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# Sensitivity analysis of a comprehensive model for a miniature-scale linear compressor for electronics cooling

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ABSTRACT

A comprehensive model of a linear compressor for electronics cooling was previously presented by Bradshaw et al. (2011). The current study expands upon this work by first developing methods for predicting the resonant frequency of a linear compressor and for controlling its piston stroke. Key parameters governing compressor performance – leakage gap, eccentricity, and piston geometry – are explored using a sensitivity analysis. It is demonstrated that for optimum performance, the leakage gap and frictional parameters should be minimized. In addition, the ratio of piston stroke to diameter should not exceed a value of one to minimize friction and leakage losses, but should be large enough to preclude the need for an oversized motor. An improved linear compressor design is proposed for an electronics cooling application, with a predicted cooling capacity of 200 W a cylindrical compressor package size of diameter 50.3 mm and length 102 mm.

# Analyse de la sensibilité d’un modèle exhaustif de compresseur linéaire miniaturisé pour le refroidissement de composants électroniques

*Mots clés :* Compresseur linéaire ; Étude sur la sensibilité ; Système miniaturisé ; Refroidissement des composants électroniques ; Analyse de pertes

## 1. Introduction

A comprehensive simulation model for a miniature-scale linear compressor was recently developed by Bradshaw et al. (2011). The model was also validated against experiments conducted on a prototype linear compressor constructed for the purpose. It was found that the overall performance metrics predicted by the compressor model are highly

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**Nomenclature**

| | |
|---|---|
| BDC | Bottom Dead Center [-] |
| c | Damping factor [N s m$^{-1}$] |
| $\dot{E}_d$ | Exergy destroyed [W] |
| $f$ | Frequency [Hz] |
| $\mathbf{f}$ | Dry friction coefficient [-] |
| $g$ | Leakage gap between piston and cylinder[m] |
| h | Enthalpy [kJ kg$^{-1}$] |
| $k$ | Stiffness [N m$^{-1}$] |
| M | Mass [kg] |
| N | Normal force from piston to cylinder wall [N] |
| P | Pressure [kPa] |
| $\dot{Q}$ | Heat transfer [W] |
| $\dot{Q}_{cool}$ | Cooling capacity [W] |
| s | Entropy[kJ kg$^{-1}$ K$^{-1}$] |
| $T_o$ | Ambient temperature [K] |
| $\mathbf{T_p}$ | Piston oscillation period [s] |
| $T_w$ | Compressor shell temperature [K] |
| TDC | Top Dead Center [-] |
| V | Volume [m$^3$] |
| $\mathbf{V}$ | Gas velocity [m s$^{-1}$] |
| $V_d$ | Displaced volume [m$^3$] |
| $\dot{W}$ | Work over a cycle [W] |
| $x_d$ | Distance between piston and valve plate at TDC [m] |
| $x_p$ | Instantaneous compressor piston position [m] |
| $x_s$ | Compressor stroke [m] |

*Greek Letters*

| | |
|---|---|
| $\varepsilon$ | Eccentricity of spring force [m] |
| $\eta$ | Efficiency [-] |
| $\omega$ | Frequency [rad sec$^{-1}$] |
| $\zeta$ | Damping ratio [-] |

*Subscripts*

| | |
|---|---|
| cv1 | Control volume 1 |
| cv2 | Control volume 2 |
| eff | Effective |
| f | Friction |
| gas | Gas |
| leak | leakage |
| mov | Moving |
| n | Natural |
| res | Resonance |
| rms | Root mean square |
| tot | Total |

sensitive to the leakage gap $g$, eccentricity $\varepsilon$, dry friction coefficient $\mathbf{f}$, and motor efficiency $\eta_{\text{motor}}$. Fig. 1 depicts the major components and design parameters of a linear compressor. The geometry of the piston is directly related to both the friction and leakage of a compressor. Therefore, for a fixed displaced volume, some piston diameter and stroke combinations will provide higher efficiency than others. The impact of changes to these parameters proves useful when designing a linear compressor, and warrants further investigation.

A linear compressor has two major practical limitations, which restrict its implementation in practical systems. Both the resonant frequency and stroke are sensitive to changes in geometry and operating conditions (Cadman and Cohen, 1969; Park et al., 2004; Pollak et al., 1979; Unger and Novotny, 2002). This poses a challenge not only to compressor design but also to modeling efforts. The ability to predict and control these two parameters provides a useful tool for linear compressor design efforts.

A method for calculating the resonant frequency of a linear compressor is developed here. An approach to numerical control is also provided that ensures compressor operation at the desired stroke. A series of sensitivity studies are presented, which highlight the sensitivity to leakage gap and eccentricity as well as piston geometry. Finally, an improved compressor design is formulated for an electronics cooling application using results from the model.

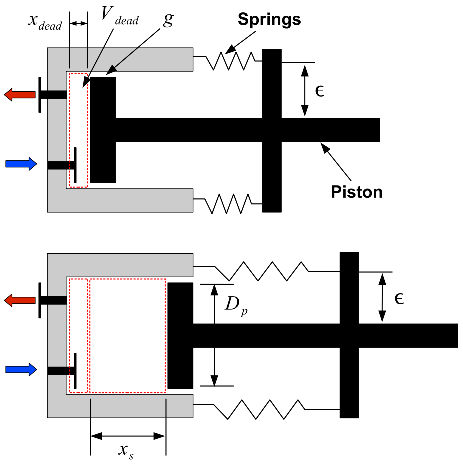

**Fig. 1 – Schematic diagram of linear compressor at Top Dead Center (TDC, top) and Bottom Dead Center (BDC, bottom) with primary linear compressor components and design parameters highlighted.**

## 2. Resonant frequency of a linear compressor

The resonant frequency of the linear compressor depends on the mechanical springs selected in the design as well as the operating conditions. To calculate the resonant frequency of a linear compressor, the stiffness associated with both the mechanical springs and the operating conditions must be estimated. The stiffness of the mechanical springs is typically reported by the manufacturer. The stiffness associated with the operating conditions is the stiffness from gas compression. Using these stiffness values, an estimate of the resonant frequency of oscillation is obtained from the following expression:

$$\omega_{\text{res}} = \omega_n \sqrt{1 - 2\zeta^2} \tag{1}$$

where the damping ratio is defined as follows (Rao, 2004)