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On the Concept of the Wave Compressor and Optimal Shock-Wave Structures

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Abstract

Objectives: This paper considers the concept of shock wave compressor in which the compression occurs not in the impeller machine, but in the optimal system of triple shock waves configurations. **Methods/Analysis:** A review of the works being conducted in the world in this field is provided. The basics of the gas-dynamic discontinuities interference theory are given; the development sequence of the theory of optimal (extreme) shock-wave structures is shown. **Findings:** The task of designing a new gas compression device - the shock-wave compressor is considered. Differences from other similar devices are discussed. The model air intake tract for the wave compressor is designed. The calculations of the model wave machine are provided. Comparison with multistage axial compressor shows that starting with a compression ratio of 25, the degree of full throating pressure restoration, provided by a shock wave compressor is not smaller than that of an impeller machine. Although, the size and weight of the shock wave compressor is much lower. **Novelty/Improvement:** Relevant is the task of reducing the size and decreasing the number of stages in the high-pressure compressors of refrigerators and other turbomachinery. Our results allow us to offer the concept of the compressor in which the number of stages is significantly reduced through the use of a gas compression in optimal shock-wave structures. The potential advantage in comparison to the traditional axial compressors is demonstrated.

Keywords: A Triple Configuration of Shock Waves, Axial Compressor, Centrifugal Compressor, Shock Wave, Shock Wave Structure, Wave Compressor

1. Introduction

In a number of tasks related to cryogenic and refrigeration equipment, it is required to achieve a high degree of static pressure increase from 25 to 250. With the traditional approach to the turbomachinery design this inevitably leads to an increase in the compressor diameter and the number of stages. This reduces the efficiency of the compression due to the appearance of local supersonic flow areas at the periphery of the paddle row. The losses, associated with the flow of gas over the axial compressor stages grow as well.

As an alternative to traditional solutions it is offered to use a fundamentally new device - a shock-wave (wave) compressor (SWC) instead of several axial and centrifugal stages. In this device the compression occurs in the optimal system of running shock waves. Comparison of dimensions is shown in Figure 1[1].

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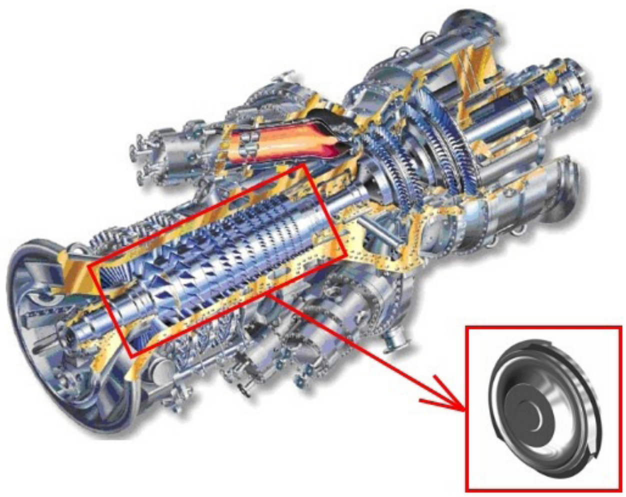

Figure 1. Replacing 11 stages of an axial compressor with the wave compressor.

It is clear that the SWC can't be the only air compressing device. As ramjet engine cannot operate at zero speed so the wave compressor requires prior acceleration and compression of air. The design of the wave compressor is based on the developed theory of optimal running oblique shock waves.

At the moment (in the last 19 years) the theory and mathematical body was created, which is adequate for the design of optimal Shock-Wave Structures (SWS). The scientific team led by V. N. Uskov consistently developed the theory of extreme SWS. First, the theory of stationary gasdynamic discontinuities interference[2] was generalized by[3] for the cases of second order discontinuities. They investigated the dependence of the flow non-uniformities behind the discontinuity on the discontinuity curvature and non-uniformity of the flow in front of it. Then the theory has been extended in the works of[5] and with the theory of one-dimensional traveling wave's interference and the interaction of oblique non-stationary waves[5]. In the same time, V. N. Uskov's graduate student Tao Gan developed the theory of optimal triple configurations of shock waves, first in uniform flow[6], and then in the non-uniform one[7]. And finally in the works of[8,9] it was generalized for the case of triple configurations of shock waves in non-stationary and non-uniform gas flow. Author in[10,11] developed the theory of SWS low-frequency oscillations for the flow in a channel with a sudden expansion.

2. Comparison of Shock-Wave Machines with Other Solutions

2.1 Machines with Combined Cycle

In recent years, therotary machines with a combined thermodynamic cycle were actively discussed[12]. Relevant stays the tasks of downsizing, primarily of the frontal section of aircraft auxiliary power units, turbo-refrigerating machines, compressors for power devices of aerospace application. For such systems, the esurience of high efficiency under tight dimensional constraints seems difficult to achieve. Aircraft power plants designers are looking for the solution by creating the combined systems[13], consisting of a gas turbine engine and some additional machine: A fuel unit, the Wankel engine, electro-chemical generators, etc. Similar trends exist in the field of terrestrial energy, industry of technical gases, CO_2 gas separation systems, cryogenic systems production.

Application of the volume machines, operating on the same shaft with the turbine increases the overall efficiency of the plant due to more complete utilization of internal energy, provided by the expanding mixture of air and combustion products.

It is considered promising to use the Miller cycle in a rotary machine. Miller cycle was proposed in 1947 by American engineer Ralph Miller as a way of combining the advantages of Atkinson engine with easier piston mechanism of Otto engine. The essence of the improvements is to make the compression stroke shorter than the working stroke. This principle is implemented in the Atkinson engine, wherein the piston moves upward faster than downward. Miller devised to reduce the compression stroke by the intake stroke, while maintaining the piston up and down movement at the same speed as in the classic Otto engine.

Existing schemes of combined engine are designs on the several shafts, and as a consequence, are quite large. Thus arises the desire to develop Miller's idea and to further reduce the compression cycle[14].

Ideal object that allows to compress gas, is a shock wave, which length is approximately of several lengths of the gas molecules free path[15].

2.2 Wave Machines

The proposed scheme of the wave compressor is a rotor with a network of special profile canals resembling the profile of a supersonic inlet, "rounded" on the cylinder. In these canals, as the rotor accelerates to the supersonic circumferential speeds, a system of shocks will occur, compressing the gas.

Using wave compressor instead of multistage axial one allows assembling the entire structure on the same shaft, thus significantly reducing the engine size. In the particular case a canal may be shaped so that the deceleration would occur in simple compression waves without loss of total pressure. There are known similar design wave compressor developments by Ramgen Power Systems. The company aims to create a system of capture, compression and storage of CO2, for which purpose, since 1998, has received more than 22 million dollars from private foundations and 30 million dollars from government contracts with the USA Department of Energy and the Ministry of Defense. Usage of the wave compressor replacing conventional 7-staged axial compressor will greatly reduce the dimensions of the unit, although a workable design yet failed to be created. Ramgen Power Systems Company conducts promising researches in the development of hybrid rotary machine (Figure 2.), which combines the wave compressor and pulsating jet engine operating by Humphrey thermodynamic cycle.

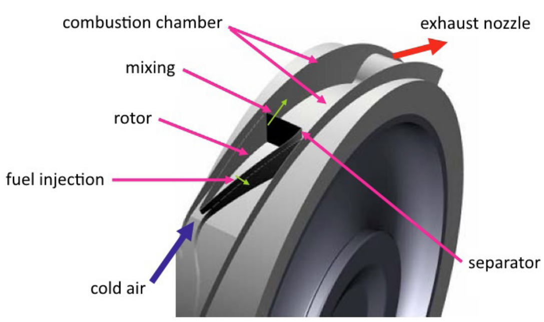

Figure 2. Example of the rotor wave machine design by Ramgen power systems company.

Ideas of SWS are ideologically close to the concept of wave pressure exchanger that was used to pressurize the air into the internal combustion engines. The idea of using the principle of wave rotor was first suggested in 1942 by Claude Seyppel of Brown Boveri Company (BBC), Switzerland. The wave pressure exchanger was used on Ferrari 126C in 1982, diesel Opel Senator in 1985 and Mazda 626 in 1988. The principal idea of the wave exchanger is the following. The basis of the design is a cylindrical cellular rotor, which have numerous of through, longitudinal channels. Air is supplied through the one of its ends and the exhaust gases from the other. The rotor is rotated by a drive of the crankshaft. Its ends are covered by valves, which have specially disposed bypass holes. The compression process is as follows. Air from one end fills the rotor's canals, the rotor rotates; form the other end the exhaust gases are supplied into the same canals. This pressure thus compresses the fresh air. Next, the rotor rotates again, and the compressed air charge passes into the intake manifold. One of the main advantages of the wave supercharger is the absence of "turbo lag" effect and the fact that the operating range is not limited to high rotation speed.

There are several advantages of SWS over wave pressure exchanger. In the system of shock waves reached a much higher compression ratio can be achieved, and the shock waves themselves have negligible length (thickness), which reduces the size of the compressor. The construction of SWS by itself is significantly simpler and more reliable than of the wave pressure exchanger.

The American government agency on promising projects in the field of energy saving Advanced Research Projects Agency Energy (ARPA-E) has issued a grant of $ 2.5 million to researchers at Michigan State University to create a rotary wave internal combustion engine. In its design, in contrast to the wave pressure exchanger, a flat "pancake" with a radial paddles is used instead of a barrel, but, more importantly, the device is intended to be used not for supercharging, but also for the combustion of the combustible mixture. This development, in fact, is some sort of hybrid of impulse-detonation engine, the Wankel engine and wave pressure exchanger. Compared with the SWS in this case there is an obvious fundamental flaw design - compression occurs in a single forward shock wave, i.e., total pressure loss are maximized and high efficiency cannot be expected.

3. Results and Analysis

Axial compressors at a compression ratio of 10 to 20 provide a restoration coefficient of the total pressure at the level of 0.85. A centrifugal compressor having the same efficiency provides a compression ratio at 2-2.5.

At the same time, supersonic multishock external compression air intake, at oncoming stream Mach number of 2.7, allows getting the compression ratio at the level of 20-22 at a total pressure loss of not more than 5%.

Numerical simulation of three-dimensional formulation has shown (Figure 3) that in the case of considered design the solution of[16] for planar configurations of shocks is indeed not fullfilled.

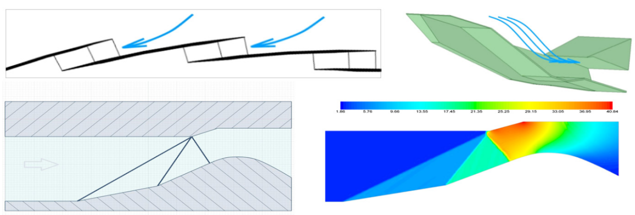

Figure 3. Canals of shock wave compressor.

In addition, the configuration of shock waves themselves may be non-stationary, and it is not associated with the phenomenon of surging. To calculate the internal channels of SWS it is necessary to apply the theory of non-stationary optimal shock-wave configurations, developed under the guidance of V. N. Uskov. As a result of SWS configuration's calculation, shown in Figure 3, the coefficient of the total pressure restoration will turn out to be at 0.85, corresponding to the level of modern compressor unit. On the scheme, presented in the work of[1] and shown in Figure 4, there is a point (circle) plotted, corresponding to the results of calculation. Positions of the points indicate that the designed geometry of the sunken air intake can be used to produce high-performance wave compressor. As seen from the scheme, such a compressor would have smaller total pressure loss than the axial compressors operating in the same ranges. On the scheme there is also the point plotted, which corresponds to centrifugal retaining stage (rhombus), developed for the wave compressor.

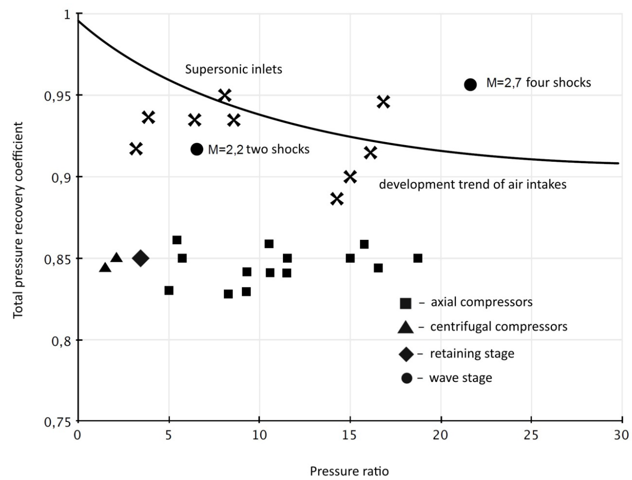

Figure 4. Comparison of different compressors according to their compression ratios and the total pressure loss.

4. Conclusion

The task of designing a new gas compression device - the shock-wave compressor is considered. Differences from other similar devices are discussed. The problem of building an optimal shock-wave structure is considered. The calculation results of the shock waves triple configurations' area of existence and centered compression waves are provided. The model air intake tract for the wave compressor is designed. The potential advantage in comparison to the traditional axial compressors is demonstrated.

Thus, the following conclusions can be made.

- Wave compressors can be designed as two- three-staged, designed for a range of Mach numbers M = 2,23-4,83 (air);
- Achievable compression ratio of single stage is 10-20.
- Wave compressor cannot be the only compression device, a retaining stage is required.

5. Acknowledgments

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