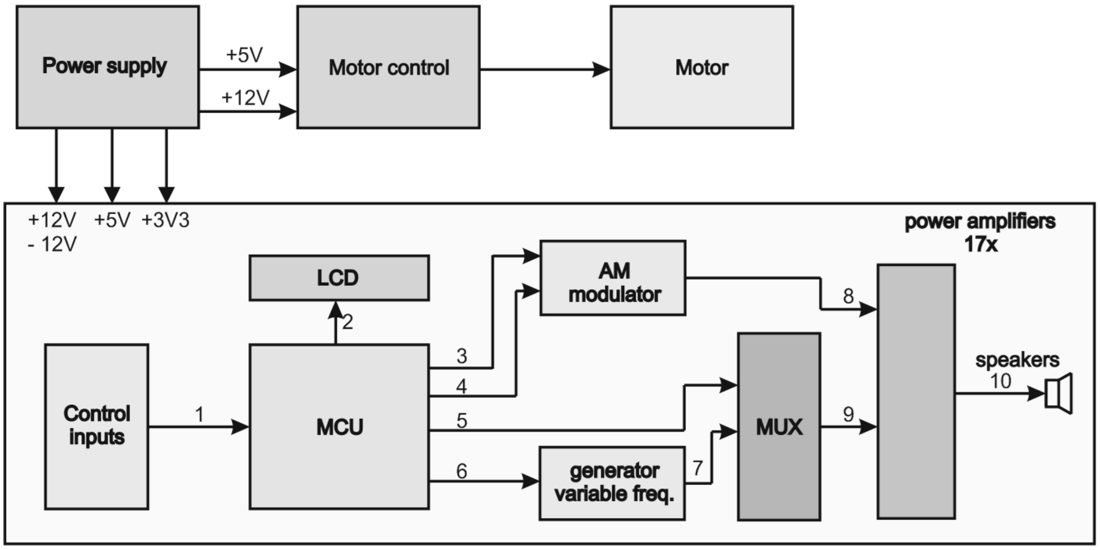

Figure 5 Block diagram of control electronic

7. CONCLUSION

The main puprose of this article was to introduce a new idea of teaching such complex system as DVOR. Article describes basic principles of DVOR system and the transformation these principles for purpose of teaching aid. From results based on real system, it was possible to make a concept of system with very similar function as real DVOR system, but in acoustic frequency. One of possible mechanical constructions is shown on 3D previews. This part can be made from plastic, aluminium alloy or steel. Basic idea is to use one ring frame with exact number of speakers with variable diameter of frame. Speakers can be electronically switched for simulation of rotation. This causes the Doppler shift. There must be one non-directional speaker for transmitting reference signal in the middle of the construction. For illustration of how is Doppler shift affected by radius of frame, a table was computed. The table shows dependency of Doppler shift on variable frame, frequency of switching and transmitted frequency. Designed system will help to understand basic principles of real ground system DVOR. In future, simulator can be supplemented by multimedia software part where aircraft part of DVOR can be shown. In result, this simulator offers modern attitude to teaching process and connects theory with the real system.

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