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DETERIORATION OF THE OPERATIONAL EFFICIENCY OF RADIAL FANS RESULTING FROM ROTATIONAL STALLING

WPŁYW ODERWANIA WIRUJĄCEGO NA WŁASNOŚCI EKSPLOATACYJNE WENTYLATORÓW PROMIENIOWYCH

Large diameter fans, as typically used in the mining and power industries have a considerably narrower range in comparison with fans intended for more general use operational range. The lower limit of the operational range could only attain the limit of hysteresis. This hysteresis is a result of rotating stalling. Rotating stalling is an interesting phenomenon that occurs in both axial and radial rotors. It is still poorly recognised in radial rotors. This stimulated investigations concerning pressure oscillation in streams of airflow, as well as on acoustic levels and flow rates in an attempt to find a means of eliminating the hysteresis set up by the entry vortex consistent with the direction of peripheral velocity. Experiments have confirmed the removal of hysteresis in the condition of forwarded whirl at a vane angle in excess of 30°. Results of tests are described in the paper.

Key words: detachment from the blade, rotational stalling, bound of hysteresis, boundary of rotational stalling

Zjawisko oderwania wirującego, nazywane też „Rotational stalling", występuje w maszynach osiowych i promieniowych. Towarzyszą mu histereza lub nieciągłość na krzywej ciśnienia, intensywne drgania i hałas. Jest ono rozpoznane lepiej w maszynach osiowych niż promieniowych dzięki pracom Greitzera (1976), Pfleiderera, Petermanna (1972), Cumpsty, Greitzera (1982) i innych. Mniejsza liczba prac dotyczy maszyn promieniowych (Fortuna 1985, 1987; Wachter, Rieder 1986).

W monografii Pfleiderera i Petermanna, przedstawiono hipotezę zjawiska oderwania wirującego, według której na rysunku 1 sporządzono model zjawiska oderwania wirującego w palisadzie osiowej. Na jego podstawie oraz pracy Bohla opracowano model oderwania wirującego (*RS*) w wirniku promieniowym, przedstawiony na rysunku 2. Na skutek oderwania się strug gazu od jednej lub dwóch łopatek w kanałach międzyłopatkowych wyodrębniają się dwie struktury przepływowe, pokazane na rysunku jako obszar wirów oraz zagęszczonych strug przedstawionych za pomocą pola

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zakreskowanego. Koncentracja strug stanowi przeszkodę na drodze przepływu, skutkiem czego nowo napływające z prędkością *w* strugi odchylają się, jedne w kierunku wirowania palisady, drugie w kierunku przeciwnym do prędkości wirnika. Na łopatce nr 4 pojawi się tendencja do oderwania, natomiast na łopatce nr 2 oderwanie będzie likwidowane. W ten sposób uruchamia się mechanizm przemieszczania oderwań od łopatek wzdłuż kierunku obwodowego z prędkością kątową ω_{RS}, mniejszą o około 50% od prędkości wirnika ω, nazywane oderwaniem wirującym (*RS*). Zjawisko to powoduje wystąpienie na krzywej dławienia histerezy pomiędzy punktami (*FCDE*), pokazanej na rysunku 3. Jeżeli oderwanie wirujące jest spowodowane oderwaniem na jednej łopatce, to zamiast histerezy na krzywej ciśnienia otrzymuje się nieciągłość (*FC*).

Zjawisko oderwania wirującego jest wielce niepożądane, gdyż wywołuje silne drgania gazu oraz intensywny hałas. Wzrost amplitud drgań pojawia się w zakresie roboczej części charakterystyki maszyny na odcinku *EM*, co obrazują przebiegi 2 na rysunkach 4 i 5 w porównaniu z amplitudami dla przepływu pełnego 1. Punkt pracy z odcinka EM może samorzutnie i skokowo przemieścić się na dolną gałąź charakterystyki do punktu *C* wtedy, gdy w przepływie powstanie oderwanie wirujące. Po przeskoku amplitudy ciśnień jeszcze wyraźniej wzrastają, jak to ilustrują przebiegi oznaczone liczbą 3 na tych rysunkach. Drgania te zagrażają wytrzymałości wirnika i z tego powodu nie można dopuścić do ich powstania przez eliminowanie oderwania *RS*.

Oderwanie wirujące powoduje także znaczny wzrost hałasu, jak ten zarejestrowany na rysunku 6 w postaci dwóch przebiegów ogólnego poziomu ciśnienia akustycznego oraz widma oktawowego dla stanu przed i po oderwaniu.

Na podstawie przyjętego modelu oderwania wirującego dokonano kinematycznej analizy przepływu uśrednionego (rys. 7a, b, c), z której wysnuto tezę, że za pomocą zawirowania gazu u wlotu do wirnika możliwe będzie zlikwidowanie histerezy i niedopuszczenie do pojawienia się oderwania wirującego, a tym samym drgań i hałasu. Przeprowadzone badania przepływowe wentylatora promieniowego typu WWOax i wykreślone na ich podstawie na rysunku 8 charakterystyki dowodzą słuszności postawionej tezy. Dla kątów ustawienia łopatek kierownicy wlotowej wynoszących +30°, generujących wstępne zawirowanie zgodne z kierunkiem obrotów wirnika, uniknięto zjawiska oderwania wirującego, a na krzywej wykreślonej przerywaną linią krótką nie ma histerezy. Na charakterystykach na rysunkach 8 i 9 wyznaczono granice oderwania (*RSG*) i histerezy (*HG*), dowodząc tym samym, że ze względów bezpieczeństwa i cichobieżności zakres pracy promieniowych maszyn wirnikowych, zwłaszcza dużych, stosowanych w górnictwie i energetyce należy bezwzględnie zmniejszyć z punktu maksymalnego ciśnienia do granicy histerezy (*HG*).

W podsumowaniu można stwierdzić, że za pomocą modelu oderwania wirującego i kinematycznej analizy przepływu uśrednionego możliwe jest poszukiwanie rozmaitych metod zapobiegania niepożądanemu zjawisku oderwania wirującego. Badania oscylacji ciśnienia wzdłuż histerezy wykazały konieczność określenia granicy histerezy (*HG*) i granicy oderwania (*RSG*) oraz zmniejszenia roboczego zakresu pracy.

Słowa kluczowe: oderwanie strugi od łopatki, oderwanie wirujące, granica histerezy, granica oderwania wirującego

1. How does the rotational stalling arise?

When the inflow angle of the stream onto a blade is too high, the stream is detached from the blade surface. This detachment also appears in the blade rim of fluid-flow machines. The detached area, rotating in relation to the rim is known as the rotational stalling. Also, in the decreasing inlet stream the angle of relative velocity inclination is diminished. When the boundary angle of detachment is exceeded the stall will follow, as is shown on blades 2 and 3 (Fig. 1).

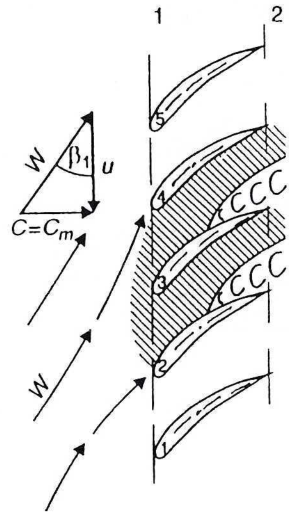

Fig. 1. The model of rotational stalling in the axial palisade (Pfleiderer, Petermann 1972)

Rys. 1. Model oderwania wirującego w palisadzie osiowej (Pfleiderer, Petermann 1972)

This is the result of inconsistency of the profile or irregularities in the stream that flows onto one or more blades of the rim. In the shaded area there is the concentration of gas, a decrease of the flow through its channels and deviation of the stream in both sides of the area of concentrated gas. This deviation will increase the flow angle on blades 4 and 5, despite its previous high level, resulting in its detachment. The deviation on edges of blades 1 and 2 will create a diminution in the inflow angle with subsequent return of the detached streams to the surface of the profile. The stall area travels over the rim in the direction of its peripheral velocity about 50% slower than the rotor velocity ($\omega > \omega_{RS}$).

The rotational stalling also appears in the blade palisade. The mechanism of its initiation is the same as in the case of axial-flow machines. This is presented in Fig. 2.

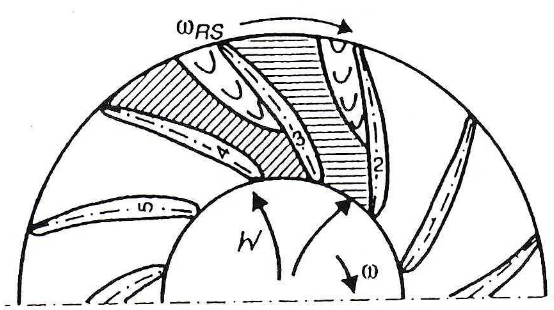

Fig. 2. The mechanism of initiation of rotational stalling in the circular palisade (Bohl 1994)

Rys. 2. Mechanizm powstawania oderwania wirującego w palisadzie promieniowej (Bohl 1994)

2. Hysteresis on the throttling curve

The specific feature of the rotational stalling phenomenon is the hysteresis on the throttling curve. It is presented in Fig. 3. The transition from the "sound" stream to the stall area follows the jump along the line (*FC*) and the return from the stall to normal,

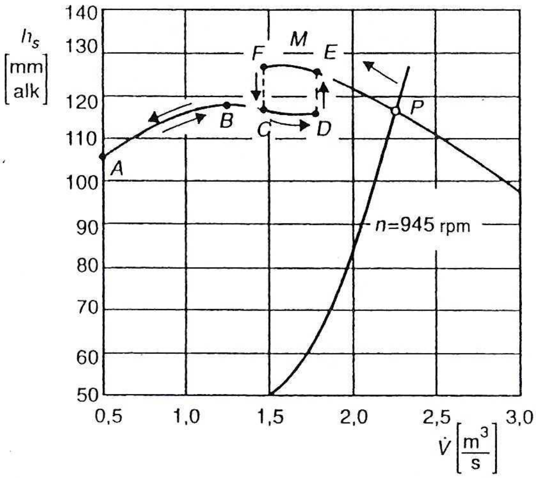

Fig. 3. Hysteresis on the throttling curve

Rys. 3. Histereza na krzywej dławienia wentylatora

stable "sound" flow also takes place over the jump line (*DE*). Between parts (*FC*) and (*DE*) occurs as a curve called hysteresis. When the operating point (*P*) is moved over the characteristic curve in a stationary mode i.e. with slow and small stroke chokes of the supply pipeline fan, slow but growing oscillations occur behind point (*E*). After the operating point (*P*) attains a level of approximately the peak (*M*) it will suddenly, without any external or extraneous reason, skip to the lower part of the hysteresis. At the same time strong oscillations in the flow develop, whose amplitude and frequency are higher than those observed on the line (*EF*).

3. Measurement of air oscillation

These oscillations can be measured on the suction line side. The recorded pressure oscillations are presented in Fig. 4 where 1 denotes the course of the pressure for the operating point of the full flow and 2 denotes the operating point near the peak, which is related to the oscillations. The course 3 describes the oscillation phase just after the pressure jump when rotational stalling is taking place in the rotor. Significantly stronger oscillation is observed behind the rotor. Variations in the pressure were measured by the sensor located next to the trailing edge of the blades close to the rear disk. Relevant data are presented in Fig. 5. In the description of lines the same notation is used as in Fig. 4. The scales of pressure and time are equal in both pressure oscillation diagrams. Therefore the amplitude and the frequency values may be compared. This oscillation is caused by the same phenomenon and has been recorded in the absolute reference system both in the inflow to the rotor side and the outflow from the rotor rim. Nevertheless the vibration consequences of the rotational stalling are much more significant in the streams, which flow out from the rotor. In the inlet chamber of the rotor and in the characteristic section $\pi\omega_1 b_1$ the oscillation of gas caused by the stall have been strongly damped. Therefore better more accurate observations of this phenomenon may be made in the downstream outlet of the rotor.

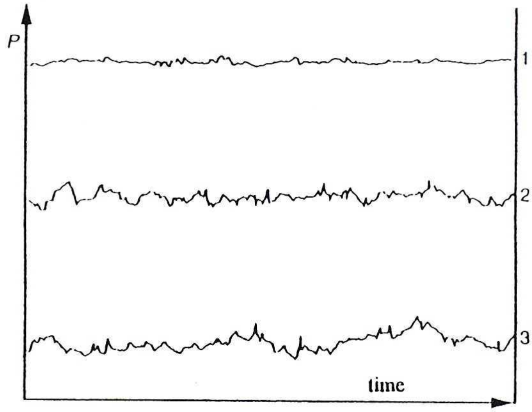

Fig. 4. Amplitudes of stationary pressures in the suction pipe recorded 20 cm before the rotor

Rys. 4. Amplitudy ciśnienia statycznego w rurze ssawnej w odległości 20 cm od wirnika

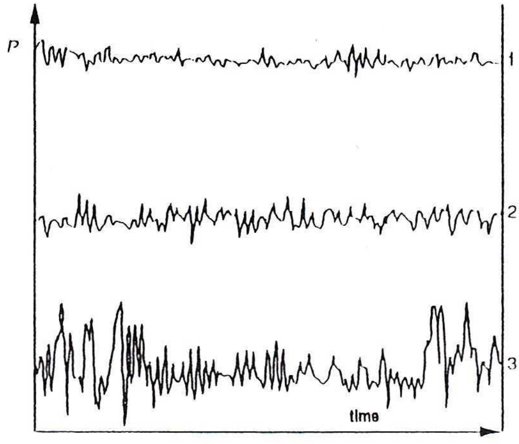

Fig. 5. Amplitudes of the total pressure behind the rotor near the rear disc

Rys. 5. Amplitudy ciśnienia całkowitego za wirnikiem przy tarczy tylnej

The oscillation, like that in Fig. 3 was sustained at all operating points over the curve (*CBA*) with the progress of the throttling procedure, as well as on the curve (*ABCD*) at the stage of throttling decrease of the system. In the point (*D*) the maximum jump of pressure may be observed, which is accompanied by the cessation of stalling and the system begins to operate in a stable and quiet mode. When the rotor has been stopped in the operating point with stall and then started in the same throttling condition, the rotational stalling was observed as previously. Thus, the phenomenon depends on the throttling condition in the system but does not depend on time.

Considering the mathematical sense of pressure jumps, they seem as discontinuities because single abscissas value v_F are related to two values of the function P_F and P_C. The lower pressure, which is maintained after the jump, results in the lower output of the machine.

The higher pressure in the point (*E*) achieved after the jump of the point (*D*) onto the upper line is the reason of a rapid increase of the output. Therefore in the diagram, (Fig. 3) discontinuities are shown in the vicinity of points (*C*) and (*E*).

4. Acoustics of rotational stalling

Low-frequency noise is characteristic of the acoustic effects which accompany the phenomenon of rotational stalling caused by non-stationary vane forces. Predominant pressure levels in the acoustic spectrum of the fan could be observed as tierces 20–25, 63–80 and 100–125 Hz.

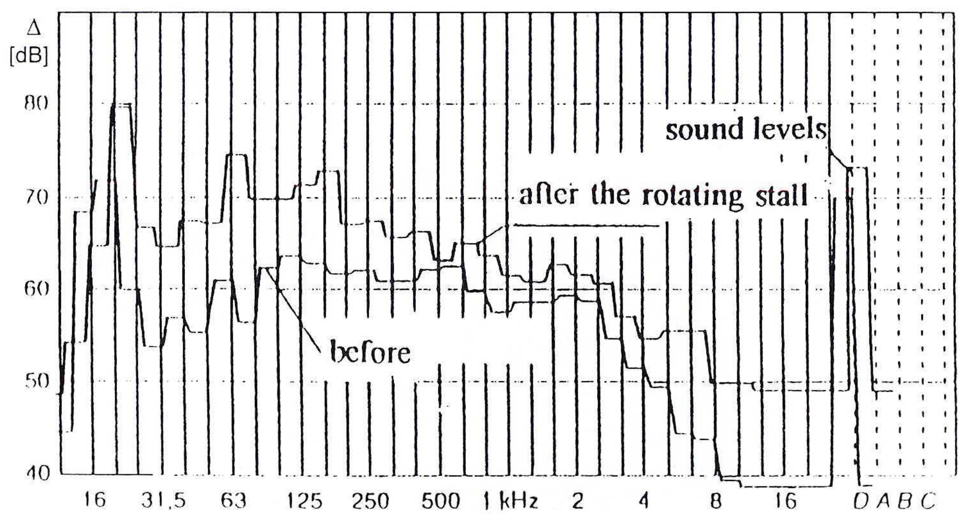

Fig. 6. Acoustic spectrum measured in the fan WWOax-56 before and after the rotational stalling and the noise level

Rys. 6. Widmo akustyczne i poziom dźwięku zmierzone w wentylatorze WW0ax-56 przed i po wystąpieniu oderwania wirującego

The result is an overall increase in the sound intensity. It is confirmed by the results of acoustic tests presented in Fig. 6. In this figure one can see the noise spectra of the fan: the first without the rotational stalling phenomenon and the other for the operating point where the rotational stalling has appeared. The graph on the right side of the spectra shows the sound levels. The increase of the sound level at the point where the stall begins is 4 dB.

5. Possibilities of hysteresis elimination

Rotational stalling in fans is an undesirable flow phenomenon. Therefore two boundaries have been drawn in the characteristics: the boundary of stall, which when exceeded causes transition of the fan into an inefficient operational regime with the stall, and the upper hysteresis boundary beyond which, the fan is moved out of the hazardous operation area. In the upper line of the hysteresis (*EF*), (Fig. 3), there is the possibility of the system operating between the two boundaries. The operation on the bottom line of the hysteresis (*CD*) is proscribed then the system has to be moved beyond the boundary of the hysteresis in the direction of higher output.

The hysteresis should be eliminated or at least shifted towards zero output or its area has to be reduced, which will result in a limitation of the disadvantageous effects of the rotational stalling.

This could be achieved in axial fans either by the control of the impeller vane-angle setting or by output control with the application of the by-pass between the inlet and the exit side.

There are other methods to influence the gas inflow angle onto the rim e.g. prewhirl of the stream before the rotor. That could be concluded from the analysis of the velocity triangles in the inlet (Fig. 7), where three flow stages are presented. When comparing triangles (b) and (c) it will be apparent that the application of the inlet guide vane should

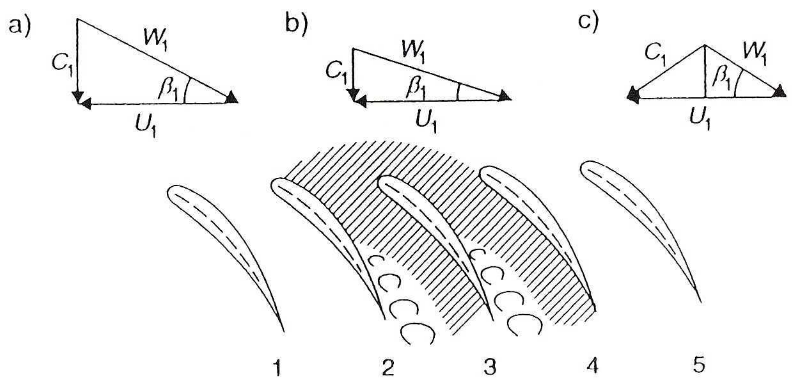

Fig. 7. Velocity triangles for different flows: full (a), throttled(b), whirled(c)

Rys. 7. Trójkąty prędkości dla przepływu: pełnego (a), zdławionego (b), zawirowanego (c) result in the same output of the fan as that produced by the operation in the throttling mode, wherein a greater angle of the inflow of the stream onto blades is maintained.

In the kinematics of the triangle (a) the inflow onto the blade is tangential to the centre line of the airfoil section. Thus the stall condition does not occur. When the output is diminished as in the triangle (b) the stream angle β_1 is substantially smaller then the angle β_1 in the flow related to triangle (a). In such a situation there are conditions conducive to the stall of the gas from blades 2 and 3. In the triangle (c) the meridional component c_{1m} is equal to the velocity c_1 in the triangle (b) resulting in equal outputs. In any case, the inclination angle in the third triangle is the same as in triangle (a). In this case there are no conditions for rotational stalling occurring. The above analysis stimulated tests (Fortuna 1985) as presented in Fig. 8. The objective of these tests was to find a method to eliminate hysteresis by means of the prewhirl forwarding the peripheral velocity u_1.

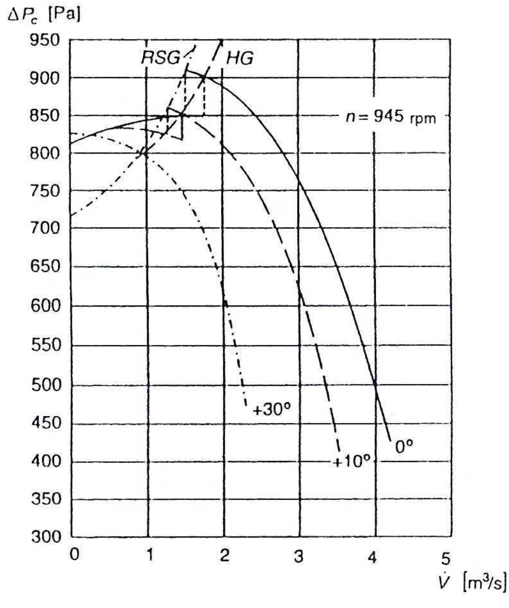

Fig. 8. The lack of hysteresis with the forward whirl

Rys. 8. Krzywa bez histerezy dla zawirowania współbieżnego 30 stopni

The backward whirl decreases the inflow angle that induces the stall phenomena. From the theoretical point of view it did not give any chance to eliminate hysteresis. The experiments in which two directions of whirls were tested confirmed the elimination of hysteresis in the centrifugal rotor with the forward whirl. It has been observed in tests with axial vane blades of the angle 30°. In tests with opposite angles the hysteresis was not eliminated.

It is not possible to move out the fan from the unstable line of the characteristics to the stable one, by increasing or decreasing the rotation velocity of the rotor because the

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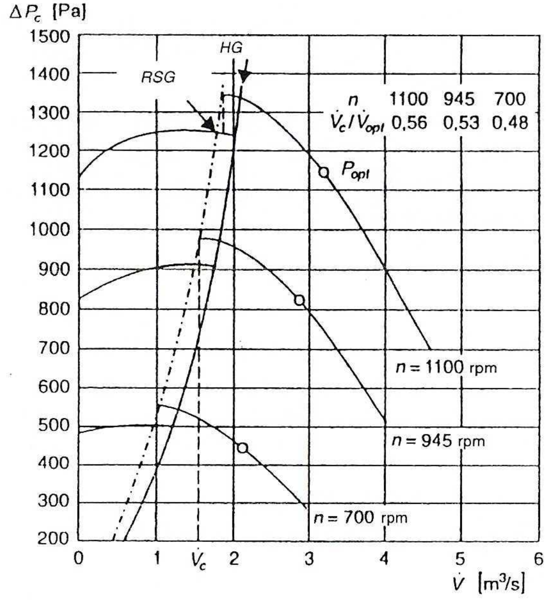

Fig. 9. Hysteresis in the fan with different rotation velocity of rotor, boundaries of hysteresis and the rotational stalling

Rys. 9. Granice oderwania wirującego (*RSG*) i histerezy (*HG*) na krzywych dla różnych obrotów wirnika

characteristics of the cooperating pipeline is the same. As it can be concluded from Fig. 9, the operating points of the system move along the characteristics of the pipeline. Similarly, the boundaries of the hysteresis (*HG*) and the stall (*RSG*) cover this characteristic.

The rotational stalling phenomenon follows the rules of flow similarity. The boundaries of rotational stalling in flow-machines whose geometry is similar or the same but different are their rotational velocities satisfy the similarity conditions:

$$V = V' \cdot \left(\frac{D_2}{D'_2} \right)^3 \cdot \frac{n}{n'}$$

$$\Delta P_c = \Delta P'_c \cdot \left(\frac{D_2}{D'_2} \right)^2 \cdot \left(\frac{n}{n'} \right)^2 \cdot \frac{\rho}{\rho'}$$

6. Conclusions

1. The hypothesis of rotational stalling, as described in point 1, enabled the kinematic analysis of the inflow (Fig. 7), and through that analysis elimination of the hysteresis in the forward whirl.

2. The gas oscillation in rotational stalling form envelopes which are characteristic for the beat phenomenon.

3. The intensive noise with low frequency pressures dominating in its spectrum accompanies the rotational stalling.

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