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(54) METHOD AND APPARATUS FOR AVOIDING SURGING IN CENTRIFUGAL COMPRESSORS

(71) We, OFFICE NATIONAL D'ETUDES ET DE RECHERCHES AEROSPATIALES (O.N.E.R.A.), a French Official Technical Research Body, of 29 Avenue de la Division Leclerc, 92320 Chatillon Sous Bagneux, France, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:-

The invention relates to a method and apparatus for avoiding surging in centrifugal compressors which do not comprise distributor blading upstream of the impeller.

Hitherto, known methods and apparatus relied upon the detection of the pressure downstream of the impeller of the compressor. Now the flow downstream of the impeller of the compressor is at a high temperature as a result of the compression and this complicates the implementation and setting in operation of the apparatus and methods using the known technique involving detection of the downstream pressure.

The present invention, which results from the study of the flow of fluids in a centrifugal compressor, undertaken by the applicants, has the object of remedying these drawbacks.

According to the present invention there is provided a method of avoiding surging in a centrifugal compressor comprising an impeller, the said method comprising the steps of detecting the direction of the absolute velocity of the fluid upstream of the impeller of the compressor, comparing this direction with a predetermined critical direction which depends on the characteristics of the compressor and beyond which critical direction there is a risk of surging, measuring the value of the radial gradient of the static pressure of the fluid upstream of the impeller of the compressor, comparing this value with a predetermined critical value beyond which critical radial pressure gradient there is a risk of surging, and using the results of these comparisons to act on regulator means, to modify the flow conditions upstream or downstream of the compressor to prevent surging.

Also according to the invention there is provided a centrifugal compressor comprising an impeller, a pressure probe and regulator means controlled by the probe and arranged to act on the flow conditions downstream or upstream of the compressor to prevent surging, the probe being disposed upstream of the impeller of the compressor and being arranged to detect the critical direction of the absolute velocity of the fluid and to detect the critical value of the radial gradient of the static pressure beyond which critical direction and critical value there is risk of surging, the said probe being provided with directional pressure ports for monitoring the direction of the absolute velocity of the fluid, situated at the same distance from the wall of the fluid intake casing of the compressor and disposed symmetrically with respect to the critical direction of the absolute velocity of the fluid beyond which a risk of surging exists, and ports for monitoring the radial pressure-gradient ports of the fluid, situated one nearer to the said wall and the other farther from the said wall.

Advantageously, the detection of the direction of the absolute velocity of the fluid and the measurement of the value of the radial gradient of the static pressure take place at a distance from the impeller of the compressor which is between 0.05R and 0.5R, R designating the radius of the intake casing.

Means for measuring and processing the data transmitted by the pressure ports are provided for comparing the values supplied by the two directional pressure ports and by the two radial pressure gradient ports.

These means for measuring and processing the data control regulator means which utilise the comparison between the two directional pressure ports and between the two radial pressure gradient ports, so that, when this comparison indicates a risk of surging the regulator means act on the flow conditions downstream or upstream of the compressor to make this risk of surging disappear.

The invention will now be further described by way of example in more detail with reference to the accompanying drawings, in which:-

Figure 1 shows half of a diagrammatic axial section of part of a conventional centrifugal compressor,

Figure 2 shows diagrammatically half a centrifugal compressor (on a smaller scale than Figure 1) with apparatus according to the invention for detecting phenomena which precede surging of the centrifugal compressor,

Figure 3 is a view on a larger scale of a detail of Figure 2,

Figures 4, 5 and *6* are sections on a further enlarged scale taken on the lines IV, V and VI of Figure 3, and

Figure 7 shows a preferred embodiment of the circuit diagram of the apparatus shown in Figure 2.

In Figure 1 there is shown diagrammatically in half view the impeller 1, having blades 2, of a centrifugal compressor. The compressor has an intake casing 3.

The work done by the applicants in the study of the flow of fluids in a centrifugal compressor without upstream distributor blading has shown that, in the conditions of operation below the surging curve, the flow of fluid immediately upstream of the impeller is without tangential component. Moreover, when the conditions of operation approach the surging curve, a tangential component to the velocity appears, this tangential component being progressively greater at positions closer to the walls of the intake casing 3 (near to the phenomenon of boundary layer).

In Figure 1 the variation of this tangential component U, relative to ωR, is represented, ω designating the angular velocity of the impeller in radians per second, and R the radius of the inlet of the impeller 1 which corresponds at close clearance to the radius of the intake casing 3.

The values of $\frac{U}{\omega R}$ are shown on the axis O-Z (parallel to the axis X-X of the compressor) and the values of the local radius r, referred to the radius R, on the axis O-Y (perpendicular to the axis X-X of the compressor).

The curve C_I, represented by a dotted line, shows the variation of the critical tangential component in the neighbourhood of surging of the compressor.

The curve C_{II}, represented in full line, shows the variation of the critical tangential component U_c beyond which the invention requires the compressor not to operate.

The apparatus shown in Figure 2 is used to prevent the compressor from being operated beyond this critical limit. This apparatus comprises a probe 4 and regulator means 5. The probe 4 is disposed upstream of the compressor and is arranged to detect the critical direction of the absolute velocity of the fluid and to measure the critical value of the radial gradient of the static pressure beyond which the compressor risks being subjected to surging. The regulator means 5 is controlled by the probe 4 in such a manner that, as soon as the critical values of the direction of the absolute velocity of the fluid and of the measure of the radial gradient of the static pressure are reached, these regulator means act on the conditions downstream or upstream of the compressor to make the risk of surging disappear.

For a centrifugal compressor without upstream distributor blading, the probe is disposed upstream of the impeller at a distance of between 0.05R and 0.5R, R designating the radius of the intake casing 3 of the compressor.

As shown on a larger scale in Figure 3, in which the same reference numerals designate the same members as in Figure 2, the probe has two directional pressure ports P_1 and P_2 and two static pressure ports P_3 and P_4. The two directional pressure ports P_1 and P_2 are situated at the same distance from the wall of the intake casing 3 (Figure 4) and are disposed symmetrically with respect to the critical direction V_c of the absolute velocity of the fluid beyond which there exists a risk of surging.

The two radial static pressure gradient ports are situated one, P_3, nearer to the said wall and the other, P_4, further from the said wall, each of these two radial pressure gradient ports P_3 or P_4 being disposed at a respective angle α_3, α_4 which the absolute velocity V_3 or V_4 makes with its axial component D_3 or D_4 at the distance considered from the wall and with account taken of the values of the tangential component U_3 or U_4 and of the axial component D_3 or D_4 at this distance (Figures 5 and 6).

The probe 4 is, as shown, preferably cylindrical so as to present a minimum drag whatever the direction of the fluid may be.

In one embodiment of the cylindrical probe 4, the distances h_1, h_2, h_3, h_4 from the wall and the angles α_1, α_2, α_3, α_4 of the pressure ports P_1, P_2, P_3, P_4 have respectively the values:

$h_1 = 0.075R$	$\alpha_1 = 45°$
$h_2 = 0.075R$	$\alpha_2 = 105°$
$h_3 = 0.05R$	$\alpha_3 = 90°$
$h_4 = 0.1R$	$\alpha_4 = 30°$

Measurement means 6 and 7 (Figure 2) are then provided for comparing the values supplied by the two directional pressure ports P_1 and P_2 and by the two radial pressure gradient ports P_3 and P_4.

These measurement means 6 and 7 control the regulator means 5 which use the comparison, on the one hand, between the two directional pressure ports P_1 and P_2 and, on the other hand, between the two radial pressure gradient ports P_3 and P_4, so that, when this comparison indicates a risk of surging, the regulator means 5 act on the conditions downstream of the compressor to make this risk of surging disappear.

The measurement means 6 and 7 comprise differential pressure pick-ups 8 and 9, not represented as far as their mechanical structure is concerned, but diagrammatically in Figure 7 as far as their electrical structure is concerned.

The differential pressure pick-up 8 comprises two strain gauges 10 and 11, and a membrane subjected, at one side, to the directional pressure at the port P_1 and, at the other side, to the directional pressure at the port P_2. These two gauges 10 and 11 are connected in a bridge system 12 with two balancing resistances 13 and 14.

The differential pressure pick-up 9 comprises two strain gauges 15 and 16, and a membrane subjected at one side, to the pressure at the port P_3 and at the other side to the pressure at the port P_4. The gauges 15 and 16 are connected in a bridge system 17 with two balancing resistances 18 and 19.

The bridge 12 is fed by a voltage source 20 and the difference in voltage at the terminals of the bridge 12 is fed to an amplifier 21. The output of this amplifier 21 is fed into a divider 23 through a diode 22 which prevents transmission of a parasitic signal due to an inversion of the pressure in the intake casing of the compressor.

This divider 23 receives also a signal $k\omega^2$ proportional to the square of the angular velocity of the impeller of the compressor, and generated on in a multiplier 24 which itself receives the signal $k\omega$ from means not shown for measuring the angular velocity of the impeller.

The divider 23 therefore delivers a signal proportional to the difference in pressure between the ports P_1 and P_2, divided by the square of the angular velocity ω of the moving impeller, which is introduced into an ON-OFF control device 25 whose output feeds a relay 26 controlling a switch 27.

The bridge 17 is supplied by a voltage source 30 and the difference in voltage at the terminals of the bridge 17 is fed into an amplifier 31. The output of this amplifier 31 is fed into a divider 33 through a diode 32 which prevents transmission of a parasitic signal due to an inversion of the pressure in the intake casing of the compressor.

This divider 33 receives also the signal $k\omega^2$ proportional to the square of the angular velocity of the impeller of the compressor, and generated in the multiplier 24.

The divider 33 therefore delivers a signal proportional to the difference in pressure between the ports P_3 and P_4 divided by the square of the angular velocity ω of the moving impeller, which is introduced into an ON-OFF control device 35 whose output feeds a relay 36 controlling a switch 37.

The two switches 27 and 37 are interposed between a current source 38 and a servo-motor 39 which controls the valve member 40 controlling an orifice 41 connected to the output 42 of the compressor (Figure 2).

In order to avoid the measuring means giving erroneous data in the case when the directional pressure ports P_1 or P_2 and/or the radial pressure gradient ports P_3 and P_4 have become accidentally blocked, provision is made for closing these pressure ports by making them include, in each of their connecting conduits with the corresponding differential pressure pick-ups, valves 53, 54 for the directional pressure ports P_1 and P_2 and 63 and 64 for the radial pressure gradient ports P_3 and P_4.

For this purpose the electrical signals delivered by the bridge 12 are amplified in an amplifier 50 whose output signal is introduced into an ON-OFF control device 51 whose output feeds a relay 52 controlling the valves 53 and 54.

Similarly, the electrical signals delivered by the bridge 17 are amplified in an amplifier 60 whose output signal is introduced into an ON-OFF control device 61 whose output feeds a relay 62 controlling the valves 63 and 64.

The angles between the axial direction and the axes of the directional pressure ports P_1

and P_2 are respectively equal to α_1 and α_2, so that $\frac{\alpha_1 + \alpha_2}{2}$ is equal to the angle α_c of the chosen critical velocity V_c.

At the approach of surging, the direction of the absolute velocity tends towards the direction of the critical absolute velocity V_c and the difference $P_1 - P_2$ (between the pressures at the ports P_1 and P_2) tends towards zero. The equality of the pressures P_1 and P_2 (at the ports P_1 and P_2) will therefore be indicative of the fact that the direction of the absolute velocity has reached its critical value α_c. Conversely, in the safe condition, that is to say remote from the surging curve of the compressor, the difference $P_1 - P_2$ will be significant.

At the approach of surging the difference $P_3 - P_4$ will be significant whereas, conversely, the safe condition will be revealed by a small difference $P_3 - P_4$, which may even be zero.

In the period of operation of the compressor far from its surging curve, different directional pressures P_1 and P_2 and equal or very close radial pressure gradients P_3 and P_4 are observed.

The switches 27 and 37 are then in the position shown in full lines (Figures 2 and 7); the valve member 40 is in its closed position as shown in full lines in Figure 2.

When the surging curve is approached, equal or substantially equal values are observed for the directional pressures P_1 and P_2 and different values for the radial pressure gradients P_3 and P_4.

The switches 27 and 37 are then in the position shown in dotted lines in Figures 2 and 7; the valve member 40 is in its open position as shown in dotted lines in Figure 2. The opening of this valve brings the compressor back towards operating conditions remote from its surging curve.

It has been assumed in the above description that the regulator means are so arranged that, as soon as the risk of surging is detected, the said regulator means act on the conditions downstream or upstream of the compressor to make the risk of surging disappear.

In a modification which is not illustrated, the switches 27 and 37 can be an interruption of the operation of the compressor.

Provision has also been made, in the case where the directional pressure inlets P_1 or P_2 and/or the radial pressure gradient inlets P_3 or P_4 become accidentally blocked, for neutralisation of these pressure inlets; in a modification, not illustrated, it will be possible, after having detected the blocking of these pressure inlets, to provide for an audible and/or visible warning.

It will be appreciated that the probe and associated apparatus are particularly simple and can be envisaged with a low manufacturing cost.

Moreover, the presence of a probe as simple as that described and illustrated in the intake casing of a compressor does not, in practice, introduce any inconvenience in using it.

WHAT WE CLAIM IS:-

1. A method of avoiding surging in a centrifugal compressor comprising an impeller, the said method comprising the steps of detecting the direction of the absolute velocity of the fluid upstream of the impeller of the compressor, comparing this direction with a predetermined critical direction which depends on the characteristics of the compressor and beyond which critical direction there is a risk of surging, measuring the value of the radial gradient of the static pressure of the fluid upstream of the impeller of the compressor, comparing this value with a predetermined critical value beyond which critical radial pressure gradient there is a risk of surging and using the results of these comparisons to act on regulator means, to modify the flow conditions upstream or downstream of the compressor to prevent surging.

2. A method according to claim 1, wherein the detection of the direction of the absolute velocity of the fluid and the measurement of the radial gradient of the static pressure takes place at a distance from the impeller of the compressor which is between 0.05R and 0.5R, R designating the radius of the intake casing.

3. A centrifugal compressor comprising an impeller, a pressure probe and regulator means controlled by the probe and arranged to act on the flow conditions downstream or upstream of the compressor to prevent surging, the probe being disposed upstream of the impeller of the compressor and being arranged to detect the critical direction of the absolute velocity of the fluid and to detect the critical value of the radial gradient of the static pressure beyond which critical direction and critical value there is a risk of surging, the said probe being provided with directional pressure ports for monitoring the direction of the absolute velocity of the fluid, situated at the same distance from the wall of the fluid intake casing of the compressor and disposed symmetrically with respect to the critical direction of the absolute velocity of the fluid beyond which a risk of surging exists, and ports for monitoring the radial pressure gradient of the fluid, situated one nearer to the said wall and the other farther from the said wall.

4. A compressor according to claim 3, wherein each of the two radial pressure gradient ports is disposed at the angle formed by the axis of the compressor intake and the direction of the absolute velocity of the fluid at the distance of the respective port from the wall and with account being taken of the values of the tangential component and the axial component of the fluid velocity at this distance.

5. A compressor according to claim 3 or 4, wherein the probe is disposed upstream of the impeller at a distance of between 0.05R and 0.5R, R designating the radius of the intake casing.

6. A compressor according to claim 5 and including measurement means for comparing the values supplied by the two directional pressure ports and by the two radial pressure gradient ports.

7. A compressor according to claim 6, wherein the regulation means use the comparison between the pressures at the directional pressure ports and between the two radial pressure gradient ports in such a manner that when this comparison indicates a risk of surging the regulator means act on the conditions downstream or upstream of the compressor to make this risk of surging disappear.

8. A compressor according to claim 6 or 7, wherein the measurement means comprise two differential pressure pick-ups with strain gauges.

9. A method of preventing surging in a centrifugal compressor substantially as hereinbefore described with reference to the accompanying drawings.

10. A centrifugal compressor having apparatus for preventing surging, substantially as hereinbefore described with reference to the accompanying drawings.

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4 SHEETS *This drawing is a reproduction of the Original on a reduced scale*

Sheet 1

FIG.1.

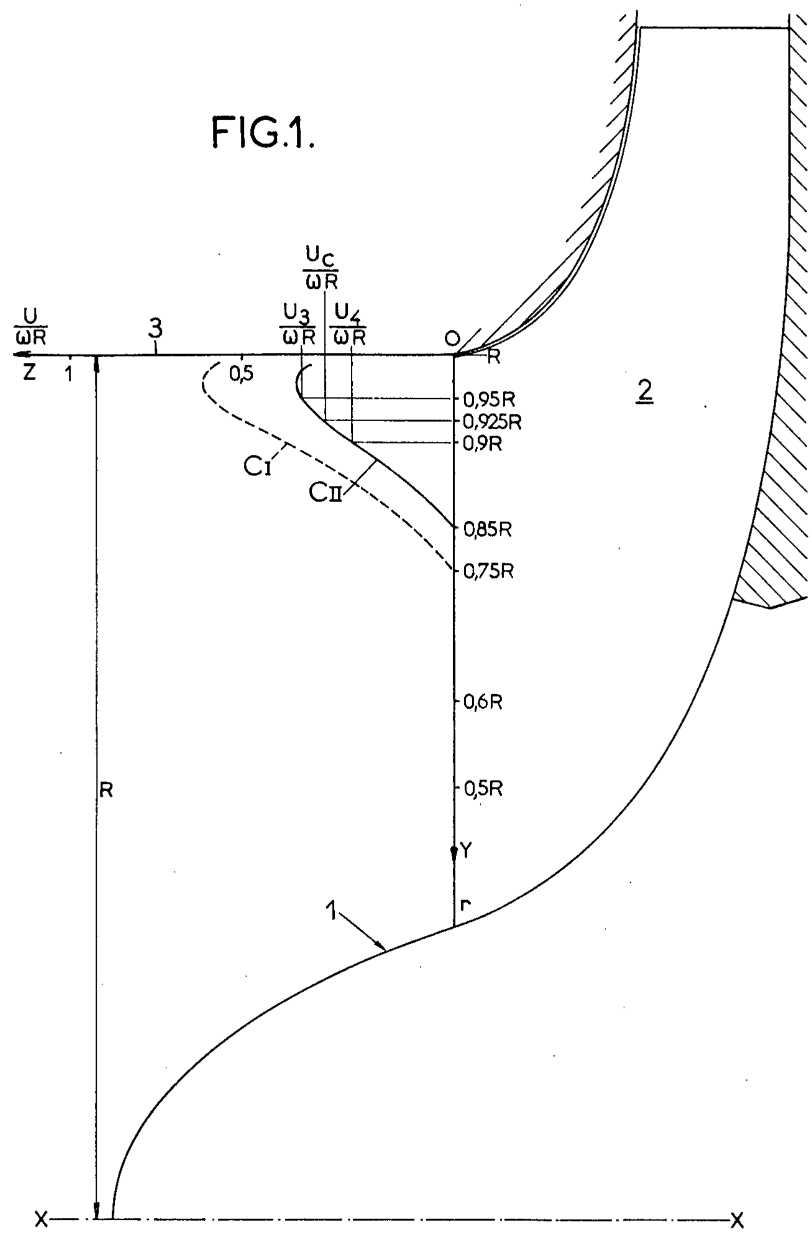


FIG. 2.

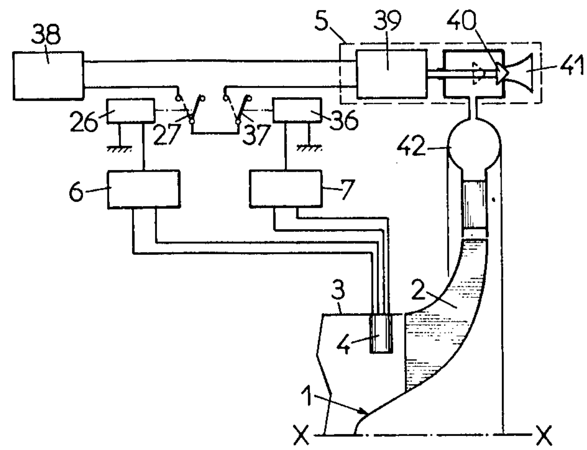
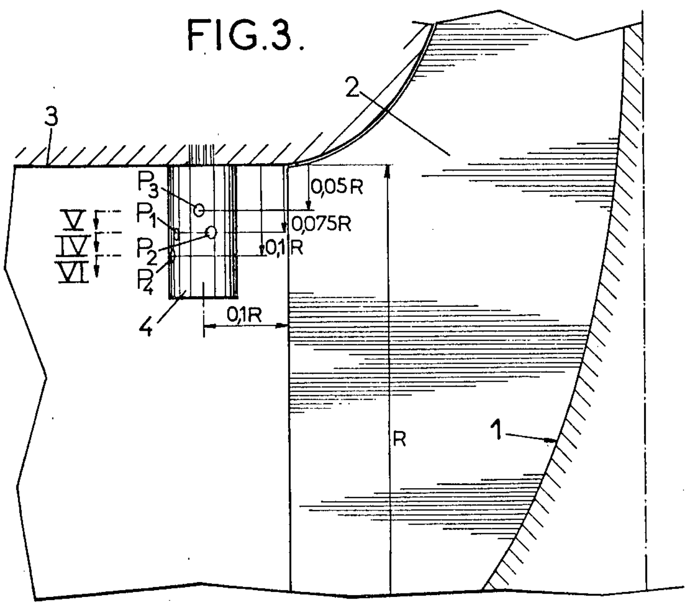

38
5
39
40
41
26
27
37
36
42
6
7
3
2
4
1
X
X

FIG. 3.


3
2
P3
P1
P2
P4
V
IV
VI
0,05R
0,075R
0,1R
4
0,1R
R
1

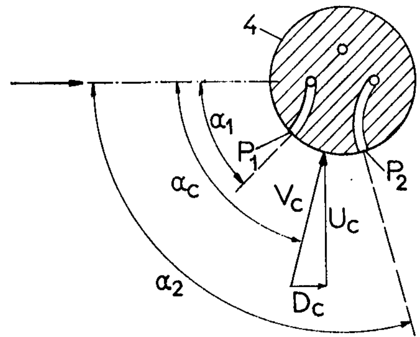


FIG.4.

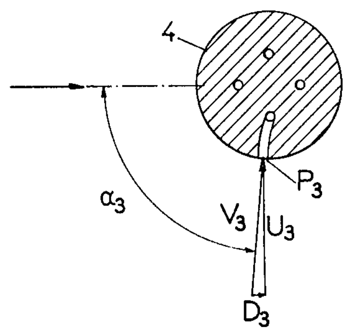


FIG.5.

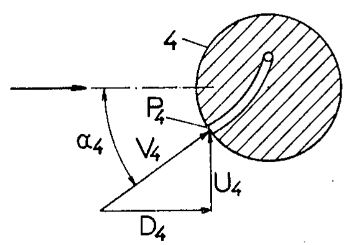


FIG.6.

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FIG.7.