A Miniature Turbocompressor System

C. Zwyssig[1], D. Krähenbühl[1], H. Weser[2] and J. W. Kolar[1]

[1]Power Electronic Systems Laboratory, ETH Zurich, Switzerland
[2]High Speed Turbomaschinen GmbH, Wolfsburg, Germany

Abstract: The trend in compressors for fuel cells, heat pumps, aerospace and automotive air pressurization, heating, ventilation and air conditioning systems, is towards ultra-compact size and high efficiency. This can be achieved by increasing the rotational speed and employing new electrical drive system technology and materials. This paper presents a miniature, electrically driven turbocompressor system running at a speed of 500 000 rpm. The design includes the thermodynamics, the electric motor, the inverter, the control and the system integration with rotor dynamics and thermal considerations. In the experimental setup, the specified pressure ration of 1.6 is achieved at a speed of 550 000 rpm, which is slightly higher than the design speed.

1. Introduction

In future cars and airplanes more and more hydraulic, pneumatic and mechanical systems, also compressors, will be replaced with electrically driven systems: this leads to more-electric aircrafts and vehicles. Examples are the compressors for heating, ventilation and air conditioning (HVAC) or air pressurization for aircraft cabins. The power levels of these compressors are from about 100 watts up to a few kilowatts. Additionally, several car manufacturers have research projects or even prototypes on fuel cell propulsion systems. Also in trucks and aircrafts, fuel cells are planned to be used as auxiliary power units. These fuel cells usually need an air compressor, which consumes around 10-20% of the output power of the fuel cell, and the pressure levels are usually between 1.5 and 2.5 bar [1]. The air compressor should be small, lightweight and efficient. Another application of compressors are heat pumps. Also there, the trend is to more compact and systems with a higher efficiency. Furthermore, distributed systems could be realized with smaller compressors.

All of these applications need ultra-compact, high-efficient, electrically driven compressor systems, where the preferred type is the directly driven turbocompressor. Power density in both turbomachinery and electrical machines increases with increasing rotational speed [2], [3]. Therefore, these systems can have a rotational speed between 100 000 rpm and 1 Mrpm at power levels of up to several kilowatts.

In this paper, a miniature turbocompressor system with a rotational speed of 500 000 rpm for a calculated pressure ratio of 1.6 and a mass flow of 2 g/s at standard conditions for temperature and pressure is presented. It is built as a first prototype for the cabin air pressurization system for the Solar Impulse airplane [4], but the technology developed during the project will be used in all the other applications. The system is

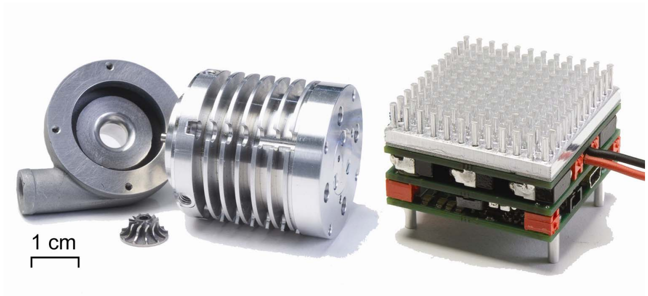

Fig. 1. Miniature turbocompressor hardware: inlet, impeller, electrical drive system including stator and rotor, and electronics including control system.

shown in Fig. 1 and it comprises of a radial impeller, a permanent-magnet (PM) motor and the power and control electronics. The paper starts with the main scaling laws and then describes the different parts as well as the system integration. Finally, measurement results are presented.

2. Scaling Laws

There are two reasons for downscaling turbomachinery. Firstly, in high power applications the power density can be increased with modularization and secondly, new emerging applications demand compressors with lower mass flow at constant pressure ratios.

2.1. Power density increase with modularization

In [2] is shown that the power density (P/V) of turbomachinery is inversely proportional to the rotor diameter D of the turbomachinery:

$$\frac{P}{V} \sim \frac{1}{D}. \qquad (1)$$

This implies that a conventional turbomachine with a certain output power can get replaced with a number of smaller units which have all together the same total output power but a smaller overall volume. This scaling implies constant surface speed, which means, that the rotational speed scales inversely proportional with the diameter *D*, shown in (4). However, this is not fully accurate, as a mayor condition for scaling of turbomachinery is a constant Reynolds number, which is also proportional to the dimension of the flow channel and the height of the air flow channel d_h, shown in (2). This dimension also decreases with miniaturisation, and therefore the proportional scaling of speed with *1/D* is an approximation.

$$\mathrm{Re} = \frac{c d_h}{\nu} . \tag{2}$$

As an example, one large turbocompressor can be replaced with 16 compressors, each with a volume of 1/64 of the conventional compressor, which together have the same output power but need just a quarter of the volume of the conventional compressor (Fig. 2). The diameter of the small units would be ¼ of the original one and the rotational speed would therefore increase by a factor of at least 4.

2.2. Downscaling of mass flow

The requirements for turbocompressor, like the Solar Impulse cabin air pressurization system, but also the other mentioned applications such as heat pumps and fuel cell compressors, demand low flow rates (e.g. 1 g/s to 20 g/s) at high pressure ratios (e.g. 1.3 to 3). The characteristic parameters volume flow $\dot{V}$, specific pressure head *Y* and rotational speed *n* can be compiled in the similarity parameter specific speed σ

$$\sigma = \frac{n \cdot \sqrt{\dot{V}}}{\left(2 \cdot Y\right)^{3/4}} \cdot 2 \cdot \sqrt{\pi} . \tag{3}$$

Downscaling of a macro turbomachine for constant specific speed and lower volume flow therefore leads to an increase in rotational speed.

2.3. Electrical machine and power electronics

The power density in electrical machines scales with speed (4),

$$\frac{P}{V} \sim n . \tag{4}$$

Therefore, the overall volume of the electrical machines in the example is also ¼ of the original one.
In contrast to electrical machines, the size of the power electronics mainly scales with power rating and is minimized by choosing the correct topology through efficiency improvements and the use of high switching frequencies. For systems with high power ratings, the size of the control electronics is negligible compared to the power electronics. However, for ultra-high-speed machines with low power ratings (e.g. 100 W), the control electronics size becomes significant. Generally, the size of the control electronics scales with the complexity of the control method selected and the complexity depends on the topology and the modulation schemes used.

3. Electrical Machine and Electronics

The rotor of the PM motor consists of a diametrically magnetized cylindrical Sm_2Co_{17} permanent magnet encased in a retaining titanium sleeve. The stator magnetic field rotates with high frequency (8.3 kHz), it is therefore necessary to minimize the losses in the stator core by using amorphous iron, and the eddy-current losses in the air-gap winding by using litz-wire (Fig. 3). The machine efficiency at rated power is 87% including air friction and ball bearing losses. A detailed description of the machine has been presented in [5]. The bi-directional power electronics consists of an active 3-phase inverter and an additional buck converter, and a DSP-based control system. The block diagram is depicted in Fig. 4 and the topology has been analyzed in [6]. The power electronics have an efficiency of 95 % at rated power. All data is summarized in Table I.

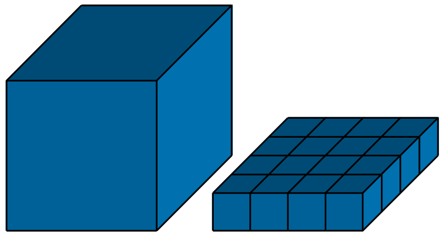

Fig. 2 Scaling of turbomachinery: 1 large system can be replaced with 16 higher speed system with only ¼ of the original volume.

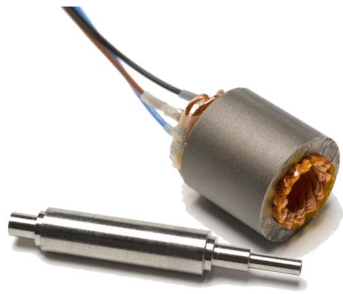

Fig. 3 150 W, 500 000 rpm machine: rotor with permanent magnet encased in titanium sleeve, stator with amorphous iron core and litz-wire air-gap winding.

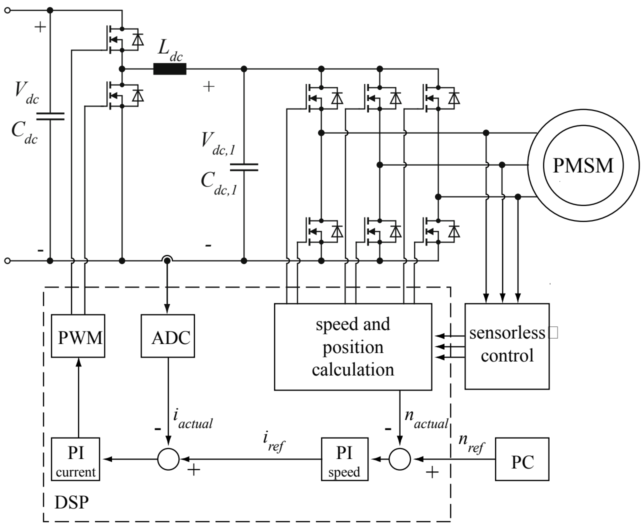

Fig. 4 Power electronics and control system for driving an ultra-high-speed permanent-magnet machine.

Table I

electrical data	
rated speed	500 000 rpm
rated electric power	150 W
machine efficiency	87 %
power electronics efficiency	95 %
dimensions power electronics (b *x* l *x* h)	45 *x* 45 *x* 30 mm

4. TURBOMACHINERY

A single-stage, radial compressor was chosen, because this type of compressors can generate high pressure ratios with a single stage. The biggest challenge is the manufacturing of the impeller and the fitting between the different pieces, especially impeller and casing. This is because the manufacturing tolerances cannot be decreased proportional with the scaling and therefore the leakage losses become more dominant for small compressors. This means that the chosen tip clearance (0.1 mm) is rather high. The impeller consists of 12 blades (no splitter blades) and has a mean streamline diameter at the inlet of 5.28 mm, while the outlet diameter is 10.5 mm. After the flow leaves the compressor, it enters the vane less diffuser and then gets collected in a volute and thereby guided into the exit flange. The compressor is directly mounted to the motor rotor shaft shown in Fig. 1. The design is for a pressure ration of 1.6 and a mass flow of 2 g/s, which is calculated to be achieved at a rotational speed of 500 000 rpm, and a power consumption depending on the mass flow and the inlet temperature of the air. The compressor data is compiled in Table II.

Table II

turbomachinery data	
rated speed	500 000 rpm
pressure ratio	1.6
mass flow	2 g/s
compressor efficiency	72 %
turbocompressor length	53 mm
turbocompressor diameter	33 mm

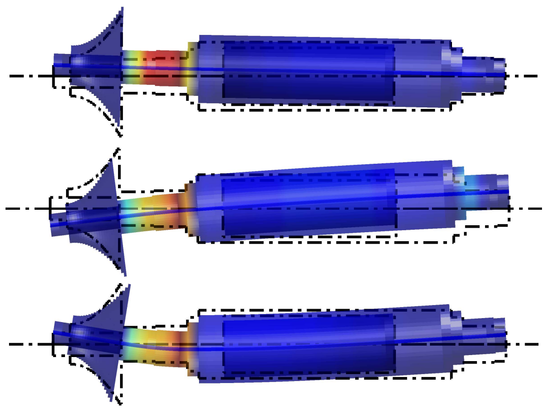

Fig. 5 Bending modes of the miniature turbocompressor rotor. First (2.94 kHz, 176 krpm), second (4.59 kHz, 275 krpm), and third bending mode (14.3 kHz, 858 krpm). The color shows the bending and therefore indicates the area of highest mechanical stresses.

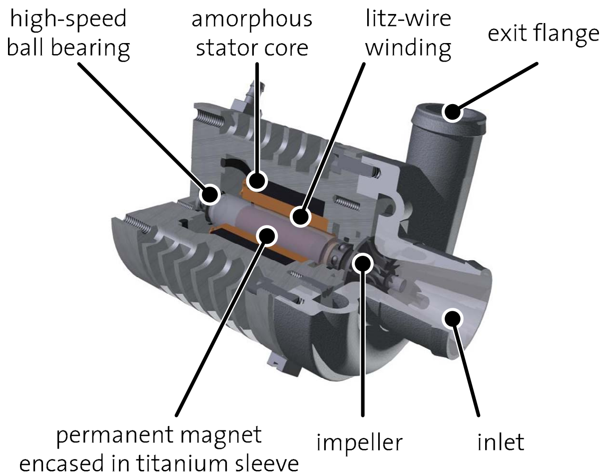

Fig. 6 Cross section view of the integrated turbocompressor system.

5. SYSTEM INTEGRATION

Beside the design of the individual components, an analysis of the mechanical stresses and rotor dynamics, and a thermal design is needed. The bending modes of the rotor are depicted in Fig. 5. The length of the shaft is adjusted such that rated speed falls between the second and the third bending modes. A cooling sleeve guarantees safe operation under laboratory conditions (ambient temperature 20 °C), the most critical spot is the ball bearings which produce high losses and have a maximal allowed temperature of 200 °C. On cross-section view of the integrated system can be found in Fig. 6.

6. MEASUREMENTS

An experimental test bench is built in order to verify theoretical considerations and the feasibility of such ultra-compact ultra-high-speed turbocompressor systems. Therefore, a valve is connected to the compressor outlet, in order to art as a variable load. Between the compressor output and the valve a pressure sensor and a thermocouple is placed. Also at the compressor inlet a pressure sensor, a thermocouple and a mass flow sensor are used. Additionally two thermocouples are used to monitor the electronic and motor winding temperature. Due to the fact that the motor is of synchronous type, the speed has not to be measured separately.

First, the motor has been tested without load up to a speed of 550 000 rpm and the total rated losses in the stator core (0.5 W), the copper losses in the winding (5 W), air friction losses (6 W) and the ball bearing friction losses were measured (8 W).

In a second step, the impeller and inlet housing are mounted and the compressor map depicting the pressure ration versus mass flow for different rotational speeds is measured. In Fig. 7 it can be seen that the specified pressure ratio of 1.6 is achieved, but with a 10% higher rotational speed as designed. One main factor for this difference is the mechanical tolerances in the manufacturing which are not sufficiently small yet, which results in leakage air flow. Due to the same reasons, the measured efficiency (63%) is slightly lower than calculated. In Fig. 8 the electric power consumption of the turbocompressor system is shown. The mass flow at 550 000 rpm is only limited to 1.75 g/s by the electric power input limitation.

7. CONCLUSION

This paper presents the design of a miniature, electrically driven turbocompressor for various applications in area of renewable energy and heating, ventilation and air conditioning systems. The manufacturing of such miniaturized compressors represents difficulties due to smallest contours and desirably small tolerances. However, measurements show that despite this difficulties the system has a performance close to the specified design operating point, and turbocompressors with speeds up to 500 000 rpm are feasible.

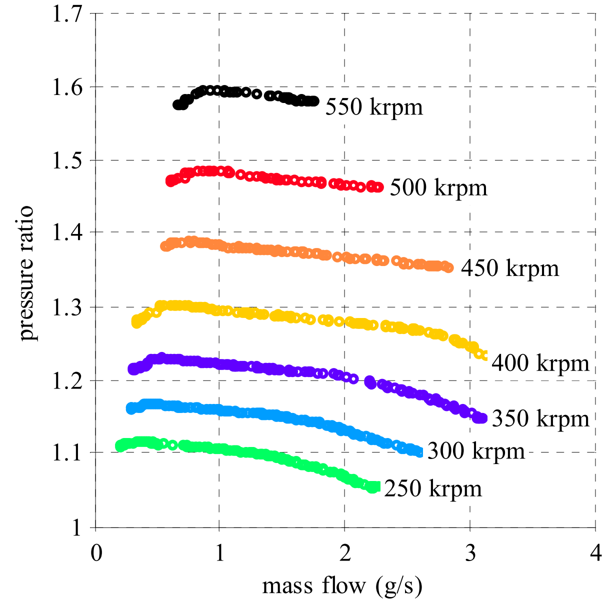

Fig. 7 Measured compressor map (pressure ratio versus mass flow for different rotational speeds) of the miniature turbocompressor.

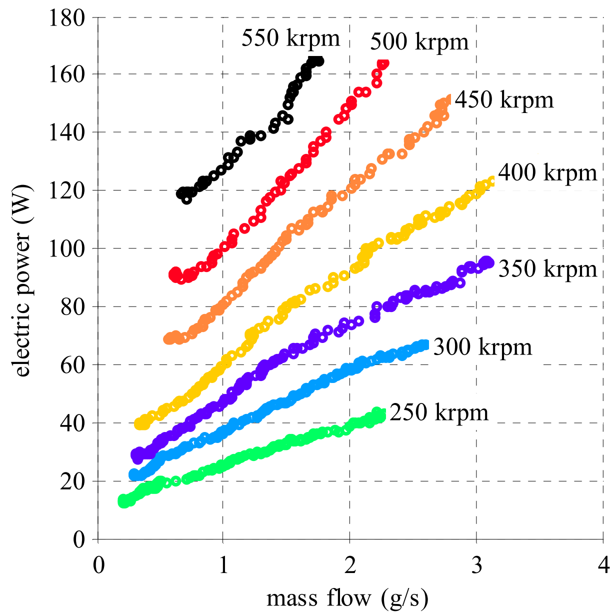

Fig. 8 Measured electric power consumed by the high speed electric drive system of the miniature turbocompressor.

This first prototype fulfils the specification regarding the mass flow and the rotational speed, but it does not yet achieve the necessary pressure ratio. One next step in the project include a two stage version of the compressor for an increase in pressure ratio. This is necessary because the maximum flying altitude will be around 12000 m, and therefore a compressor ratio of approximately 3.6 is needed. Furthermore, magnetic and gas bearings are under investigation in order to realize an oil-free compressor system.

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