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Experimental Investigations of Acoustic Characteristics of Two Counter–Rotating Rotors

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The presented investigations are continuation of earlier researches performed in the Institute of Turbomachinery (Lodz University of Technology, Poland). The main aim of this paper is to investigate the acoustics properties of the chosen configuration of a flow set–up consisting of two coaxial counter–rotating rotors. Description and analysis of measurements are presented. As a consequence, conclusions about possibility of noise reduction of such a system are presented. According to the EU Directives, the main areas of application are multi–purpose helicopters with two coaxial counter–rotating rotors, drones and future passenger–aircrafts with next–generation aeroengines.

Keywords: aeroengine, counter–rotating rotors, fan, acoustics, noise reduction.

1. Introduction

Nowadays the acoustic analysis of the machines is important issue in engineering in general and in aeronautical industry in particular. There are two main reasons for such a situation.

Firstly, world industry is evolving very fast and new solutions are found almost every day. Proper control of the noise level generated by aeronautical engines proves to be a necessity. It is due to the fact that all devices, used e.g. in power industry, petrochemical industry and great number of other branches, generate great noise. It can be harmful for the people and may also result in inefficient functioning of, for example, industrial plant. For this reason proper method of lowering the noise level is essential.

Secondly, vibrations and oscillations, which are inseparably connected with the acoustic phenomena, are also of great importance [1]. Vibrations, which are also an effect of the operation of fluid flow machines, e.g. axial ones, are significant threat to the operation of such equipment. Preventing (or controlling) noise and noise-induced vibrations requires proper management of design, construction and operation of a device. This is due to the fact that all physical objects are characterized by their specific resonant frequencies. If the value of the exciting frequency, which can be created due to the construction of certain system, is close to the resonance frequency, as result this may cause excitation of vibration [1]. Further, if the amplitude increases, due to the lack of attenuation, this process may lead to destruction of the construction. For this reason the ability to properly investigate and manage phenomena closely related to aeroacoustics is of great importance. In this case the lack of sensitivity to this issue may lead to major financial losses of companies and, what is more important, to fatal accidents.

The last aspect of such analysis is the possibility to generally enhance and improve the performance properties of certain devices in aerospace industry.

The most reliable way of making sure that both the acoustic and oscillation aspects are treated with proper attitude and attention is to perform laboratory tests under various conditions that reflect expected operating conditions of subjected devices. This kind of tests may also be done as part of product tuning to minimize the level of noise and vibration. The presented investigations are continuation of some earlier researches on similar rotor-interactions aspects performed in the Institute of Turbomachinery (Lodz University of Technology, Poland) [2–5].

2. Test–rig

All measurements sessions were performed in aeroacoustic anechoic room especially designed for such tests [6, 7]. The schematic top and side views of the test–rig are presented in Fig. 1. At the inlet to the test set–up, the first rotor was placed. In this case it was equipped with 3 cylindrical rods. It was rotating with constant rotational speed 35 Hz. The main task of the inlet rotor was to simulate the inlet flow conditions to the fan. Using cylindrical rods at the inlet is one of classical methods of testing such configurations [8, 9]. The main part of the test set–up was the fan with 8 blades. This fan, previewed as the main rotor, was working as the second rotor. During the tests its rotational speed was in the range 20 to 50 Hz.

The height of the fan blades, as well as cylindrical rods, was identical and equal to 120 mm. They were fixed to the hubs of the same diameter of 140 mm. The diameter of the cylindrical rods was 3.5 mm. The thickness of the straight radial fan blades was 4 mm, and their pitch was 55 mm, what make it easier to test numerical models [10, 11].

The inverters (for controlling the velocities of both rotors), analogue–to–digital converter (ADC) and recording computer were placed in the control room, outside of the anechoic room, a separated room especially designed for obtaining data from experimental investigations [12].

3. Measurement equipment

The chain for acoustical measurements was similar to other configuration during earlier tests [2–4]. It consisted of 3 microphones (M1, M2, M3, see Fig. 1) with built–in preamplifiers connected through the main amplifier and next the Analogue–to–Digital Converter (ADC channels # 1, # 2, and # 3) to the controlling computer.

The 1/2" microphones were checked before every measurement session using an acoustic calibrator. Accuracy of calibration was ± 0.3 dB and the lower and the upper limiting frequencies were set–up to 20 Hz and 20 kHz respectively. The background noise levels for all acoustic measurement channels, including the electronic background noise (of all above mentioned electronic devices connected in series in the measurement chain) for all days of presented researches were less than 31.9 dB. The estimated accuracies of all measurement acoustic signals laid in the range ± 0.5 dB. The measurement time was 10 s. All microphones were placed around the object under investigation at the distances shown in Fig. 1. The first one was above the center of the test–rig; the second and the third ones were placed horizontally at the main axis height at the flow–inlet side (Fig. 1).

The tuning–up for all acoustic channels were established during preliminary measurement sessions according to proper standards and earlier experience [13]. The distances between the microphones and the tested two-rotor system were according to the ISO standards [6. 13] and were determined during earlier tests [2, 7]. They are shown in Fig. 1. All microphones were placed outside the airflow region to avoid influence of the flow unsteadiness on the measured acoustic signals (so called pseudonoise) [7, 14].

For thermoanemometric measurements of the air flow, a constant temperature thermoanemometer (CTA) system was used. The signal from the hot–film thermoanemometric nickel probe (T, see Fig. 1) was connected to the ADC channel # 4. Basing on earlier tests with thermoanemometric elements [7, 15] the temperature of the hot–film sensor was more than 130^0 C above the temperature of the flowing air (18^0 C). The hot–film fiber probe (dia. 70 μm, 1.25 mm long) with a heavy coating (0.5 μm) was chosen due to the open air entrance to the fan system and absence of the dust filters at the inlet to the test rig. The previewed upper frequency limit for such sensors is 170 kHz but, in the thermoanemometric system conditioner of this channel, signals corresponding to very small vortices were cut off by an analogue filter above 20 kHz according to the needs of acoustic signals analysis.

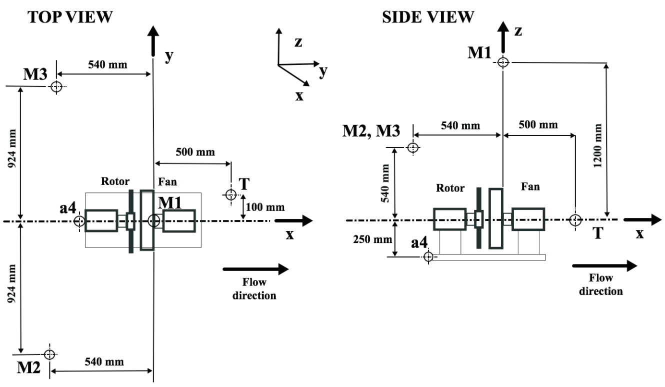

Figure 1 Schematic presentation of the two–rotor system under investigation

Firstly the thermoanemometric system was tune–up and all resistances, including the operating resistance, were set–up according to the producer's indications and the testing needs. Secondly, the square wave tests were generated and the output signal was checked with an oscilloscope, eliminating (by tuning the measurement system) electronic oscillations of the thermoanemometric bridge and to avoid other electronic excitations of electric signals. Next, the thermoanemometric probe was calibrated in a low-speed wind tunnel in the flow velocity range including the maximum value of the airflow speed observed during preliminary. The more details of this procedure were described in earlier tests or manuals about using such a thermoanemometric system, for example [7, 16].

The data acquisition system with ADC was set–up with the sampling frequency of 50 kHz and the input filters were used at 20 Hz and 20 kHz, as in both measuring chains.

4. Results of measurements

The basic measurements were performed to find out the dependence between rotational speeds of rotors and the emitted noise levels. The results of noise levels L measured in three microphones positions (presented in Fig. 1) are shown in Fig. 2.

The aim of this part of measurement sessions was to allow comparing two tested cases: the first - the fan alone (left side of Fig. 2), i.e. without the inlet rotor, and the second - when both rotors were working together (right side of Fig. 2). The latter one simulates real conditions of a two-counter rotating rotors system [8]. Changing the rotational speed of the fan for these two cases gives insight into different operating conditions of the system and for checking if there are any rotational frequency zones where the noise level can be controlled.

In the analysis of the obtained results it was found out that the polynomial functions of the second degree were enough to approximate properly the obtained results. As it can be seen, there are few zones of the fan performance where the emitted noise levels are higher or lower than the expected values. What is very interesting, adding the second rotor at the inlet to the fan somehow smooths these observed deviations, however, as expected, the overall noise was getting higher (Fig. 2). Of course the noise diminution zones are of greater importance from the point of view of overall noise reduction.

The next analysis was to find out if these zones are due to the fluid dynamics phenomena in the flow passing through the fan. For this purpose the analysis of flow velocity and turbulence level was conducted, expecting that unsteadiness of the flow is the main factor influencing the observed noise levels.

The results of the measurements of this factor (using thermoanemometric hot–wire probe), determined as turbulence level Tu, are presented in Fig. 3 and all correlation coefficients are presented in Tab. 1. It can be seen that acoustic measurements from all microphones are strictly correlated, and, taking into consideration almost the same noise levels measured by three microphones, it can be stated that microphones positioning was chosen properly and the acoustic results were verified.

As to flow parameters measurements it can be found that the overall noise emitted by two counter–rotating rotors is correlated with the flow velocity but not depended on the unsteadiness of the flow. Basing on that, the next step in analysis of the measurement signals was performed.

To find out the main frequency components FFT analysis was conducted for some chosen time signals. An example of the results, the obtained results for the case when only the fan was working with rotational speed of 42.5 Hz, are presented in Fig. 5. For the case when both rotors were counter-rotating with rotational speeds of 42.5 Hz (the fan) and 35 Hz (the rods rotor) are shown in Fig. 6. As it could be observed, and in agreement with above mentioned independence on unsteadiness of the flow, the main sources of noise are correlated with tonal sounds connected to the blade passing frequency. To a much lesser extent this applies to the first rotor since the rod passing frequencies were observed with significantly smaller amplitudes of the acoustic signals.

5. Conclusions

During presented herein experiments the acoustic properties of a system consisting of 8-blades fan and an impeller with 3 cylindrical rods were tested. Similar systems are used by other scientific centers to investigate different aspects of the fluid flows in turbomachinery, especially for modeling influences of incoming wakes [17, 18]. The presented test rig was built basing on design of one of the NASA test rigs [10].

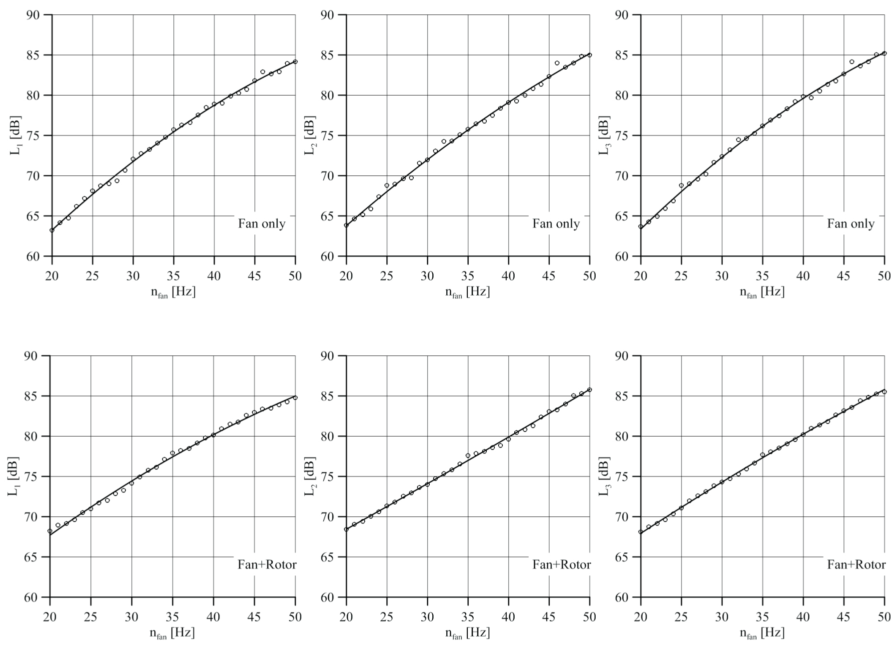

Figure 2 Measurement results of noise levels L measured in three microphones positions in function of the rotational speed of the fan for two cases: with (lower plots) and without (upper plots) inlet counter–rotating rotor

Table 1 Correlation coefficients between measured parameters

	n	L_1	L_2	L_3	c	Tu
n	1	0.996	0.999	0.999	0.804	0.101
L_1	0.996	1	0.995	0.998	0.802	0.110
L_2	0.999	0.995	1	0.999	0.803	0.105
L_3	0.999	0.998	0.999	1	0.799	0.118
c	0.804	0.802	0.803	0.799	1	-0.275
Tu	0.101	0.110	0.105	0.118	-0.275	1

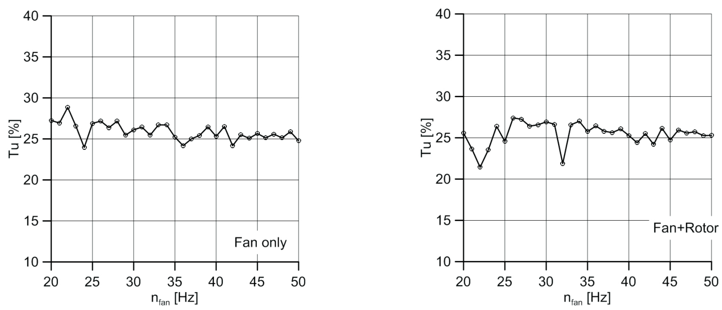

Figure 3 Turbulence level T_u in function of the rotational speed of the fan for two cases: with (right side) and without (left side) inlet counter–rotating rotor

In the presented measurement results there was attempt to define basic relations between flow parameters and the emitted sound levels in the function of rotational velocity of fan rotor. The data were also analysed in the frequency domain. It was found out that there are certain settings of the investigated system, which can result in lowering of flow losses, its unsteadiness and emitted noise levels. The accuracy of the obtained results was proved by the fact that noise levels measured by all microphones are the same (taking into consideration the accuracy of such measurements), not depending on their positions in relation to the tested object. Long time of the constantly recorded measurements (10 s of real measurements, i.e. without combining any time windows) ensured rich experimental material and allowed for detailed analysis in the frequency domain.

Basing on the obtained results, it was possible to observe mostly blades passing frequencies and their harmonics what is in agreement with other turbomachinery tests [3–5]. Rods passing frequency and its harmonics are weaker but they may influence the overall acoustic phenomena. Basing on this and after the comparison of the measured spectra of noise it can be also stated that there are also other aeroacoustic phenomena, which need additional investigations, probably connected

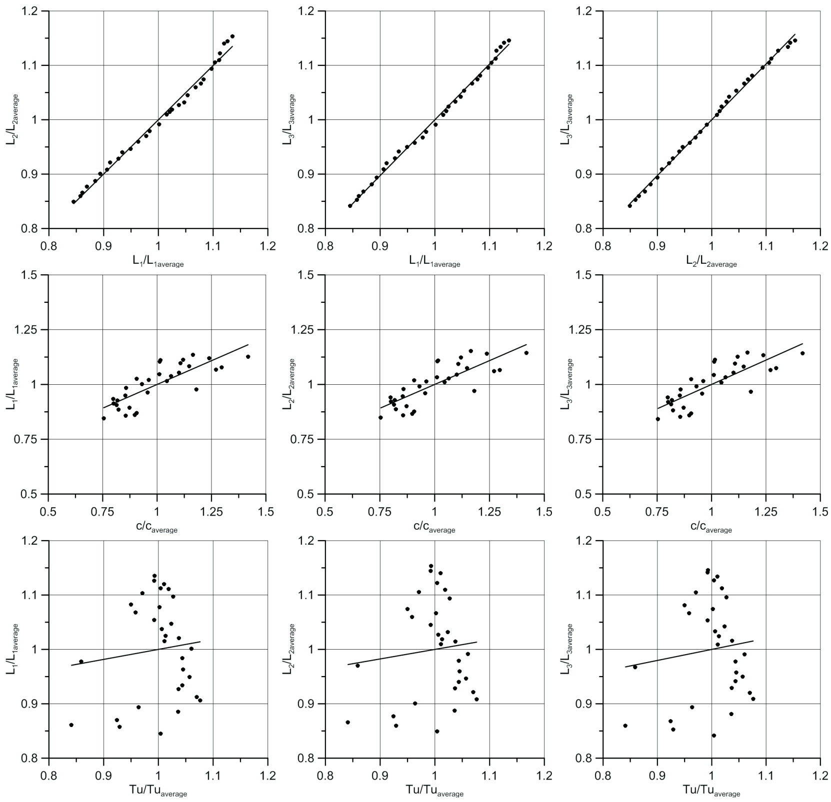

Figure 4 Comparison of the relationships between the parameters measured during the tests of both rotors

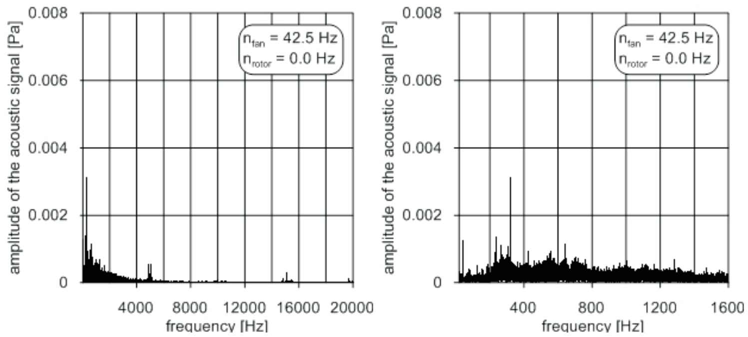

Figure 5 Main components of the acoustic signal only of the fan in function of frequency, the case when the fan rotational speed was $n_f = 42.5$ Hz; left side: whole acoustic range of the signal; right side: more detailed image of the lower part (up to 1600 Hz) of the acoustical frequency range

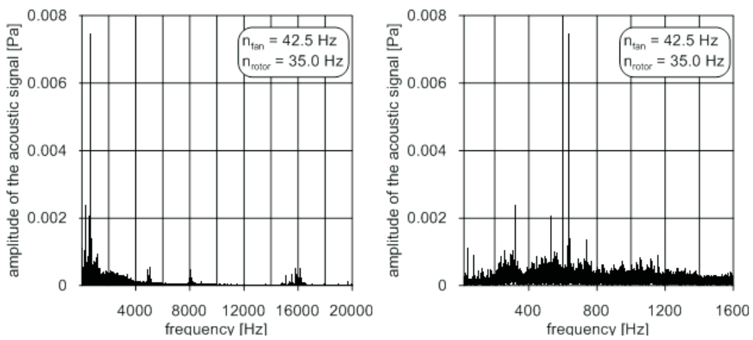

Figure 6 Main components of the acoustic signal of both rotors in function of frequency for fan rotational speed $n_f = 42.5$ Hz and rotor rotational speed $n_r = 35.0$ Hz; *left side: whole acoustic range of the signal; right side: more detailed image of the lower part (up to 1600 Hz) of the acoustical frequency range*

with blades boundary layers flows like it was observed in other boundary layers testing[15, 17, 18]. The measured noise levels were approximated by parabolic polynomials to predict steady and undisturbed growth of SPLs in function of the fan rotational speed. The usage of additional impeller (in the presented investigations simulated by a rotor with cylindrical rods) influenced in slightly manner on any deviations to such approximation.

The investigations showed that it is difficult unequivocally state the possibilities of the noise reduction of the tested system (maybe to small scale when compared to the real aeroengines), however the real nature of these phenomena can be decoded basing mostly of blade passing frequency and its harmonics. It was also found out that it is not possible to find and define dependable detailed patterns without very time-consuming additional measurement sessions and analyzing huge amount of experimental data.

The obtained results should be considered in designing process of flow machines when noise reduction is special issue. They may be used in designing the modern aeroengines with two counter-rotating propellers for passenger planes, helicopters or drones when the noise aspect is important. It can be done not only from the performance tests of such flow machines, but also, according to modern trends, from the point of view of noise reduction. This is in agreement with new demands, especially considering that nowadays noise plays very significant role. It can be found not only in lately modified ISO standards. Additionally, in the EU, the XXI century directives introduced the concept of noise pollution, aside of the air and water pollutions, as one the most important things of our times. The results presented herein fit themselves very well in these modern trends.

References

[1] **Rydlewicz, J.**: Wentylatory i pompy przepływowe, *Lodz University of Technology*, **1989**.

[2] **Wojciechowski, K., Błaszczak, J. R.**: Experimental Investigation of an Interaction between Two Rotating Rotors, *CMP–Turbomachinery*, 140, 225–234, **2011**.

[3] **Błaszczak, J. R.**: Flow Noise Correlation with Efficiency and Vibration Level, *J. of Systems Science*, 11, 1, pp. 8–15, **2006**.

[4] **Błaszczak, J. R.**: Noise Reduction and Efficiency Improvement through Vane Indexing of a Two-Stage Turbine, *AIAA*, 2006–2578, **2006**.

[5] **Błaszczak, J. R.**: Noise Reduction through Vane and Blade Clocking of a Two–Stage Turbine, *Advances in Vibration Engineering*, 11, 2, 121–129, **2012**.

[6] **Błaszczak, J. R., Comte–Bellot, G. and Smolny, A.**: New Aeroacoustic Facility at the Institute of Turbomachinery, *CMP–Turbomachinery*, 128, 79–86, **2005**.

[7] **Błaszczak, J. R.**: Experimental Investigations of a Turbine Stage Load on Boundary Layers and Noise Generation, (in Polish), Scientific Project # 4 T10 B 04323, *Polish Committee of Science*, **2005**.

[8] **Heidmann, J. D., Lucci, B. L. and Reshotko, E.**: An Experimental Study of the Effect of Wake Passing on Turbine Blade Film Cooling, *NASA Technical Memorandum*, 107425, **1997**.

[9] **Womack, K. M., Volino, R. J. and Schultz, M. P.**: Measurements in Film Cooling Flows With Periodic Wakes, *J. of Turbomachinery, ASME*, 130, 041008, **2008**.

[10] **Koch, D. L.**: Predicting the Inflow Distortion Tone Noise of the NASA Glenn Advanced Noise Control Fan With a Combined Quadrupole-Dipole Model, NASA/TM—2012-217673, *AIAA*, 2012–2196, **2012**.

[11] **Sobczak, K., Smolny, A., Błaszczak, J.R.**: Quasi-Unsteady Simulations of the Clocking Phenomena in the Two-Stage Turbine, *Mechanics and Mechanical Engineering*, 12, 2, 111–124, **2008**.

[12] **Błaszczak, J. R.**: Vane-to-Vane and Blade-to-Blade Indexing of a Highly-Loaded Two-Stage Turbine, *ASME*, GT2007-27639, **2007**.

[13] **Błaszczak, J. R.**: Performance Improvement and Noise Reduction through Vane and Blade Indexing of a Two–Stage Turbine, *AIAA*, 2008-2941, **2008**.

[14] **Crocker, M. J., ed.**: Handbook of Acoustics. Wiley–Interscience, *John Wiley & Sons*, New York, **1997**.

[15] **Smolny, A., Błaszczak, J. R.**: Boundary Layer and Loss Studies on Highly Loaded Turbine Cascade, *AGARD/NATO*, CP-571/4, 1–13, **1996**.

[16] **Jorgensen, F.E.**: How to Measure Turbulence with Hot–Wire Anemometers, *Dantec Dynamics*, Tonsbakken, **2002**.

[17] **Błaszczak, J. R. and Borzecki, T.**: Badania warstw przyściennych na profilach kierownic wysokoobciążonej turbin, *J. of Systems Science*, 11, 1, 136–144, **2006**.

[18] **Smolny, A., Błaszczak, J. R. and Sobczak, K.**: Performance Improvement through the Vane Clocking Effect in a Two–Stage Impulse Turbine, *Mechanics and Mechanical Engineering*, 15, 3, 343–354, **2011**.