PERFORMANCE INDICATORS OF LINEAR ALTERNATORS AT DIFFERENT ELECTRIC LOADS UNDER THERMO-ACOUSTIC-POWER-CONVERSION CONDITIONS

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Moving-magnet linear alternators are integral parts of thermoacoustic power converters. The acoustic energy generated by a thermoacoustic engine causes the linear alternator's piston, which carries a permanent magnet, to oscillate inside a set of copper coils and thus to deliver electric power to an electric load. Efficient operation of the system made of the thermoacoustic engine, linear alternator and electric load requires the satisfaction of many matching conditions including the generation of the rated electric power at the rated mechanical stroke and requires measures to maximum the power transfer from the linear alternator to the electric load. To further understand and quantify the factors involved, this work experimentally investigates the dependence of the generated voltage, current and electric power on the piston's oscillatory motion as indicated by the mechanical stroke, for a range of two different types of electric loads: a range of linear (resistive) loads, and a range of non-linear constant-voltage DC electronic loads. The results are carried-out under operating conditions that are close to the typical conditions employed in thermoacoustic operation, including different helium/argon concentrations, different mean gas pressures and different input dynamic pressure ratios. The results reveal how different electric loads affect the relationship between the generated current, voltage and electric power versus the mechanical stroke. Additionally, the conditions under which the generated voltage is linear with the mechanical stroke are identified. The results can be used to optimize the operating conditions in order to achieve the different requirements needed for maximum power generation.

Keywords: Thermoacoustic power converters, linear alternator, mechanical stroke, generated power and electric loads

1. Introduction

A thermoacoustic power converter converts thermal energy into acoustic energy using a thermoacoustic engine and then into electrical energy using a linear alternator. The acoustic power applied to the alternator's piston causes the piston, which carries a permanent magnet, to oscillate. This oscillatory motion creates an oscillating magnetic field between the permanent magnet and the stationary copper coils. The oscillating flux induces voltage in the copper coils causing electric power to be delivered to the electric load.

Recent moving-magnet linear alternators have been developed specifically for thermoacoustic power converters. They utilize a new technology based on flexure bearing and clearance seal which allows a non-contact reciprocating motion of the piston thus eliminating the need for sliding seals or lubrication. This non-contact sealing technology grants these devices the merits of durability and reliability and thus significantly reduces the maintenance costs. For example, some linear alternators have been in continuous operation for more than eight years [1].

The matching between the thermoacoustic engine, linear alternator and the electric load is essential for achieving stable and efficient operation but is also complicated because several factors have to be achieved simultaneously. One of the matching conditions necessitates that the electric load used to dissipate the generated electric power leads to an operating point defined by the intersection of the load's characteristic curve and the linear alternator's characteristic curve that is characterized by nearly the rated mechanical stroke and also the rated electric power, while not exceeding the rated voltage or current. This is because if the full rated power is delivered at more than the rated mechanical stroke, the thermoacoustic power converter will never achieve its rated power capacity and if the full power is delivered at less than the rated mechanical stroke, excessive current will be required. On the other hand, operating at the rated mechanical stroke while generating less than the rated power involves carrying the full mechanical-motion loss at less than the rated output power, leading to a loss in the conversion efficiency.

This necessitates knowledge on how a certain electric load affects the resulting mechanical stroke, the generated voltage, current, and electric power, under different operating conditions, which is the first objective of this work.

Other objectives of this work are to [2] - to investigate how the dependences identified in the first objective are affected when using a realistic electric load, like a constant-voltage electronic load, that simulates the grid which is a constant-voltage load as well, as opposed to a linear (resistive) load, that simulates loads with a resistive nature like a heater or an incandescent light bulb lamp, and [3] -to examine under which conditions the generated voltage exhibit a linear relationship versus the mechanical stroke, allowing using the former as an indication of the latter by measuring the generated voltage only, which is much less expensive during normal operation in the field.

2. Experimental setup

The work presented in [2] presented a platform to test linear alternators under different operating conditions and electric loads, allowing simultaneous measurements of the main linear alternator variables, including the dynamic pressure at the alternator's piston (hereinafter referred to as resonator pressure), input acoustic power to the alternator, mechanical stroke, generated voltage, current, and electric power for any given electric load. This measurement platform is employed in this work. The equations used to calculate the performance indices from the measured variables are presented in [2-3]. The specifications of the linear alternator used in this work are presented in [3].

The experimental conditions used in this article are selected to be close to the conditions typically encountered in thermoacoustic power conversion, which typically are in the frequency range of 50-90 Hz, with working gases/gas mixtures made of argon and helium, and operating at a mean gas pressure in the range of 25-50 bar [4-6].

The linear load used to dissipate the generated electric power is a high-power, low-inductance variable resistance with a rated power of 150 W, a maximum resistance of 350 Ω (model RLS350E, supplied by Ohmite) and thus has a quadratic dissipation characteristic curve between the dissipated voltage and the load's resistance.

The non-linear load consists of a rectifier (made of 4 capacitors of 470 µF each connected in parallel) followed by a constant voltage DC electronic load rated at 150 W (model 8540, supplied by BK precision).

The sampling parameters are selected to ensure sampling of an integer large number of cycles with fine time and spectral resolutions without aliasing and with negligible amplitude leakage. Consequently, 400 points were sampled per acoustic cycle for 50 complete cycles with a total of 20,000 samples. When operating at 56 Hz, this yields a sampling rate of 22,400 samples/s and a total sampling time of 0.89 second with a quantization resolution of 0.3 mV, a time resolution of approximately 45 μs and a spectral resolution of 1.36 Hz.

3. Results

For the purpose of proper comparison between the two electric loads employed, the experiments are carried-out for both loads under identical working gas mixture composition (60% helium and 40% argon), which is the helium/argon gas mixture with the minimum Prandtl number of 0.4 of all helium/argon gas mixtures [7] and thus has a minimum ratio of the viscous penetration depth to the thermal penetration depth; identical mean gas pressure of 30 bar; identical operating frequency of 56 Hz, which is the mechanical resonance frequency at 30 bar, measured as the frequency of free decay of the linear alternator in situ, with consideration of the gas spring forces in the linear alternator's enclosure; and identical input pressure ratio to the linear alternator (0.6%), defined as the ratio of the dynamic pressure at the face of the alternator's piston to the mean gas pressure. Table 1 summarizes the operating conditions and performance indices of the reference cases considered in linear and in non-linear loads. The conditions stated in Table 1 refer to the conditions of the reference experiment that achieves electric resonance under both loads. Electronic resonance is achieved when the added capacitance balances the alternator's inductance (which in turn depends on the mechanical stroke [3]). This yielded using a power factor correcting capacitance of 60 μF and 80 μF for the linear and non-linear loads, respectively at the reference experiment detailed in Table 1. The same capacitances are used throughout the range of the loads.

Table 1: Operating conditions and performance indices of the reference experiments carried-out in linear and non-linear loads

Linear Loading		**Non-linear Loading**	
Operation Factor		**Value**	
Helium molar fraction		0.60	
Argon molar fraction		0.40	
Mean gas pressure		30 bar	
Input pressure ratio to the linear alternator		0.6 %	
Frequency		56 Hz	
Operation Factor	**Value**	**Operation Factor**	**Value**
Resistive load	200 Ω	DC constant-voltage load	20 V
Tuning capacitor	60 μF	Tuning capacitor	80 μF
Performance Index	**Value**	**Performance Index**	**Value**
Input acoustic power	15.3 W	Input acoustic power	9.4 W
Mechanical stroke, RMS	2.17 mm	Mechanical stroke, RMS	1.18 mm
Input gas acoustic impedance	8.5 MPa. s/m^3	Input gas acoustic impedance	15.7 MPa.s/m^3
Generated electric power	7.95 W	Generated electric power	7.01 W
Acoustic-to-electric conversion efficiency	52 %	Acoustic-to-electric conversion efficiency	74.4 %
Generated volt, RMS	39.9 V	Generated volt, RMS	21.8 V
Generated current, RMS	0.20 A	Generated current, RMS	0.45 A
Mechanical-motion loss	2.66 W	Mechanical-motion loss	0.77 W
Ohmic loss	0.28 W	Ohmic loss	1.4 W
Fluid-seal loss	0.097 W	Fluid-seal loss	0.038 W

For each data set, several operating conditions are investigated: operation at different helium concentration in the helium/argon gas mixture used (0% helium, 60% helium and 100% helium), different mean gas pressures (10 bar, 20 bar and 30 bar) and different input dynamic pressure ratios (0.4%, 0.6% and 0.8%). The results are presented and discussed in Subsections 3.1, 3.2 and 3.3, respectively.

3.1 Effects of gas mixture composition

Fig. 1A and Fig. 1B present the relationship between the generated voltage, current and electric power and the mechanical stroke for linear and non-linear loads, respectively for three helium concentrations: 0% helium (100% argon), 60% helium and 100% helium.

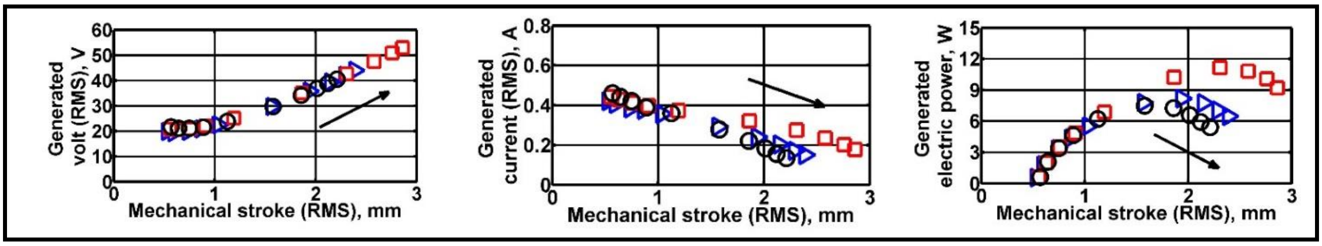

Figure 1A: The generated voltage, current and electric power versus mechanical stroke for a range of linear loads at three different helium concentrations in a helium/argon gas mixture: 0% He (circular symbols), 60% He (triangular symbols) and 100% He (square symbols). The mean gas pressure is 30 bar, the operating frequency is 56 Hz, and the dynamic pressure ratio is 0.6%. The linear loads consist of a 60-μF capacitor followed by a variable electrical resistance (3, 10, 20, 30, 50, 100, 150, 200, 250 and 300 Ω). The arrow shows the direction of increase in the load's resistance.

For the linear load, it can be observed in Fig. 1A that as the load resistance increases, the load absorbs lower current from the linear alternator, causing the generated voltage to increase and thus the mechanical stroke to increase. Generally, the generated voltage is proportional to the mechanical stroke because larger penetration of the moving magnet into the electric coil results in larger generated voltage.

The observation that the mechanical stroke is proportional to the load resistance has been reported in [8] (Fig. 2), where a sensitivity analysis was carried-out and its results identified the load resistance as one of the main factors that causes the mechanical stroke to increase. Furthermore, this dependence was exploited to protect linear alternators from over-stroking by introducing a low resistance of large power rating that absorbs a large current, causing the generated voltage and correspondingly the mechanical stroke to decrease if the mechanical stroke approaches its rated value, as illustrated in [2] (Fig. 3).

Additionally, Figure 1A indicates that the helium concentration does not have a significant effect on the mechanical stroke, which is supported by the results of the sensitivity analysis [8] (Fig. 2).

The generated electric power is not necessarily equal to the power dissipated at the load. It can be estimated as the dot product of the generated voltage and current signals. In linear loads, a power-factor-correcting capacitor is connected in series with the electric load. The power factor observed at the linear alternator's output (i.e., on the load) does not include the alternator's inductance and can be expressed as:

$$\text{Power Factor} = \cos\left(\tan^{-1}\left(\frac{-1/\omega C}{R_L}\right)\right), \tag{1}$$

where ω is the angular frequency, C is the capacitance of the power-factor-correcting capacitor connected in series with the load and R_L is the load's resistance. This equation indicates that when operating with a fixed capacitance, this power factor approaches one for larger values of the load's resistance.

The load resistances can be categorized into two different regimes: a relatively-low range of resistances (3 Ω -100 Ω), where the power factor is relatively low (0.06 to 0.90), as per Eq. (1). The low resistances withdraw a large current (0.42 A to 0.29 A); and a high-resistance range (100 Ω - 300 Ω), where the power factor is relatively high (0.90 to 0.99) (Eq. (1)) and the generated current is relatively low (0.29 A to 0.15 A) with respect to the low-resistance regime.

In the low-resistance range, the generated electric power increases as the mechanical stroke increases, indicating that the large generated current in this range overcomes the effects of the low power factor. This indicates that in field operation at a constant electric load, proper selection of the power factor capacitance can lead to a significant increase in the electric power delivered to the load. In this resistance range, the generated voltage is still proportional to the mechanical stroke, but at a lower rate than in the high-resistance range.

In the high-resistance range, the decrease in the generated current overcomes the increases in the power factor and in the generated volt giving rise to a decline in the generated power as the load resistance increases, as observed in the right part of Fig. 1A.

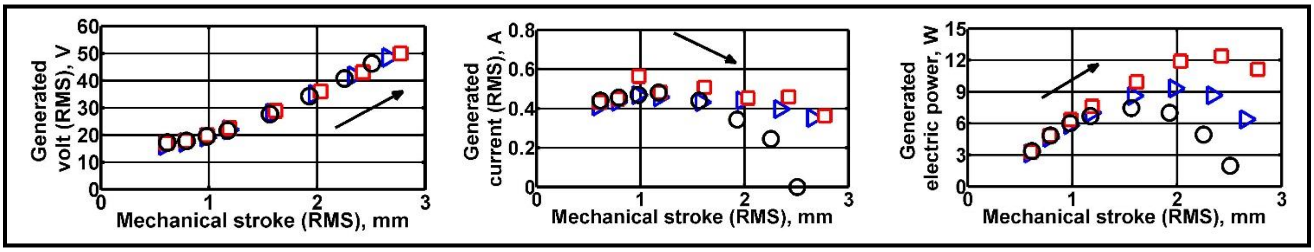

Figure 1B: The generated voltage, current and electric power versus mechanical stroke for a range of non-linear loads at three different helium concentrations in a helium/argon gas mixture: 0% He (circular symbols), 60% He (triangular symbols) and 100% He (square symbols). The mean gas pressure is 30 bar, the operating frequency is 56 Hz, and the dynamic pressure ratio is 0.6%. The non-linear loads consist of a 80-μF capacitor followed by a rectifier and then by a variable constant-voltage DC electronic load (5, 10, 15, 20, 30, 40, 50 and 60 V_{DC}). The arrow shows the direction of increase in the load's voltage.

The results of the non-linear load are presented in Fig. 1B. They reflect the main trends observed in the linear load: as the set voltage increases, the generated voltage increases and the generated electric power experiences a peak at a certain voltage load due to the combined effects of the decrease in the generated current and the increase in the power factor in the AC part of the electric load prior to the rectifier. These observations are supported further by previous measurements such as [2] (Fig. 4). A linear relationship between the generated voltage and the mechanical stroke was also observed in another type of non-linear load [9] (Fig. 3).

In the non-linear load, two regimes can be identified: if the supplied input dynamic pressure ratio results in a driving force higher than that caused by the dissipation load controlled by the set DC voltage, then the generated voltage is larger than the set voltage. The first four data points in Fig. 1B fall in this range and they experience an increase in the generated current and in the generated electric power with the set voltage load.

On the other hand, if the supplied input dynamic pressure ratio results in a driving force lower than that caused by the set voltage load, then the generated voltage is less than the set voltage load and this regime is characterized by an increase in the generated voltage to approach the set voltage and a decrease in the generated current and the generated power with the set voltage load.

In both regimes, the generated voltage is linear with the mechanical stroke, but the slope is lower in the first regime than in the second regime.

The gas mixture composition does not seem to affect the mechanical stroke in the non-linear load range considered, which is in agreement with previous measurements [2] (Fig. 7).

In contrast with the above results obtained at variable resistances or variables set voltage loads, the results of [10] (Fig. 3) and [2] (Fig. 4) explored the effects of different input dynamic pressure ratios at a fixed resistive load and a fixed set DC voltage load, respectively. These results show a linear-relationship between the generated voltage and the mechanical stroke throughout the range studied.

3.2 Effects of mean gas pressure

Figures 2A and 2B present the relationship between the generated voltage, current and electric power versus the mechanical stroke for linear and non-linear loads, respectively for three mean gas pressures: namely 10 bar, 20 bar and 30 bar. The mean gas pressure controls the gas impedance and thus its affects the matching between the working gas carrying the acoustic power and the system made of the linear alternator and the electric load.

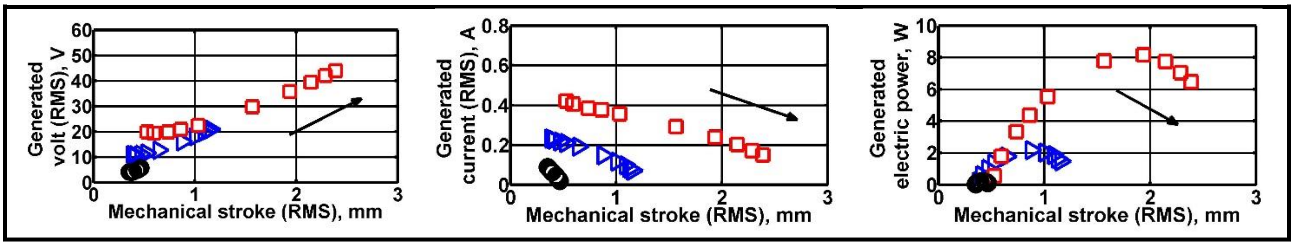

Figure 2A: The generated voltage, current and electric power versus mechanical stroke for a range of linear loads at three different mean gas pressures: 10 bar (circular symbols), 20 bar (triangular symbols) and 30 bar (square symbols). Same conditions as in Figure 1A, except that the helium concentration is 60% and the mean gas pressure is varied. The shows the direction of increase in the load's resistance.

A low mean gas pressure (e.g., 10 bar) with a low pressure ratio (e.g., 0.6 %) results in poor acoustic matching and low driving force, yielding a low range of mechanical strokes. This is evident in both linear and non-linear loads. For example, for a linear load, the range of mechanical stroke at 10 bar is only 5.9 % of the corresponding range at 30 bar. This is in agreement with the results of the sensitivity analysis [8] (Fig. 2) that recognized the mean gas pressure as one of the dominant factors that affect the mechanical stroke. This ratio drops to only 1.4% for the non-linear load used, indicating that this operating factor plays an even more critical role in this non-linear load type.

Similar to the observations made in Subsection 3.1 above, the load resistances investigated can be categorized into two different regimes for each mean gas pressure: at a mean gas pressure of 30 bar, the first regime spreads from 3 Ω - 100 Ω (with a power factor in the range of 0.06 to 0.90 and current is in the range of 0.42 A to 0.29 A). In this range, the effect of the large generated current overcomes the effect of the low power factor, giving rise to an increase in the generated electric power as the stroke increases. This range exhibits a linear relationship between the generated voltage and the mechanical stroke and a decrease in generated current as the stroke increases.

The second resistance regime spreads from 100 Ω - 300 Ω, where the generated voltage exhibits a linear relationship with the mechanical stroke at a higher rate than in the first regime; the generated current continues to drop with the stroke, also at a higher rate in comparison with the first regime. Other mean gas pressures exhibit the same trends but at different resistance values.

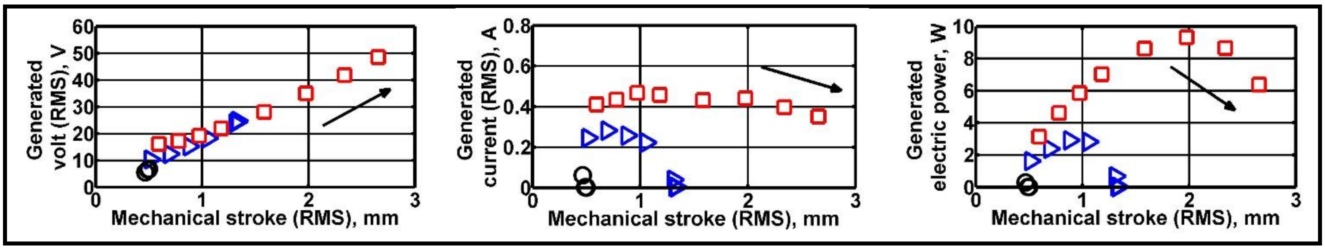

Figure 2B: The generated voltage, current and electric power versus mechanical stroke for a range of nonlinear loads at three different mean gas pressures: 10 bar (circular symbols), 20 bar (triangular symbols) and 30 bar (square symbols). Same conditions as in Figure 1B, except that the helium concentration is 60% and the mean gas pressure is varied. The arrow shows the direction of increase in the load's voltage.

In the non-linear load, the two regimes identified in Subsection 3.1 can be observed, giving rise to a non-monotonic behaviour in the generated current and the generated power with the stroke.

3.3 Effects of input dynamic pressure ratio

Figures 3A and 3B present the relationship between the generated voltage, current and electric power versus the mechanical stroke for linear and non-linear loads, respectively for three input dynamic pressure ratios: namely 0.4%, 0.6% and 0.8%.As the driving force increases with the increase in the input dynamic pressure ratio, the range of mechanical stroke increases, causing the generated voltage, current and electric power to increase. This observation was also observed in the sensitivity analysis carried-out in [8] (Fig. 2).

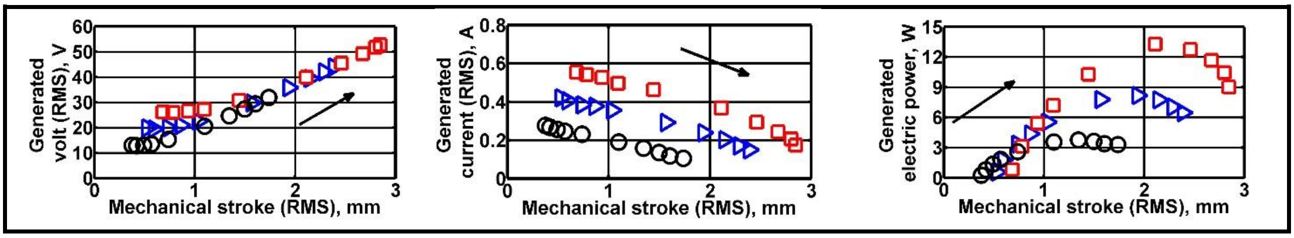

Figure 3A: The generated voltage, current and electric power versus mechanical stroke for a range of linear loads at three different input dynamic pressure ratios: 0.4% (circular symbols), 0.6% (triangular symbols) and 0.8% (square symbols). Same conditions as in Figure 1A, except that the helium concentration is 60% and the input dynamic pressure ratio is varied. The arrow shows the direction of increase in the load's resistance.

Similar to the observations made in Subsection 3.1 above, the load resistances investigated can be categorized into two different regimes for each input dynamic pressure ratio: at an input dynamic pressure ratio of 0.6%, the first regime spreads from 3 Ω - 100 Ω with a power factor from 0.06 to 0.90 and a generated current from 0.42 A to 0.29 A. This range exhibits a linear relationship between the generated voltage and the mechanical stroke and a decrease in generated current as the stroke increases. In this range, the effect of a large generated current overcomes the effect of the low power factor, giving rise to an increase in the generated electric power as the stroke increases. The second resistance regime spreads from 100 Ω - 300 Ω, with a power factor from 0.90 to 0.99 and a generated current from 0.29 A to 0.15 A. The generated voltage exhibits a linear relationship with the mechanical stroke, at a much higher rate than the first range; the generated current continues to drop with the stroke, at a slightly higher rate in comparison with the first range. Although the power factor is relatively large (0.90 to 0.99), the severe decrease in the generated current overcomes the increase in the power factor, leading to a decline in the generated electric power. Other mean gas pressures exhibit the same trends but at different resistance values.

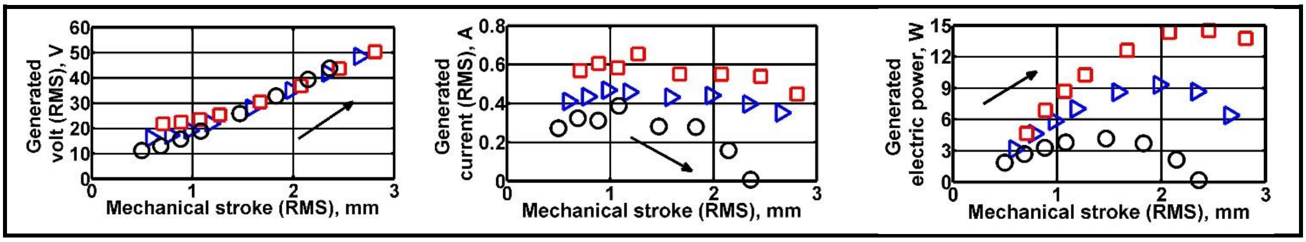

Figure 3B: The generated voltage, current and electric power versus the mechanical stroke for a range of non-linear loads at three different input dynamic pressure ratios: 0.4% (circular symbols), 0.6% (triangular symbols) and 0.8% (square symbols). Same conditions as in Figure 1B, except that the helium concentration is 60% and the input dynamic pressure ratio is varied. The arrow shows the direction of increase in the load's voltage.

When applying the non-linear load, the two regimes identified in Subsection 3.1 can be observed, giving rise to a non-monotonic behaviour in the generated current and the generated electric power with the mechanical stroke.

4. Summary and Conclusions

The conditions that lead to large output power are identified under operating conditions typical in thermoacoustic-power-conversion conditions. In linear and non-linear loads, increasing the helium concentration, the mean gas pressure or the input dynamic pressure ratio lead to increase in the range of mechanical stroke, generated current and generated electric power.

In linear loads, low resistances withdraw large current but with a low power factor while the opposite occur with high resistances, giving rise to a maximum power generation at a certain resistance. Therefore, in field operation, proper adjustment of the power-factor correction at fixed or at variable loads can lead to significant increase in the power generated from the linear alternator. The generated voltage is proportional to the mechanical stroke in both regimes but at a lower rate in the low-resistance regime than in the high-resistance regime.

Under the constant voltage DC electronic load, if the supplied input dynamic pressure ratio results in a driving force higher than that of the dissipation load, the generated voltage is observed to be larger than the set voltage and the generated current and electric power increase with the set voltage. The opposite occurs in the second regime. In both regimes, the generated voltage is linear with the mechanical stroke, but the slope is lower in the first regime than in the second regime.

In both linear and non-linear loads, the constant of proportionality between the generated voltage and the mechanical stroke seems to depend slightly on the mean gas pressure and to be almost independent of the gas mixture composition or the input dynamic pressure ratio.

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