1. INTRODUCTION

Pneumatically activated Stirling-like cryocoolers and all types of the Pulse Tube Refrigerators (PTR) are driven by a pure pressure oscillator, which is sometimes referred to as a valve-less compressor. Concerning a PTR, the pressure oscillator is a critical component, since it is the only mechanically active part subject to wear and failure, and therefore, the lifetime of the cryocooler depends mostly on the compressor reliability. Additionally, occasional contamination of the working gas originates generally from the compressor, which may be a source of wear products, outgassing, lubricant vapour, etc. In an effort to improve the efficiency and reliability, as well as to eliminate the electromagnetic emissions, it was proposed to replace the driving mechanism of the conventional linear compressor by a device activated by a piezoelectric stack-type element (PZT actuator), which is frictionless, has a high volumetric power density and extremely long lifetime. To minimize the electrical power required to elongate exclusively the PZT stack, which is extremely stiff due to its ceramic nature, it was proposed to replace the driving mechanism of the conventional linear compressor, which may be a source of wear products, outgassing, lubricant vapour, etc. Additionally, occasional contamination of the working gas originates generally from the compressor, which is the only mechanically active part subject to wear and failure, and for which the lifetime of the cryocooler depends mostly on the compressor reliability. To do this, the proposed compressor is driven by the piezoelectric actuator to as a valve-less compressor. Concerning a PTR, the pressure oscillator is a critical component, since it is the only mechanically active part subject to wear and failure, and for which the lifetime of the cryocooler depends mostly on the compressor reliability. To make the piezo compressor competitive with the conventional one in terms of size and weight, it was critical to force the driving system to operate at mechanical resonance, thus minimizing the electrical power required to elongate exclusively the PZT stack, which is very stiff due to its ceramic nature.

Optimization of the actual compressor concentrated on its ability to drive a miniature Pulse Tube cryocooler, particularly our MTSa model operating at 103 Hz, as well as our future models, which should have similar dimensions, but operate at higher frequencies. The currently available MTSa Pulse Tube requires 11 W average PV power, 40 Bar filling pressure and a pressure ratio of 1.3 to produce a net cooling of 0.4 W at 110 K.

2. THEORY

Detailed three-degrees-of-freedom spring-mass-damper model:

\[ 2 \dot{\theta} + (1 + 1) \dot{\theta} + \theta = \frac{\Delta P}{\mu} \]

where:

\[ \mu = \text{amplification ratio} = \frac{A_1}{A_2} \]

\[ l_2 = \text{PZT stiffness} \]

\[ l_3 = \text{cryocooler gas stiffness} \]

Natural frequency of the idealized one-degree-of-freedom model:

\[ f_1 = \frac{1}{2 \pi} \sqrt{\frac{\Delta P}{k_1}} \]

3. DESIGN

Strain gauge wires

Gas filling valve

PZT: high voltage hard PZT multilayer actuator P-016-40F: 58 x 36.6 mm, of PI company. A, = 94 N/mm, C, = 510 N/F, N = 5.5 N/A, \( F_p \) up to 5500 N and quasi-static elongation up to 60 μm.

A1: stroke to diameter ratio about 1:1000, pressure amplitude up to 40 bar, implemented as a gas-sealed piston-cylinder assembly. The fluid separation occurs on the opposite side of the piston, outside the PZT housing, by using a compliant diaphragm.

A2: stroke to diameter ratio about 1:10, pressure amplitude up to 6 bar. Implemented as a composite structure, consisting of a stack of the spring steel semi-flexural disks with spiral-like cuts filled and coated with soft silicone rubber.

4. RESULTS

MISCELANEOUS

MTS Pulse Tube characteristics estimated at 012 mm piston boundary using SAGE™ with piston amplitude retained at 0.5 mm and hot heat exchangers kept at 300 K:

Measured and calculated mean input powers:

Calculated electromechanical conversion factor vs. structural stiffness:

5. SUMMARY AND CONCLUSIONS

1. A PZT driven compressor for Stirling-type pneumatic cryocoolers operating in mechanical resonance was modelled, optimized, designed, constructed and tested in this research work.

2. An experiment showed that under an actual load applied to the compressor the PZT stack amplitude increased at 110 Hz by 62% relative to the quasi-static operation, and thus proved the concept of the low frequency PZT resonance, which is the main point of the proposed compressor.

3. Despite some mismatching between the impedances, the compressor demonstrated the feasibility to drive our miniature Pulse Tube cryocooler MTSa, operating at 103 Hz. A cryocooler similar to MTSa optimized for operation at a frequency about 115 Hz should fit perfectly to our produced compressor.

4. A satisfactory agreement was obtained between the model simulations and experiments on the actual compressor, with the experimental results somewhat lower relative to the simulations. This can be explained by the secondary losses and non-linear effects that were not considered in the model.

5. Insufficient structural stiffness obtained within the actual assembly relative to the ideal CAD model (1.5a, relative to 5a) decreased drastically the initially expected electromechanical conversion factor. According to the model, the compressor efficiency can be increased, on account of the reactive power, by 55% when the present structural stiffness is doubled, and by 81% when increasing the stiffness four times.