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Modeling of the Transient Response for Compressible Air Cushion Vehicles (ACV)

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Abstract. A model for compressible Air Cushion Vehicles (ACV) is presented. In this model the compressible Bernoulli's equation and the Newton's second law of motion are used to predict the dynamic behavior of the heave response of the ACV in both time and frequency domains. The mass flow rate inside the air cushion of this model is assumed to be constant. The self excited response and the cushion pressure of the ACV is calculated to understand the behavior of the system in order to assist in the design stage of such systems. It is shown in this study that the mass flow rate and the length of the vehicle's skirt are the most significant parameters which control the steady state behavior of the self excited oscillations of the ACV. An equation to predict the transient time of the oscillatory response or the settling time in terms of the system parameters of the ACV is developed. Based on the developed equations, the optimum parameters of the ACV that lead to minimum settling time are obtained.

Introduction

Optimization in the design of the ACV allows utilization of these vehicles for different purposes and missions. Fig. (1) shows a simple diagram of an ACV. One the basic components of an ACV is the skirt. Since the beginning of ACV designing there has been great effort to develop a good skirt system. Excellent performance in terms of power consumption, stability, maneuverability can be guaranteed with a good skirt design [1-6].

In all these studies, the aim was to introduce a design for the ACV skirt system which can be amphibious and tolerant to unfriendly environment and terrains. Ma and Sullivan model [6] developed a numerical theory on the linear heave dynamics of a two dimensional section of a flexible skirt and flexible bag-finger skirt system. It was found in [6] that the skirt system mass is an important parameter in craft dynamics only at high frequency, which is around the skirt bounce frequency.

In modeling the heave dynamics of the ACV, there are many sources of nonlinearities which contribute to the limit cycle oscillations. The nonlinearity sources were identified and studied for an incompressible air cushion flow rate model in reference [7] with different air cushion geometries. Hinchey et. al. [7] showed that the frequency of oscillation in most cases was low enough to allow the incompressibility condition to be adopted in analyzing the heave dynamics of the ACV.

A key success in designing the ACV is to use the flexible air cushion skirt system, which is attached to the base of the vehicle from where the pressurized air is exited. The work presented in references [7-8] carried an analytical and experimental investigation of the oscillation dynamics in a flexible skirted ACV. Despite the presence of highly non-linear sources, in reference [8] Bernoulli model had been used to model the flow inside the skirt of the air cushion ignoring the compressibility as well as the fluid friction effects.

Simulation of an ACV in waves was made possible by introducing linearized compressible hydrodynamic model based on transient wave Green's function [9-11]. It was shown in [9] that it was necessary to smooth out pressure in an artificial and empirical manner near the edges in order to obtain a finite wave resistance.

Problem Statement and Motivations

Several investigations to understand the ACV's dynamic behavior have been done by many researchers using linear modeling analysis [6-8]. The ACVs suffered setbacks during their early development period due to the occurrence of self excited oscillations. These oscillatory motions are simply a translation in the vertical direction and are very undesirable because sometimes they may lead to the destruction of the vehicle. The self excited behavior in the ACVs is encountered in most of the linear models which have been studied in the literature. In this paper, a non-linear model is introduced which is based on the approach presented in [7, 8,12].

The model presented in this paper contains two nonlinear coupled differential equations. The nonlinearities included in the governing equations of this model are present due the compressibility effects and the polytropic nature of the compression expansion process. The governing equations are solved numerically to study the dynamics behavior of the self excited oscillations in the vertical direction. A parametric study is carried out in order to develop an equation for predicting the settling time of the oscillatory motion of the ACV. Therefore, the work presented in this paper will allow the reader to better understand air cushion vehicle's dynamic behavior and will provide room for design improvements.

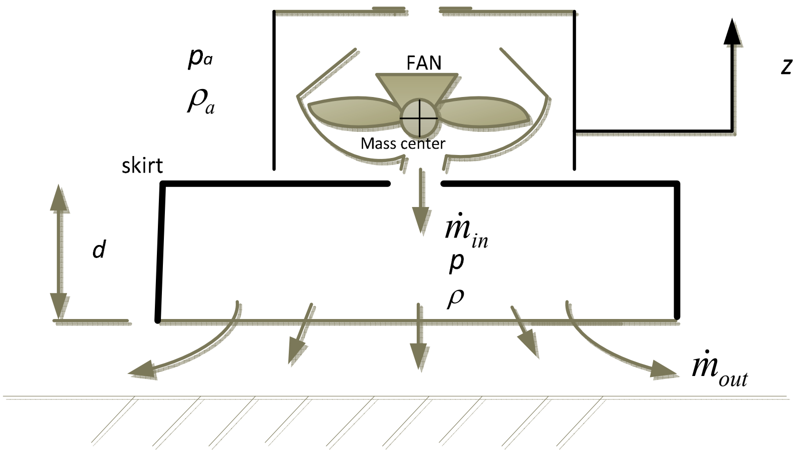

Fig. 1: Simple schematic of Air Cushion Landing system.

Methodology and Governing Equations

The flow of the air from the cushion in Fig. (1) is assumed to be subsonic and compressed isentropically. Also the thermodynamic equilibrium is assumed inside the cushion volume. Using Newton's Second law of motion leads to the writing the vertical equation of motion as:

$$M\ddot{z} = (p - p_a)A - Mg \tag{1}$$

where M is the mass of the vehicle, $\ddot{z}$ is the acceleration in the vertical direction, p is the inside cushion pressure, p_a is the atmospheric pressure, A is the cross-sectional area of the cushion, and g is the gravitational acceleration. The total amount of air mass inside the cushion $m = \rho V$, where m is the mass of air inside the cushion volume, V is the cushion volume, and ρ is the density of air inside the cushion volume. The net mass flow rate inside the cushion is $\dot{m} = \dot{m}_{in} - \dot{m}_{out}$, where $\dot{m}_{in}$ is mass flow rate inside the cushion and it is a fixed quantity governed by the properties of the blower fan. On the other hand, $\dot{m}_{out}$ is the mass flow rate outside the cushion which is dependent on the vertical displacement y and both the atmospheric and cushion pressure. Taking the time derivative to total amount of air mass inside the cushion $m = \rho V$ yields:

$$\dot{m} = \dot{\rho}V + \rho\dot{V} \tag{2}$$

The polytropic relationship between pressure and density for an isentropic process is $p\rho^{-\gamma} = constant$, and the pressure is related to temperature by the perfect gas equation $p = \rho RT$, where R is the gas constant. Therefore, the conservation of mass can be written using the isentropic relation as:

$$\frac{\rho V\dot{p}}{\gamma p} + \rho\dot{V} = \dot{m}_{in} - \dot{m}_{out} \tag{3}$$

The variables in Eq. (3) are all related to the cushion zone. Also, $\dot{V} = A\dot{z}$, and at the cushion zone $\rho = p/RT$, therefore one can evaluate $\dot{p}$ as:

$$\dot{p} = \frac{\gamma RT}{V}\left[\dot{m}_{in} - \dot{m}_{out} - \frac{pA\dot{z}}{RT}\right] \tag{4}$$

where T is the surrounding temperature which is assumed to be constant. This model contains three unknown quantities, which are the vertical displacement z, the cushion pressure p, and the unknown air mass flow rate outside the cushion volume $\dot{m}_{out}$. A third constitutive equation has to be included with equations (1) and (4), which can be introduced using the compressible Bernoulli's equation [13]. Using the compressible Bernoulli's equation, the air mass flow rate $\dot{m}_{out}$ is given by the following equation:

$$\dot{m}_{out} = \frac{c_0 pLz}{\sqrt{RT}}\left\{\frac{2\gamma}{\gamma - 1}\left[\left(\frac{p_a}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_a}{p}\right)^{\frac{(\gamma+1)}{\gamma}}\right]\right\}^{\frac{1}{2}} \tag{5}$$

This equation should be corrected by a correction coefficient factor c_0 that accounts for some losses due to the mathematical idealization of this model and can be found experimentally [5,10].

Results and Discussion

The governing equations (1), (4) and (5) can be written in state space model representing a physical system as three first order coupled nonlinear differential equations. The state space form of the governing equation is given by the following equations:

$$\dot{z_1} = z_2 \tag{6}$$

$$\dot{z_2} = \frac{A}{M}(p - p_a) - g \tag{7}$$

, and

$$\dot{p} = \frac{\gamma RT}{A(d + z_1)}\left[\dot{m}_{in} - \dot{m}_{out} - \frac{pAz_2}{RT}\right] \tag{8}$$

This form is better suited for computer simulation than a second order input-output differential equation. This system of first order differential equations (Eq. (6)-(8)) is solved using a program written in Matlab. The solution to the system of equations (6)-(8) is performed using dimensionless controlled parameters which are defined as follows: $\bar{L} = L/d$, $\bar{M} = M/\rho_a d^3$, and $\bar{\dot{m}}_{in} =$

$\dot{m}_{in}/\rho_a v_0 d^2$. In these formulas $\bar{L}$ is the dimensionless skirt length of the ACV, $\bar{M}$ is the dimensionless mass of the ACV, $\bar{\dot{m}}_{in}$ is the dimensionless cushion air mass flow rate of the ACV, and v_0 is the initial velocity.

Without loss of generality, the results in this paper are obtained using the following the dimensionless control parameters values: $\bar{M}$=70 to $\bar{M}$=180, $\bar{L}$=3 to $\bar{L}$=4.5, and $\bar{\dot{m}}_{in} = 25$ to $\bar{\dot{m}}_{in} = 250$. Samples of the results are shown in Figs. (2) and (3) for some selected parameters. Fig. (2) shows a decaying time history for both the heave and the cushion pressure for parameter values $\bar{M}$=85, $\bar{\dot{m}}_{in} = 65$ and $\bar{L}$=3.

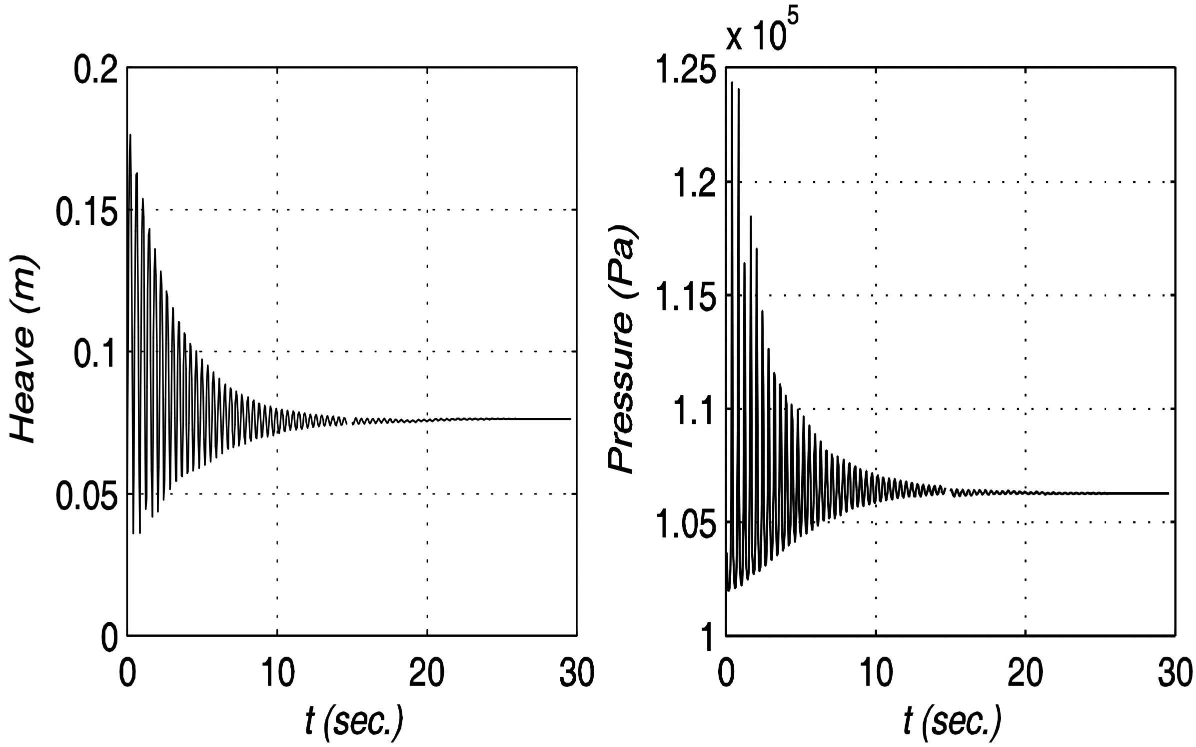

Fig. 2: Time history of the heave and cushion pressure for $\bar{M}$=85, $\bar{\dot{m}}_{in} = 65$ and $\bar{L}$=3.

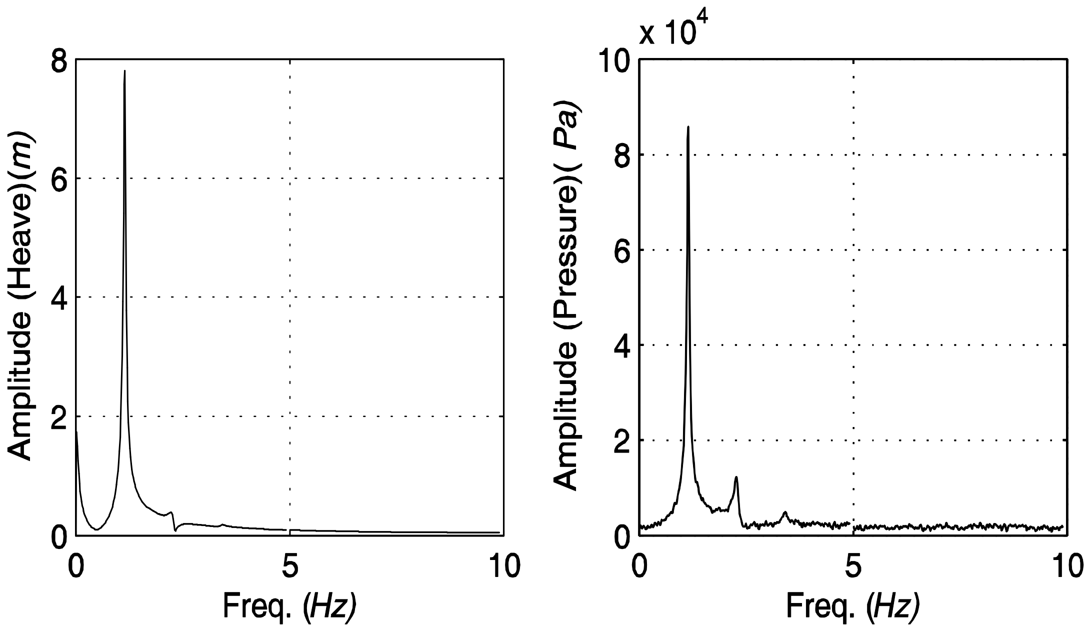

Fig. 3: Spectrum of the heave dynamics and cushion pressure for $\bar{M}$=85, $\bar{\dot{m}}_{in} = 65$, and $\bar{L}$=3.

It is evident from these figures that the self excited response has a distinct frequency component as shown in the frequency spectrum in Fig. (3). The oscillations in the response depend mainly on values of ACV control parameters. Therefore, in designing these vehicles a proper choice of the values of these parameters can lead to suppress these oscillations. This will be discussed in more detail in the next section.

Parametric Study of the Model

The objective of this section is to explore the influence of the control parameters on the transient response in order to improve the oscillatory behavior of ACV. The transient response of the ACV is obtained by varying the control parameters: $\bar{M}$, $\bar{\dot{m}}_{in}$, and $\bar{L}$, one at a time. This has led to generating substantial amount of data, a summary of which is presented here. Furthermore, the optimum control parameters are determined.

Since we are interested in minimum oscillatory response, a parameter to measure the transient response is introduced. This parameter is called the settling time T_{ss}. The settling time is the time at which the oscillations start to cease. To develop an equation to predict the normalized settling time $\bar{T}_{ss}$, the equation of motion is integrated using Runge Kutta numerical scheme and the parameters such as the air mass flow rate into the cushion volume $\bar{\dot{m}}_{in}$ varies while skirt length $\bar{L}$ and mass $\bar{M}$ are fixed. Fig. (4) shows a sample of the results where the trend is linear between the $\bar{T}_{ss}$ and $\bar{\dot{m}}_{in}$.

It should be noted that our numerical simulation reveals insignificant changes in the settling time $\bar{T}_{ss}$ by changing the vehicle mass $\bar{M}$. This is performed by fixing the vehicle skirt length $\bar{L}$ and the cushion air mass flow rate $\bar{\dot{m}}_{in}$. Consequently, the settling time $\bar{T}_{ss}$ is independent of mass ratio $\bar{M}$.

Fig. (4b) shows a linear correlation between settling time $\bar{T}_{ss}$ and skirt length $\bar{L}$. It is readily seen that the slope of the straight lines in Fig. (4b) depends on the cushion air mass flow rate $\bar{\dot{m}}_{in}$. Plotting the slope of the straight lines in Fig. (4b) versus $\bar{\dot{m}}_{in}$ one can obtain the curve shown in Fig. (5b). On the other hand, Fig. (5a) shows the interception of the straight lines in Fig. (4b) with the y-axis versus the mass flow rate $\bar{\dot{m}}_{in}$. Combining the equations from Figs. (4) and (5) one can obtain the following correlation which can be used to predict $\bar{T}_{ss}$:

$$\bar{T}_{ss} = \left[\tfrac{2}{3\pi^5}\bar{\dot{m}}_{in}^2 v_0^2 \rho_a^2 d^6 - \tfrac{\pi}{7}\bar{\dot{m}}_{in} v_0 \rho_a d^3 + 12\right] * \bar{L}d - \frac{\bar{\dot{m}}_{in}^2 v_0^2 \rho_a^2 d^6}{100} + \tfrac{\pi^2}{4}\bar{\dot{m}}_{in} v_0 \rho_a d^3 - 5(2)^{\pi} \tag{9}$$

By using equation (9), one can optimize the control parameters which are: the cushion air mass flow rate $\bar{\dot{m}}_{in}$, and the skirt length $\bar{L}$. Therefore, the optimum value of the mass flow rate can be expressed as:

$$\bar{\dot{m}}_{in} = \frac{\frac{7}{\pi} - \frac{\pi^4}{4}}{\frac{4}{3\pi^5}\bar{L}\,d - \frac{1}{50}} \times \frac{1}{v_0 \rho_a d^3} \tag{10}$$

Also, the optimum value of the skirt length $\bar{L}$ reaches its maximum value in the interval considered as shown in Fig. (4b).

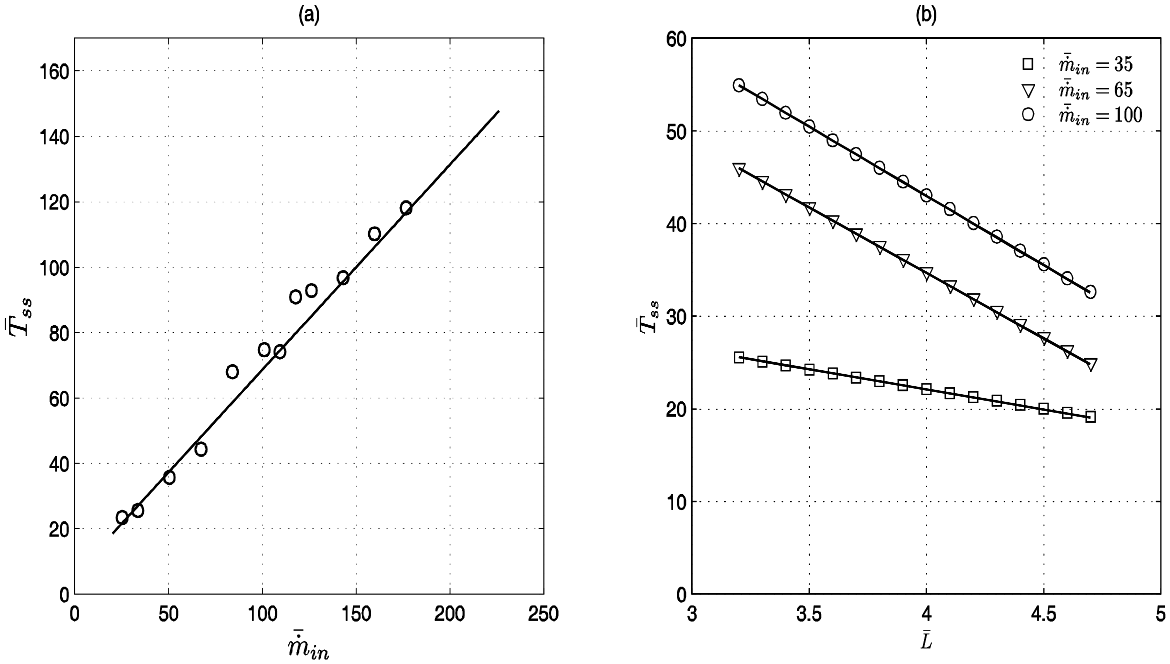

Fig. 4: (a) Settling time versus mass flow rate $\bar{\dot{m}}_{in}$ for a fixed $\bar{M}$=*85,* and $\bar{L}$=*3.5,* (b) Settling time versus Skirt length $\bar{L}$ for fixed $\bar{\dot{m}}_{in}$ and $\bar{M} = 85$.

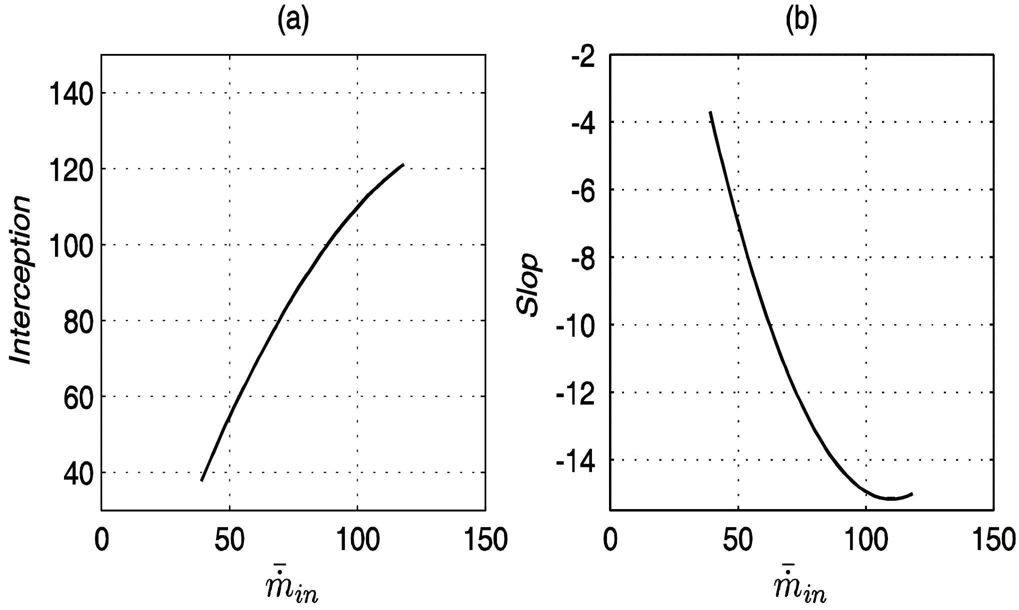

Fig. 5: (a) Interception of the straight lines in Figure (4b) versus $\bar{\dot{m}}_{in}$,(b) The slope of straight lines of Fig. (4b) versus$\bar{\dot{m}}_{in}$.

Conclusions

A highly nonlinear model for the dynamic behavior of ACV is considered. The control parameters that influence the transient response are found to be: the skirt length, and the cushion air mass flow rate. A parametric study to investigate the influence of the control parameters on the dynamic response is conducted. A dimensionless equation is developed to predict the settling time of the response. Furthermore, the optimum values of the control parameters of the ACV are obtained. This can guide the designers of such vehicles to select the proper values of these control parameters for better performance.

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Nomenclature

M	Mass of the vehicle (*kg*)	T_{ss}	settling time (*s*)
L	Skirt length (*m*)	v_0	Initial velocity (*m/s*)
d	Skirt height (*m*)	$\bar{L}$	Normalized ACV skirt length
z	Heave displacement (*m*)	$\bar{\dot{m}}_{in}$	Normalized mass flow rate
$\ddot{z}$	Vertical acceleration (m/s^2)	$\bar{M}$	Normalized ACV mass
p_a	Atmospheric pressure (101000 *Pa*)	$\bar{T}_{ss}$	Normalized settling time
p	Cushion pressure (*Pa*)	m	Mass of air inside the cushion volume (*kg*)
A	Cushion area (m^2)	$\dot{m}$	Net mass flow rate of air (*kg/s*)
γ	Specific heat ratio $\gamma = c_p/c_v$	$\dot{m}_{in}$	Mass flow rate of air inside the cushion (*kg/s*)
R	Gas constant	$\dot{m}_{out}$	Mass flow rate of air outside the volume (*kg/s*)
T	Temperature of air (*K*)	c_0	Correction coefficient factor
ρ_a	Atmospheric Air density (1.189 kg/m^3)	g	Gravitational acceleration ($9.81\ m/s^2$)
V	Cushion volume (m^3)	ρ	Air cushion density (kg/m^3)

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