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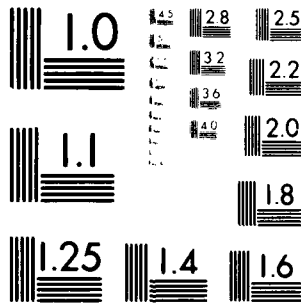
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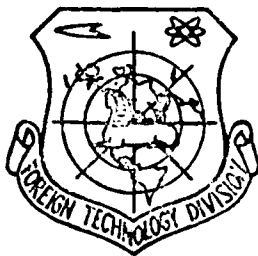


THREE DIMENSIONAL FLOW IN THE TURBINE

by

Liu Daozhi

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## EDITED TRANSLATION

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THREE DIMENSIONAL FLOW IN THE TURBINE

by Liu Daozhi

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In January of this year, this journal published the first part of this article and introduced the concept of three dimensional flow. The reader is referred to that article.

Why is the Theory of Three Dimensional Flow Needed?

Following the raising of flight speed, engine thrust continually increased and lighter weight was urgently required. For this, it was necessary to work hard to raise turbine rotational speed and gas flow speed. Therefore, there appeared the transonic and supersonic turbines. In the subsonic gas compressor, the supercharge of each level is low, the corresponding airflow passage contraction is slow and the inner and outer walls of the passage approach a cylindroid as shown on the left side of chart 7. In the supertransonic gas compressor, the supercharge of each level is high, the corresponding airflow passage contraction is fast and the inner and outer walls of the passage do not approach a cylindroid. However, it does possess a relatively large slope

and curvature as shown on the right side of chart 7.

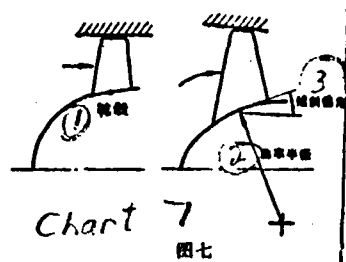


Chart 7

1. Hub
2. Curvature radius
3. Angle of inclination

To decrease flight resistance, it is hoped that the windward side area of the engine would be small. To increase engine thrust, it is further hoped that the airflow entering the engine would be great and because of this the diameters of the front few hubs in fans and gas compressors in modern jet engines (see chart 7) are made relatively small. The hubs of gas compressors are reduced and formed into long blades. The difference of the long blade tip and the tangential speed  $U$  of the blade root is especially large. When the blade tip  $U$  is high, the functioning power is strong and when the blade root  $U$  is low, the functioning power is weak. When the edge blade is high, the airflow increase in power size in each section is different. When the blade tip  $U$  is high, there is supersonic speed flow and impact wave loss is large. when the blade root  $U$  is low, there is still possibly

subsonic speed flow but there is no impact wave. When the edge blade is high, the flow efficiency in each place is different. In thermodynamics, commonly used entropy is used to show the efficiency and when the efficiency of the high edge blade is different, then the entropy of the high edge blade is different. Because of this, this type of flow is called the high edge blade changing power changing entropy flow.

When we use the simplest radial equilibrium theory to calculate the changes of flow velocity  $C$  high edge blade, the centrifugal inertia force  $C_u^2/r$  induced by the airflow tangential velocity component  $C_u$  was considered but the slope and curvature of the flow line were not considered. Therefore, it is only suitable in isopower and isentropic cylindrical flow. Its equation is simple, it can be calculated by hand, its use is convenient and when using it to design a low pressure ratio subsonic gas compressor excellent results were obtained. However, when using modern high pressure ratio supertransonic gas compressors and fans which belong to the changing power changing entropy non-cylindrical flow for calculations, it is not very precise.

The front edge of a low speed gas compressor blade is blunt. The incoming flow direction has a relatively large change and is able to smoothly wind around and flow passed the blade as shown on the left side of chart 8. To decrease impact wave loss, the

front edge of the high speed gas compressor blade must be made sharper. In this way, the adaptability of the incoming flow direction was lacking and the slight changes of the incoming flow direction can cause separation and vortex flow as shown on the right side of chart 8. The airflow angle and actual deviation measured by the simplest radial equilibrium theory are relatively large and its disposed blade and actual flow direction can be very different with the result that the flow deteriorates and often the design fails.

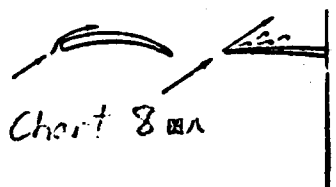


Chart 8

Aside from the calculations of the high edge blade, the conditions of the gas flowing around the blade surface is also very important. This then is the blading circumferential flow. Many methods have already been developed to calculate the blading circumferential flow and all have been successful. Because of the viscosity action existing between the gas and blade, accurate calculations tend to be complex. When comparing calculation

results and the actual flow, it is still difficult to reach satisfactory results. The good and bad of the blading circumferential flow still mainly depends on a large number of wind tunnel blower tests and the design of the blade form also mainly depends on experimental investigations. When compared with these experiments, present calculations still only hold a subsidiary position.

Because of this, we urgently need to develop a method which can calculate the flow field precisely.

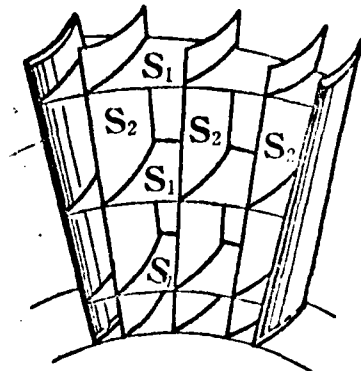
#### Two Flow Surface Theories

To attain a high performance turbine, it is not only necessary to calculate the distribution of the high edge blade airflow parameter, it is best to also calculate its edge cycle direction distribution. It is not only necessary to calculate the flow velocity of the blade's inlets and outlets but it is best to also be able to calculate the flow velocity in the inner part of the blade. This is also saying that it is necessary to calculate the three dimensional flow field in the entire space. This problem is quite difficult and for a long time many foreign scientists have been unable to solve it. However, at the time, the computer level was still very low, they were only able to make two dimensional flow calculations and they were far from

having any great capacity and speed to carry out three dimensional flow calculations. Under these conditions, comrade Wu Zhonghua, a Chinese engineering thermophysicist, studied assiduously and at the beginning of the 1950's he systematically derived a three dimensional basic formula for the turbine, creatively established two flow surface theories and introduced an effective computer method for the simple subsonic and simple supersonic relative flow.

Looking at chart 9, if we draw a circumference line in the cross span of the two blades and the gas flow flows passed this circumference line to form a flow surface in the back, it is called the  $S_1$  flow surface. Under simple conditions, we can assume that the  $S_1$  flow surface is a rotation surface and even a cone surface or cylindrical surface. Generally speaking, it is possibly a wing curve surface. A series of  $S_1$  flow surfaces can be drawn from the inside diameter to the outside diameter. If a curve line is drawn between the two blades, for example a radial line, the airflow that flows passed this radial line will also form a flow surface in the back and this is called the  $S_2$  flow surface. On the whole, the  $S_2$  flow surface is more or less the same as the blade shape. In between the two blades there can be drawn many  $S_2$  flow surfaces and generally speaking their forms are not the same. Under simple conditions, along the circumference

there can be obtained a representative  $S_2$  flow surface which acts as a representative for carrying out calculations.



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Chart 9

After the basic equation is differentiated and derived for each flow surface we can use a computer to find the solution. When computing, we can first estimate the gas flow parameter on the  $S_1$  flow surface and substitute it in an equation of the  $S_2$  flow surface. After results are obtained, we again substitute back the  $S_1$  flow surface curve. From this type of repeated investigation, we can gradually approach and attain an accurate solution of the three dimensional flow. The flow in space is originally three dimensional and the flow on a plane or curved surface is two dimensional. When decomposing all three dimensional space into two flow surfaces, each time it is only necessary to solve the

problem of two dimensions on one curved surface. This is a great breakthrough in mathematics and for the first time there is the possibility of seeking to realize the problem of three dimensions in a computer. This theory is a pioneer contribution for the turbine three dimensional theory. It has received international praise and China has gained fame. Since the 1950's, the Chinese Academy of Sciences has carried out work on calculating the  $S_1$  and  $S_2$  flow surfaces. Outside of China, following the raising of the level of computers, there was the continuation of the use of this method during the 1960's to make  $S_2$  flow surface calculations. After excellent results were obtained, during the last several years they again used it for calculations of a rotating  $S_1$  flow surface and each time the calculations of these two flow surfaces attained satisfactory test proof.

At present, comrade Wu Zhonghua is in the United States participating in the Fourth International Air Breathing Engine Conference and the International Gas Turbine Conference. In the conferences, comrades from the Chinese Academy of Sciences reported their newest achievements on the three dimensional flow theory including the use of curved line coordinates to calculate turbine flow fields and the application of the three dimensional flow function in the turbine.

## The Flow Line Curvature Method

During the 1950's and 1960's, the use of the flow line curvature method to calculate the airflow parameter of a high edge blade was expanded.

Chart 10 is a turbine longitudinal section chart cut from a turbine rotating axis line. On the high edge blade in the chart, there are drawn many flow lines and they are the projection made in the airflow space path rotating longitudinally along the circumference. At the same time, it is again necessary to draw radial or oblique lines on the different axial positions. They interweave and form a network in the longitudinal section and each intersecting point on the network is then a calculating point.

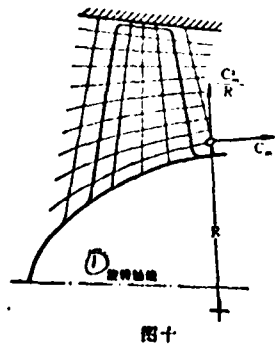


Chart 10

### 1. Rotating axis line

In the chart, the circled calculated point is an example. The projection of that point's flow velocity  $C$  on the circumference is the rotating component velocity  $C_u$  and the projection on the longitudinal section is  $C_m$ . The centrifugal inertia force related to the  $C_u$  is  $C_u^2/r$ . On the other hand, looking at it from the longitudinal section, at that point the flow line has a curvature radius of  $R$ , when the airflow makes a curved line motion there is a tendency to move towards the outside, the newly produced centrifugal inertia force is  $C_m^2/R$  and it influences the radial force equilibrium. Besides this, the influence of the flow line slope and the influence of the changing power changing entropy of the high edge blade should also be calculated so that the calculations are as precise as possible.

In order for the flow line to be even smoother and be able to conform to the actual conditions, a special sample line model was often used to simulate the slope and curvature of the flow line. When calculating, they can first estimate the shape of the flow line and based on these estimated flow line slopes and curvatures they can calculate the airflow parameters of each intersecting point in the network. Afterwards, based on the computations of that place's airflow parameter, the flow quantity in the small flow tube formed from the adjoining two flow lines is checked. If each place's flow quantity along the axis is different, then they should again change the flow line shape to change the coarseness

of the flow tube and carry out a second calculation. It is approached in this way until accuracy is attained. Only a few minutes time is needed in a computer when calculating a multilevel gas compressor.

This method and the  $S_2$  flow surface flow field matrix method both arise out of the same basic equation of the three dimensional flow, only the solutions are different. Therefore, the accuracy and time occupied using the computer are more or less the same. The flow line curvature method can be seen as the mean value of the airflow parameter used along the circumference. It does not calculate the flow in the blading along the circumference and the good and bad points of the blading flow usually depend on the blading wind tunnel blower test for solution. This type of method has been widely used in production and for the design of many high performance subsonic and supertransonic air compressors and fans and a great deal of experience has been gained.

The use of the flow line curvature method in each axial position to calculate the flow of the high edge blade is a two dimensional problem and the calculation of the flow around the blading is also a two dimensional problem. In recent years, they have already extended the flow line curvature method to three

dimensional space to form the so-called "orthogonal surface method" which can directly explain the three dimensional flow field.

#### Development of the Three Dimensional Flow Theory

Because the three dimensional flow theory has still not been perfected, in engineering they must to a very large degree rely on half experienced methods. At present, the shapes of the blade surfaces are not theoretically calculated but the blade types obtained from blading blower tests are disposed to the calculated flow fields of high edge blades. Although they are already very experienced in this type of system yet the level reached for the high pressure ratio supertransonic turbine is still limited and requires the wasting of a lot of time for repeated debugging. When designing, it was very difficult to clearly predict the consequences and it was very difficult to obtain initial success. To raise the performance of the turbine even faster, besides strengthening experimental research, it is very necessary to further strengthen theoretical foresight, gradually decrease the half experienced areas and decrease the blindness of tests and debugging. In order to do this, each nation must work hard to develop the three dimensional flow theory.

We know that in the advanced turbines there will not again be the simple subsonic flow nor the simple supersonic flow but they will most often have subsonic flow as well as supersonic flow and moreover they will also carry impact wave transonic flow. Former calculation methods were unable to calculate the position and shape of impact waves and thus had no means of explaining the flow chart of the turbine. In recent years, there has arisen the time elapse method to introduce time as an independent variable. As time went by, step by step they calculated the flow changes, calculated the gradual formation of impact waves and for the first time explained the transonic impact wave carrying flow field. Because it added an independent variable the calculating time was too long. Later, there was further developed a theory called the transonic relaxation method. It can calculate the position and shape of an impact wave and it has already become a useful tool for calculating transonic impact wave flow. Because of the emergence of a new generation of large capacity high speed computers, recently outside of China they have already successfully utilized the three dimensional transonic relaxation method and the three dimensional time lapse method to directly solve the three dimensional equation so that it is not again necessary to change the two dimensional flow problem to seek solutions.

High pressure ratio supertransonic fans and air compressors are totally sensitive to the heterogeneity (distortion) of admission flow fields and can create gas flow and blade surface separation and then proceed to surge.

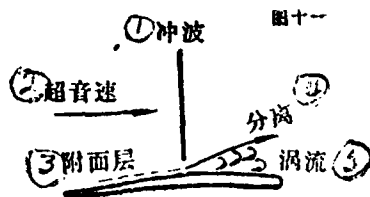


Chart 11

1. Impact wave admission
2. Supersonic speed
3. Boundary layer
4. Separation
5. Vortex

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