EXPERIMENTAL STUDY OF THE EFFECT OF FLOW VELOCITY AT THE INLET ON THE AZIMUTHAL MODE RADIATION: STATIC AND FLIGHT

Nikolay Ostrikov

Central Aerohydrodynamics Institute (TsAGI), Acoustic Department, 105005 Moscow, Russia
Perm National Research Polytechnic University, 614990 Perm, Russia
email: aeroacoustics@tsagi.ru

Mikhail Yakovets

Moscow Institute of Physics and Technology (MIPT), Department of Aeromechanics and Flight Engineering, 141700 Dolgoprudny, Russia
Central Aerohydrodynamics Institute (TsAGI), Acoustic Department, 105005 Moscow, Russia

Maksim Ipatov, Ivan Pankratov and Stanislav Denisov

Central Aerohydrodynamics Institute (TsAGI), Acoustic Department, 105005 Moscow, Russia

The investigation is aimed at experimental extracting the difference in directivity for the radiation of the same duct mode from an engine inlet when operating in static condition versus in the forward flight. The results of first stage devoted on the problem of adjustment of azimuthal mode generator installed in duct to provide the possibility of generating different specified spinning duct modes are presented. The high accuracy method of adjustment of azimuthal modes generator taking into account the difference of loudspeakers electroacoustic parameters is elaborated.
Keywords: azimuthal mode, generation, radiation, inlet

1. Introduction

The numerical simulations carried out in the work [1] demonstrate a significant difference in directivity for the radiation of the same duct mode from an engine inlet when operating in static condition versus in the forward flight. It was shown that the large change in directivity is the result of the combined effects of diffraction and refraction realized near inlet orifice due to flow inhomogeneity in the static conditions. The present work is aimed at the experimental investigation of this effect.

The scheme of experimental test rig designed for installing in anechoic chamber AC-2 TsAGI is presented in Fig. 1. The test rig can be operated either in the static conditions (the incoming flow is absent) or in the flight conditions with the co-flow velocities up to 80 m/s. The principal part of this test rig is small scale model inlet with a diameter of 20 cm containing an azimuthal mode generator consisting of 6 acoustic drivers for different azimuthal modes generation. These drivers are installed regularly on inner duct surface in azimuthal direction and are assigned for generating different spinning duct modes.

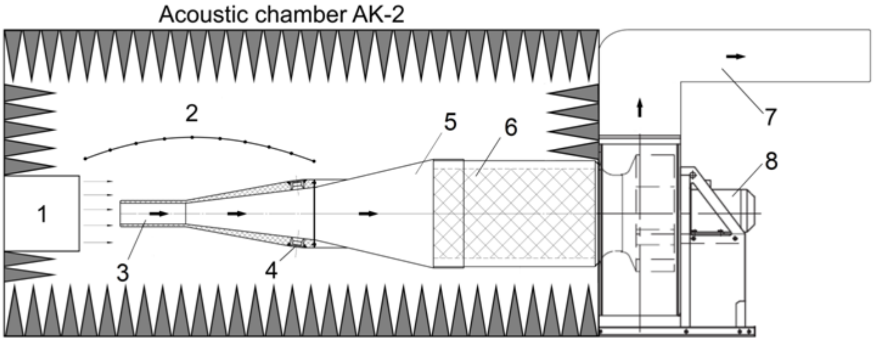


Figure 1: The scheme of experiments in TsAGI's anechoic chamber AK-2. 1 – co-flow nozzle; 2 – microphone array; 3 – model inlet; 4 – azimuthal loudspeaker array; 5 – conic pipe; 6 – muffler; 7 – exhaust tube; 8 – suction fan.

The present paper is devoted to the problem of adjustment of azimuthal mode generator to provide the possibility of generating different specified spinning duct modes. It is the first stage of this investigation. The problem is arisen from the following peculiarity.

It is well known that if the acoustic drivers are absolutely identical and electric signals supplied each two adjacent drivers have the same amplitudes and the following the same phase shift

$$\Delta\phi = \frac{2\pi m_0}{K}, \quad (1)$$

where K – the number of acoustic drivers, then the azimuthal spinning modes with azimuthal numbers $m = m_0 + lK$ (here l is arbitrary integer) are generated in duct with the same amplitudes. The different azimuthal spinning modes (each azimuthal mode is mixture of modes with some radial numbers) can be realized in duct by varying integer m_0. However, acoustic drivers manufactured in one lot have as usual some difference of electroacoustic parameters. As a result, the controllability of azimuthal modes generation according the phase shift (1) is lost.

The high accuracy method of adjustment of azimuthal modes generator taking into account the difference of drivers electroacoustic parameters is elaborated in present investigation.

2. Description of the test rig and the problem of acoustic drivers adjustment

Small-scaled model inlet with inner diameter of 20cm comprises 12 mounted flush MJ-1T loudspeakers arranged regularly in circle and powered by B&K type 3560 signal generator with Apart Revamp 1680 amplifier. Since the generator has 6 synchronized channels, the number of drivers used in experiments is reduced accordingly. Sound field is measured by microphone ring array which consists of 13 B&K model 4957 microphones mounted regularly at duct orifice (Fig. 2.) and complex amplitudes of azimuthal modes with numbers $-6 \le m \le 6$ are extracted by standard Fourier decomposition.

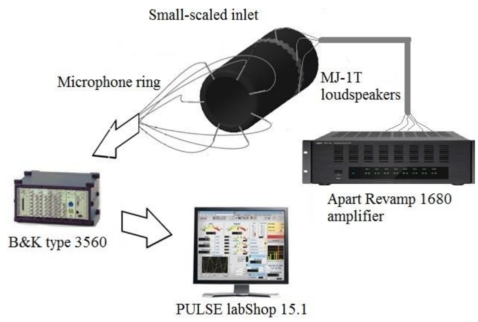
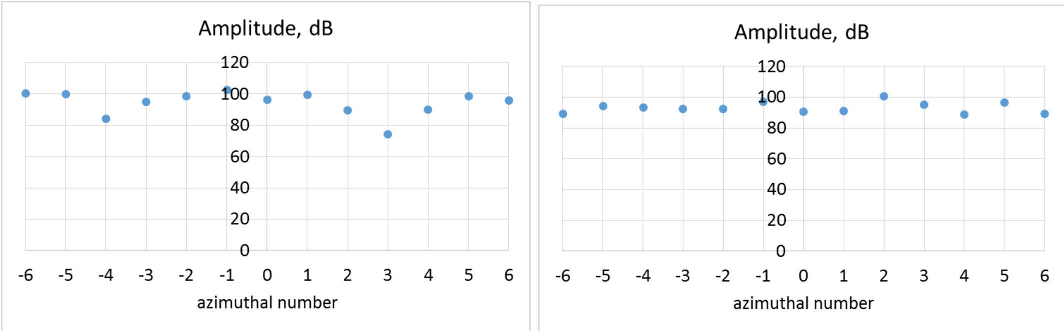


Figure 2: Test rig for mode generation adjustment.

This test rig configuration was used to check possibility of azimuthal mode generation based on the phase shift given by expression (1) with some azimuthal number m_0 .The magnitude of electric signal for each loudspeaker was adjusted in this case to result in equal sound pressure level at the duct axis. In the Figure 3, two azimuthal mode amplitude distributions are presented for phase shifts $\Delta\phi = 0°$ and $\Delta\phi = 60°$.



(a) (b)

Figure 3: Azimuthal mode distribution at frequency $f = 4000$ Hz. (a) $\Delta\phi = 0°$, (b) $\Delta\phi = 60°$.

One can see from Fig. 3 that phase shifts chosen to provide dominant mode with $m_0 = 0$ (Fig. 3a) or $m_0 = 1$ (Fig. 3b) lead to absolutely another amplitude distribution. Consequently, the assumption about absolutely identity of phase characteristics of drivers was failed. The scheme of direct measurements of phase shifts between electric and acoustic signals for different drivers when microphones are pointed to drivers one by one is presented in Fig. 4 and the obtained phase shifts at different frequencies are given in the Table 1. Thus electro-acoustic characteristics of drivers are unique, and new technique for drivers' adjustment is to be elaborated.

Table 1: Electro-acoustic phase shift of different drivers

f, Hz	$\Delta\phi^{(1)}_{E-A}$	$\Delta\phi^{(2)}_{E-A}$	$\Delta\phi^{(3)}_{E-A}$	$\Delta\phi^{(4)}_{E-A}$	$\Delta\phi^{(5)}_{E-A}$	$\Delta\phi^{(6)}_{E-A}$
2000	-29.4°	156.1°	162.4°	-179.5°	154.5°	136.3°
4000	-173.7°	14.8°	28.9°	-65.12°	29.2°	13.4°

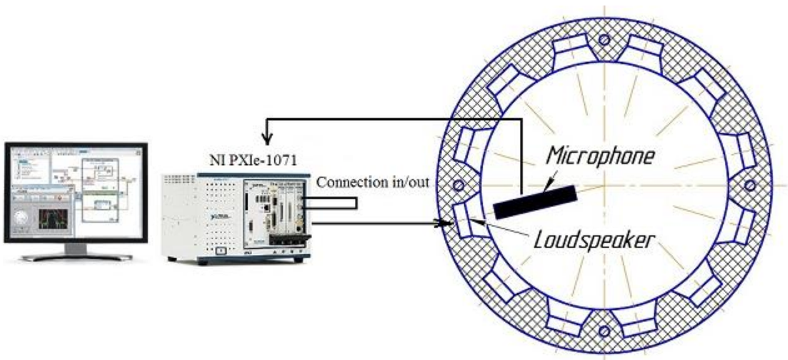


Figure 4: Electro-acoustic phase shifts test configuration.

3. Antiphase adjustment method

The following method was considered for the adjustment of phase shift of signals for each speaker. It is based on the idea of superposition of equal signals from two speakers at the duct axis. According this idea, the microphone is placed in the center of the ring at an equal distance from all the speakers (Fig. 5). At first step here, the magnitudes of any speakers are set to provide the same pressure level at the center point. At second step, the phase shift between electric signals for two speakers are set so that the pressure amplitude in the center is redoubled (in-phase method) or is close to zero (antiphase method).

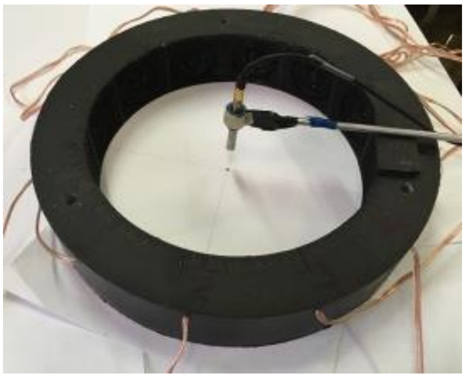


Figure 5: Antiphase adjustment experiment.

The sound pressure level measured at the center point for different phase shifts between two drivers is presented in Fig. 6 for two different frequencies. One can see that the range of phase shifts for maximum pressure level is much wider than the range for the minimum. Therefore, the antiphase adjustment method is more accurate than the in-phase method.

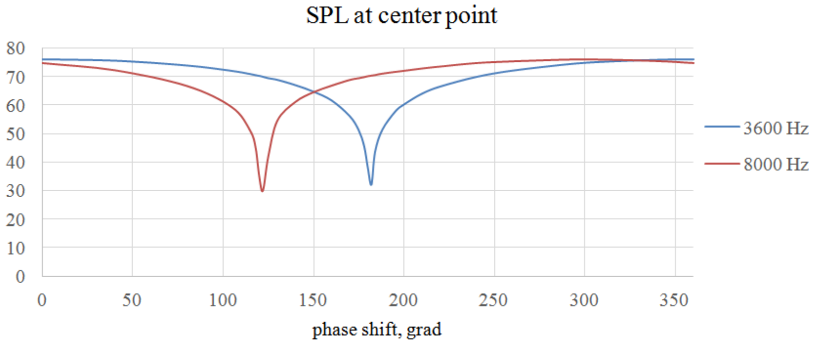
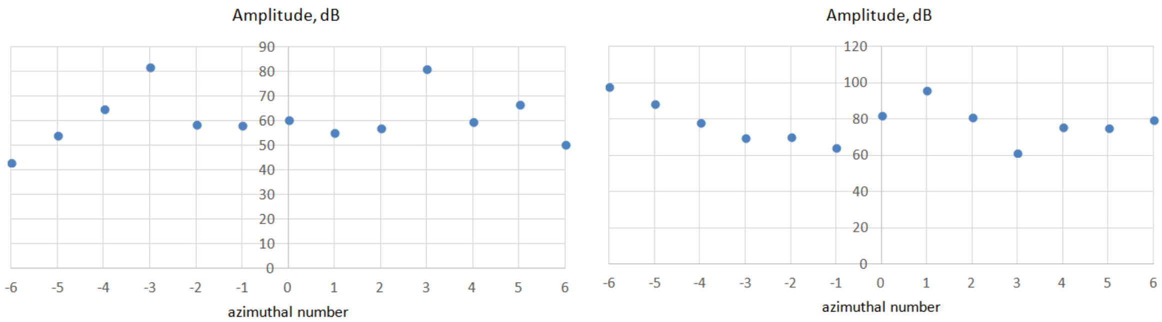


Figure 6: Sound pressure level at the center point for different phase shifts between two drivers for two different frequencies.

Phase shifts between electric signals obtained by antiphase method are to be summed up with corresponding shifts given by expression (1). The measured mode distributions in duct are presented in Fig. 7 for predicted dominant mode $m_0 = 3$. One can see that the result is acceptable for frequency $f = 4000$ Hz, but the method is absolutely failed for frequency $f = 6000$ Hz.



(a) (b)

Figure 7: Azimuthal mode distribution obtained with antiphase adjustment method.

(a) $f = 4000$ Hz, (b) $f = 6000$ Hz.

The drop in the adjustment quality at high frequencies can be explained by the influence of inaccuracy in the positioning of the calibration microphone (Fig. 5). Indeed, if the microphone deviates from the center of the circle by a distance l, the error in determining the phase shift equals $2kl$, and it grows with frequency. In addition, if the number of speakers is more than two, the possible asymmetry of their installation in the ring can lead to an increase of this error or to the impossibility of using this method in principle. At low frequencies, as experiments have shown, this method is quite applicable, but it takes a lot of effort to set up, thus, it hardly can be used in real tests with acoustic chamber environment.

4. Advanced method of adjustment

An analysis of drivers' system adjustment results described above shows that the influence of different loudspeakers on each other during their joint operation is insignificant under the conditions of the considered model inlet. Thus, the sound field generated by several drivers for given electrical signals is a superposition of the sound fields provided by these drivers operated under the same electrical signals separately. This feature allows us to propose a new method for adjusting modes generation system that can be implemented on a fully assembled test rig with microphone ring array installed at the inlet edge.

In step 1 of the adjustment, the tuning frequency is selected, and then each of the drivers is started individually one by one with the same harmonic electrical signal and zero phase shift with respect to ground phase of signal generator. The result of measuring the acoustic signal on the microphone with the number m ($m=1,\ldots,M$) from the driver j ($j=1,\ldots,S$) has the following complex form

$$p_m^j = A_m^j e^{i\Delta\varphi_m^j}, \tag{2}$$

where $\Delta\varphi_m^j$ – phase shift between microphones with number m and number 1, S – number of drivers and M – number of microphones in the ring array.

In step 2, all the drivers are started jointly, and each driver operates with the same signal parameters that were implemented in the first step. The signal on the microphone with the number m has the form

$$p_m^{sum} \equiv A_m^{sum} e^{i\Delta\varphi_m^{sum}} = \sum_{j=1}^{S} e^{i\alpha_j} p_m^j, \tag{3}$$

where α_j – unknown phase shift between electric signal supplied driver with number j and acoustic signal generated by it.

In step 3, the unknown phase shifts α_j are calculated on the basis of measured data and the relation (3). This procedure is realized by minimizing the corresponding functional with the help of the method of least squares

$$\Phi(\alpha_1,\ldots,\alpha_S) = \sum_{m=1}^{M} \left| \sum_{j=1}^{S} e^{i\alpha_j} p_m^j - p_m^{sum} \right|^2 \to \min. \tag{4}$$

In step 4, the magnitude and phase shift for electric signal supplied each acoustic driver, at which the initially desired sound field azimuthal structure is realized at inlet orifice, are determined. According the superposition principle, if $D_j = d_j e^{i\Delta\beta_j}$ ($j=1,\ldots,S$) are complex parameters determining drivers' adjustment, where d_j are gain factors and $\Delta\beta_j$ - phase shifts for electric signals, then complex amplitudes of propagating azimuthal modes $\tilde{C}_l$ ($l=-r,\ldots,-1,0,1,\ldots,r$, $N=2r+1$,

N - the number of propagating azimuthal modes at given frequency) realized in duct under these parameters are expressed through complex amplitudes C_l^j of azimuthal modes generating by values p_m^j (2) at step 1 in the following complex form

$$\tilde{C}_l = \sum_{j=1}^{S} e^{i\alpha_j} C_l^j \cdot D_j \, . \tag{5}$$

where

$$C_l^j = \frac{1}{M} \sum_{m=1}^{M} \hat{p}_m^j \cdot e^{i\frac{2\pi l(m-1)}{M}} \, .$$

For generating preassigned azimuthal modes, the expressions (5) are to be considered as linear in which amplitudes $\tilde{C}_l$ are specified for given frequency, while complex parameters D_j are to be found. However, the number of propagating modes in duct N is larger as usual than the number of drivers S. Therefore, the system (5) cannot be solved for arbitrary amplitudes $\tilde{C}_l$, but for solving system of equations (5), complex vectors $\tilde{C}_l$ are to be belonged to linear complex subspace Ξ having dimension S and basis vectors $\left\{e^{i\alpha_1} C_l^1, \ldots, e^{i\alpha_S} C_l^S\right\}$.

The choice of the realized azimuthal structure can be carried out in various ways by selection appropriate vector $\tilde{C}_l$ within subspace Ξ, which depend on the goals and tasks of the tests. The further results are presented for cases when the vectors $\tilde{C}_l$ are founded as orthogonal projection of vectors in the form

$$\tilde{C}_l^{(l_0)} = \begin{cases} 1 & \text{at } l = l_0 \\ 0 & \text{at } l \neq l_0 \end{cases}$$

into subspace Ξ. In this case, the azimuthal mode with number l_0 denotes as ‘target mode’.

5. The validation of advanced adjustment method in AK-2

The developed method was tested in acoustic chamber AK-2 in a configuration shown in Fig. 8. Target modes with m_0 from 0 to 6 were generated with obtained adjustment for values of signal magnitudes and phase shifts. The examples of obtained azimuthal distributions at different frequencies are presented in Figs. 9-11.

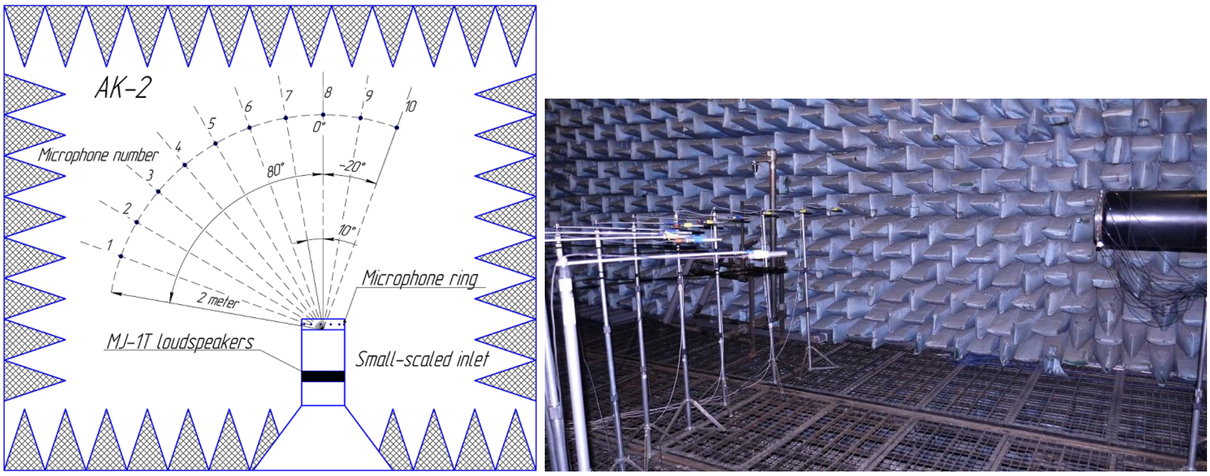
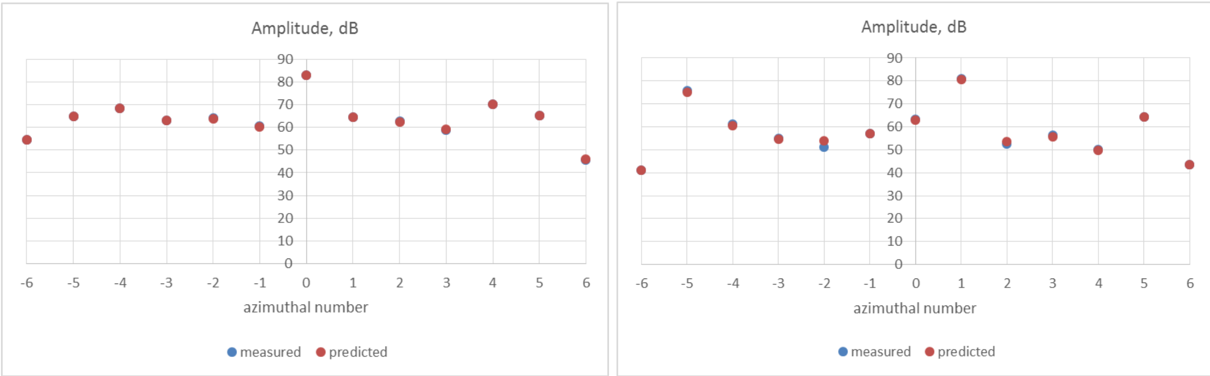
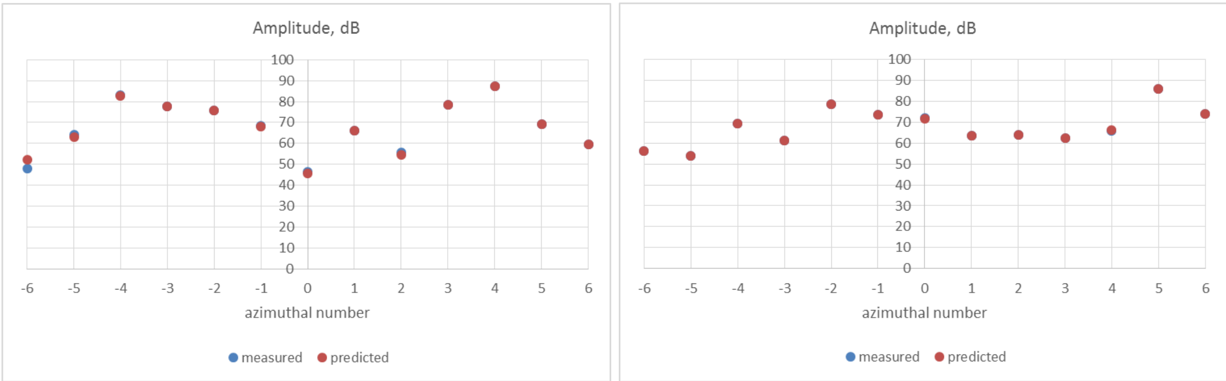


Figure 8: Scheme and photo of the small-scaled inlet in chamber AK-2 experiment.



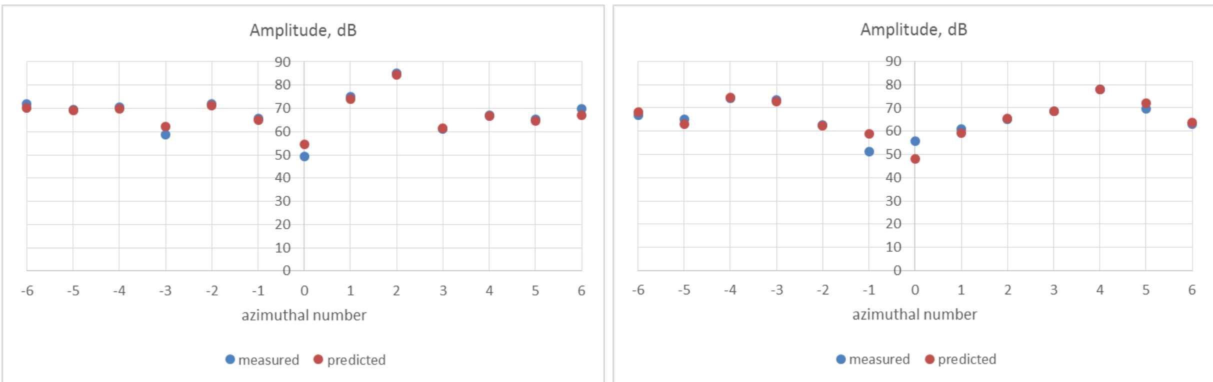
(a) (b)

Figure 9: Azimuthal mode distribution $f = 4000$ Hz. (a) $m_0 = 0$, (b) $m_0 = 1$.



(a) (b)

Figure 10: Azimuthal mode distribution $f = 6000$ Hz. (a) $m_0 = 4$, (b) $m_0 = 5$.



(a) (b)

Figure 11: Azimuthal mode distribution $f = 8000$ Hz. (a) $m_0 = 2$, (b) $m_0 = 4$.

The average deviations of the measured azimuthal mode amplitudes from the specified target values are presented in Table 2. These data demonstrate the operability of the proposed procedure for the generation of certain modes over a wide frequency range.

Table 2: Average deviation of obtained azimuthal modes amplitudes from predicted values

f, Hz	All modes, dB	Target modes, dB
4000	0.3	0.098
6000	0.45	0.087
8000	1.2	0.35

The results of tuning the mode generation system have shown that there are parameters at all frequencies in which a number of modes dominate the others, exceeding their amplitude by more than 5 dB. Moreover, there are parameters when only one azimuthal mode dominates, which cannot be realized with perfectly identical acoustic drivers. Thus, non-identity of the drivers can be used to generate only one dominant mode when using the developed procedure for tuning the mode generation system.

6. Conclusions

The investigation is aimed at experimental extracting the difference in directivity for the radiation of the same duct mode from an engine inlet when operating in static condition versus in the forward flight. The results of first stage devoted on the problem of adjustment of azimuthal mode generator installed in duct to provide the possibility of generating different specified spinning duct modes are presented. The high accuracy method of adjustment of azimuthal modes generator taking into account the difference of loudspeakers electro-acoustic parameters is elaborated. This method is used for experimental investigation of mentioned effect.

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