Control of Pressure-Comfort and Motion in Mega-rise Elevators

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Abstract

Elevators are becoming faster in order to increase peak load capacity in mega rise buildings. However, minimum flight time in long descents will be determined by ear pressure comfort constraints. As a consequence, the motion control of high speed elevators will be need to contain logic to slow the car flight in some instances in order to maintain pressure-comfort. Passive and active methods of pressure control can be used to provide pressure-comfort with less impact on flight times. The elevator will be able to move most quickly with active pressure control, less quickly with two-speed passive control, and least quickly with conventional motion dictation.

Introduction

The need to maintain pressure-comfort will constrain the usefulness of very high speed elevators for mega rise buildings. Increasing elevator car speeds is meant to significantly reduce flight time in mega rise buildings, thus increasing the elevator's peak passenger carrying capacity. However, mega rise buildings have significant variations in air pressure between the top and bottom, and humans are comfortable with changes in pressure only as long as the pressure change is not too great or doesn't occur too quickly. As a consequence, the motion control of an high speed elevator will be need to contain logic that slows the car flight in some instances in order to maintain pressure-comfort. This paper describes a method for specifying ear comfort requirements, analyzes the impact of pressure comfort requirements on flight time and contract speed, when standard dictation is used, and describes several methods for controlling car pressure and integrating pressure and vertical motion control in order to effectively exploit higher speeds while still maintaining ear comfort. This paper is relevant for elevator speeds greater than 7 m/s and travels of 150 to 2000m. This flight envelop includes the most advanced elevators in current use, which have contract speeds of 9 to 12 m/s and rises up to 340m. It also extends to faster elevators for future elevator designs for mega rise buildings. The purpose of this study is to anticipate requirements of this extension and to suggest and analyze approaches to meeting those requirements.

In this paper, pressure change is sometimes expressed in terms of the rise above sea level in the International Standard Atmosphere that has the same magnitude pressure change. A 12.01 Pascal pressure change is equivalent to 1 meter altitude change. Extensions of the results to other atmospheric conditions are straight-forward.

Pressure-Comfort Requirements

Effects of Pressure Change on Passengers

There has been much research on this subject, with an emphasis on aeronautics and underwater operations. The research considered both comfort and perception of pressure change as well as how large a pressure change trained personnel can endure. Comfort and perception results are reviewed here. Changes in pressure might cause gases in the body to move, to change from a dissolved state in the blood tissue into a gaseous state, called the "bends," or to expand or contract within body cavities (Ref. 1, 2, 4). The bends do not occur for pressure changes equivalent to less than 6,000 m of altitude change, so this disorder is not a factor when considering elevator comfort (Ref. 1, 2, 3, 4). However, gases expanding or contracting in the digestive tract, the teeth, and the ears can potentially cause discomfort.

The human digestive tract contains gas, because of bacterial metabolic action and air swallowed during eating or drinking. The elasticity of the walls of the digestive tract allow this body cavity to expand considerably. A series of experiments determined that approximately 1% of those subjected to the pressure change of 610 m would experience abdominal fullness (Ref. 1), while another stated that discomfort would usually not be encountered with less than 2100 m (Ref 5). Even with a pressure change associated with 10,000 m altitude change only 3.6% of those sampled experience discomfort (Ref. 4). Discomfort due to abdomen gases can be neglected.

A dentist may trap gas between a tooth and its filling during an incorrect operation. During changes in barometric pressure, a toothache can occur because the trapped gas expands. However, even at aircraft pressure-altitudes, only 0.5% of routine altitude indoctrination flights caused toothache (Ref 1). It is extremely unlikely that such problems will occur at the altitudes traveled by elevators.

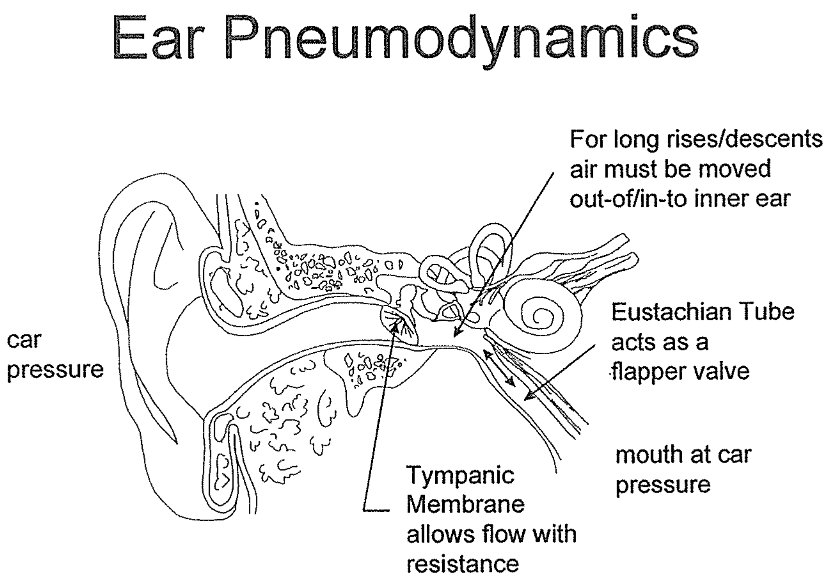
The body cavity of the middle ear is, however, more sensitive to changes in pressure which needs to be considered when designing an elevator system.

Ear pressure-comfort

The middle ear is a gas filled cavity located between the outer ear and the inner ear. The tympanic membrane, a slightly flexible partition that nominally does not pass air, separates the outer ear from the middle ear. The eustachian tube is a narrow slit which sometimes opens, thereby connecting the middle ear to the back of the nose, and sometimes closes, thereby sealing off the middle ear. When the elevator car pressure, P_{car}, falls, the pressure gradient opens the eustachian tube, allowing air to flow so as to reduce $P_{car} - P_{ear}$, the ear pressure differential. When P_{car} rises, the pressure gradient does not open the eustachian tubes (Ref. 1, 2, 3, 4, 5, 6).

During the elevator's ascent P_{car} falls, the tympanic membrane gradually bulges and produces a distinct feeling of fullness, until at an average of 2000 Pascals (equivalent to 166 meters), the eustachian tube is forced open, automatically relieving the strain on the tympanic membrane. The eustachian tube remains open until the pressure difference across the tympanic membrane falls to approximately 500 Pa. If the elevator continues to ascend, the eustachian tube opens approximately every 150m, thereby effectively controlling pressure across the tympanic membrane. (Ref. 2, 3, 4). There is no need for pressure control in an ascending elevator.

During the elevator's descent, the eustachian tube remains closed causing the tympanic membrane to bulge inward. Because the eustachian tube does not automatically open in descent, the ear pressure equalizes to car pressure more slowly, due to air leakage around the tympanic membrane. If car pressure increases too rapidly some discomfort will result. To alleviate this discomfort a passenger must swallow, stifle a yawn, pop his ears, or perform similar acts to open the eustachian tube. Humans unconsciously swallow approximately every 90 sec, but this is longer than it takes for a fast elevator flight to cause uncomfortable ear pressure. In the unlikely event that pressure across the tympanic membrane exceeds 10,700 Pa, the individual will be unable to voluntarily vent his middle ear (Ref. 1, 2, 3, 4).



The following table summarizes the relationship between the pressure across the tympanic membrane and the level of discomfort experienced (Ref. 1, 5). Note that due to the ear dynamics, a 300m descent results in less than 3603 Pa of pressure-differential.

Pressure Across Tympanic Membrane (Pa)	Symptoms	Pressure-Altitude (m)
0 - 400	No perception	0 - 41
500 - 1300	Perception of fullness in ears	41 - 108
1300 - 2000	Distinct fullness in ear; lessen sound intensities	108 - 166
2000 - 4000	Discomfort, fullness, tinnitus, desire to clear ears	166 - 333
4000 - 10000	Increasing pain, dizziness, and nausea	333 - 832
10000 - 20000	Voluntary clearing difficult or impossible	832 - 1665
>20000	Tympanic membrane ruptures	>1665

New Perspective on Elevator Pressure Comfort Requirements

A new method for specifying pressure-comfort requirements is presented here. It uses a mathematical model of ear pneumodynamics in order to analytically predict the pressure difference across the ear tympanic membrane for various elevator velocity profiles. The requirement for providing pressure-comfort is then stated in terms of a maximum allowable pressure difference across the tympanic membrane, as predicted by the model.

Ear Pressure Mathematical Model

Mathematical models of the dynamics of middle ear pressure have been developed. This analysis uses a model for predicting the pressure across the tympanic membrane, ΔP, used by the commercial aerospace industry for developing aircraft environmental control systems.

$$\frac{d\Delta P}{dt} = b - \sqrt{a * \Delta P + b^2} + \frac{dPcar}{dt},$$

where Pcar is the car pressure in Pascals, a = 7.078 Pa/sec^2, b = 35.412 Pa/sec and t is time in seconds. Note, if car pressure is constant, ΔP will decay to zero.

The maximum pressure developed across the tympanic membrane for various tall buildings was determined by using an elevator simulation of elevator car altitude for express flights from top to bottom as an input to the above ear model. Results are shown in the following table for some very tall buildings with fast elevators.

Building	Rise, m	Max speed m/s	Max acceleration, m/s^2	Maximum tympanic pressure, Pa
John Hancock Center	344	9.14	1.2	1824
Landmark Tower	267	12.5	0.8	1655
Sears Tower	410	8.0	1.2	1769
World Trade Center	420	7.62	1.2	1724

Note that the ear pressure differentials in the three tallest buildings shown are about 1800 Pa, even though the elevators have various heights, contract speeds, and acceleration limits. The contract speeds of these elevators have been adjusted to satisfy passengers and building managers. These three independent designs end up with nearly the same predicted ear pressure maximums. It is useful to base pressure-comfort specifications in terms of the above mathematical model of the ear because these three elevator designs implicitly agree on a specification in this form, the tradeoff between contract speed and pressure-comfort is explicit, and, as will be shown, this model is amenable for analyzing the impact of pressure comfort on motion control and for designing integrated motion and pressure comfort controllers.

Recommended Pressure Comfort Requirement

The recommended pressure-comfort requirement is to keep the pressure difference across the tympanic membrane under ΔPear =1840 Pascals, as predicted by the above dynamic model of the ear. The relatively aggressive 1840 Pa level of pressure-comfort specification is used in the illustrative examples. However, the results can be modified to meet different specifications of pressure differentials, for other degrees of comfort.

For any ΔPear, there is an associated constant car velocity, Vear, for which ΔP will approach the constant value of ΔPear, as predicted by the ear model. A steady car pressure rate of change of 84 Pa/s will produce a steady state ΔPear of 1840 Pa. Assuming the pressure in the car is the same as that in the hoistway, Vear is 7.0 m/s for this pressure specification.

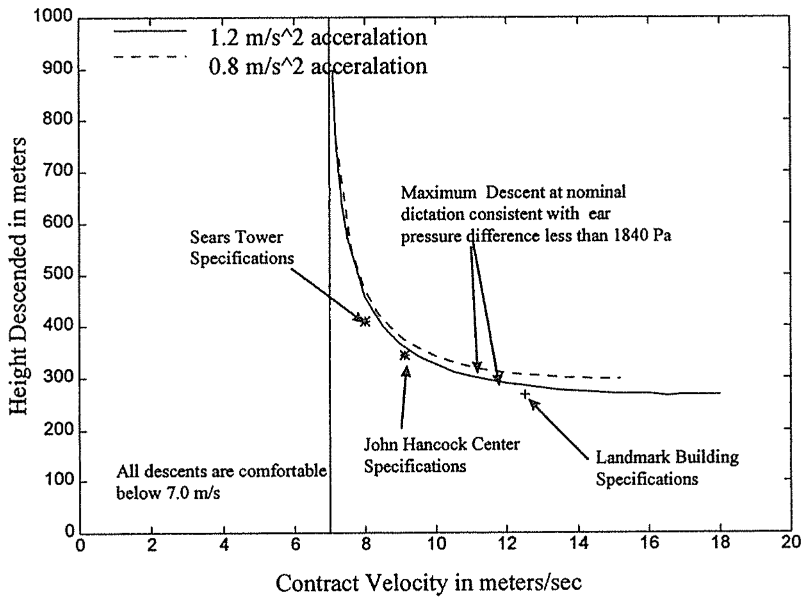
Impact of Pressure Comfort Requirement on Elevator Design

The maximum height from which an elevator can comfortably descend to sea level can be determined as a function of peak elevator speed with the following analysis.

(1) Solve for the ear pressure difference, **ΔPc**, when the decel phase of the flight must begin so that ΔP just reaches ΔPear (1840 Pa) when the car speed has dropped to Vear (7.0 m/s). This involves solving the ear pneumodynamics backwards in time (Ref. 9).

(2) Solve the ear pneumodynamics along the nominal car trajectory in forward time, starting when the car is at rest, going through the acceleration phase, and into an indefinite constant velocity phase. Note the distance the car has traveled, **Hd**, when ΔP = ΔPc. This is where the car must begin its decel in order to maintain pressure-comfort. Hmax is Hd plus the distance that would be traveled in a nominal deceleration.

Maximum Descent Height That Will be Pressure-Comfortable as a Function of Contract Velocity and Acceleration



Hmax is the maximum descent distance that can be traveled using the nominal trajectory that will still meet the ear pressure specification. The results of this analysis is shown in the plot above. Using this plot, the maximum contract speed for an elevator using standard velocity dictation methods can be determined for any given rise. The rise and contract speeds for several existing very high rise elevators are also shown for comparison. Since their contract speeds were partially chosen based on empirical rules and partially based on elevator passenger complaints, the fact that meet fall below the maximum speed line tends to validate the method of analyzing pressure-comfort described here.

Indirect Pressure-Comfort Control via Elevator Motion Control

In indirect control, the elevator velocity is controlled to indirectly control car pressure and thus to control the pressure differential across the ear tympanic membrane. Due to ventilation, the pressure inside the car differs from that of the hoistway by only an imperceptible amount. For practical purposes, the rate of change of car pressure altitude is the descent velocity of the car. This method modifies the motion control algorithms so that when the pressure differential predicted by the model reaches ΔPear, the car speed in the remainder of the descent is less than or equal to the critical ear speed, Vear. This ensures that ΔP will not exceed ΔPear, since Vear is the rate of pressure change that will result in a stable, steady pressure differential of ΔPear.

A two-speed indirect control algorithm is presented here that uses two deceleration phases instead of one. The first deceleration phase reduces car speed from a constant Vp to a constant Vear. The second deceleration reduces car speed from a constant Vear to a constant zero (Ref. 9)

The control algorithm is as follows:

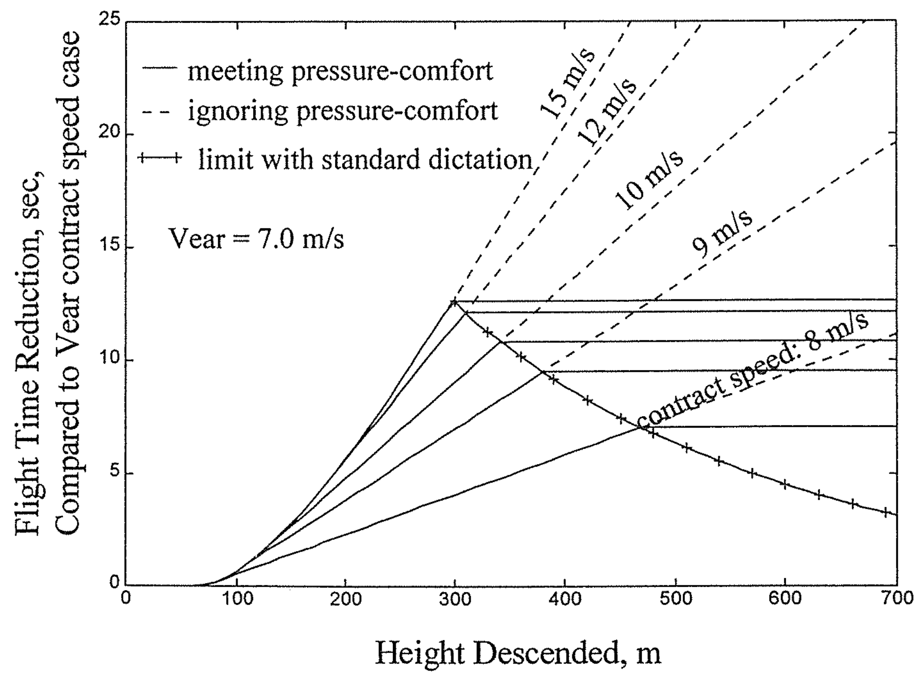
(1) Compare the descent distance to Hmax, which is the maximum descent distance that can be traveled using the nominal trajectory that will still meet the ear pressure specification. If the distance to be traveled is less than or equal to Hmax use a standard trajectory with a single decel phase. If the descent is greater than Hmax, then use two decel phases as per steps (2) and (3).

(2) Begin the first deceleration, to speed Vear, after distance **Hd** is traveled.

(3) Hold velocity at Vear until the distance to go is **H2**, then begin the final deceleration.

Hmax and Hd are determined via the method described in the previous section. H2 is determined by standard methods of the elevator industry.

Two-speed Indirect Control of Pressure-Comfort Allows High Speeds During a Portion of Descent, Thus Reducing Flight Time



The elevator with two-speed control will be faster than that with a standard trajectory because it uses a higher speed for a least part of the flight. The plot above shows the results of simulation analysis comparing two-speed cases with standard dictation if pressure comfort were ignored. It also shows the limiting case if pressure-comfort were provided using standard dictation. Consider the example of a 400m descent with a car that can potentially reach 12 m/s speed. Disregarding pressure comfort allows this car to make the descent 17.5 sec faster than a car with a contract speed of Vear. If pressure comfort were provided with standard dictation, the contract speed can not exceed 8.5 m/s and thus the descent is only 8.86 sec faster. When the two-speed dictation is used, a comfortable ride is provided with a descent that is 12.14 sec faster.

Active Control of Ear Pressure-Comfort

This approach uses a mechanism for active control of car pressure, pressure trajectory logic that moves air into the inner ear quickly and comfortably, coordination logic that ensures that the car arrives at its destination at the same time that the car air pressure arrives at the ambient pressure at the destination, and a minor modification to the motion control logic that allows the coordinating algorithm output to vary the time of flight. The resulting elevator controller provides both motion and pressure comfort.

Pressure Trajectory Logic

The time between the initial door closing and their opening at the destination must be long enough for the passenger's ears to adjust to the pressure change for long flights. In descent, air must flow into the inner ears of the passengers. The fastest acceptable elevator trip will be provided by the elevator that accomplishes the required air flow most quickly without causing discomfort. Since the flow into the ear increases monotonically with the pressure difference, **the fastest long elevator descent will be the one which most quickly creates and maintains the largest comfortable pressure difference across the tympanic membrane.** The optimal pressure trajectory algorithm follows this strategy. The algorithm is described graphically below.

The minimum time trajectory is as follows:

1) Car pressure at the start of the run should remain equal to the ambient air pressure as long as the car doors are open.

2) After the car doors shut, the fan should be run at its maximum rate, which causes car pressure to change at w Pa/sec.

3) After te seconds, the car pressure should vary at the rate of Vu until it reaches the ambient pressure at the destination, where

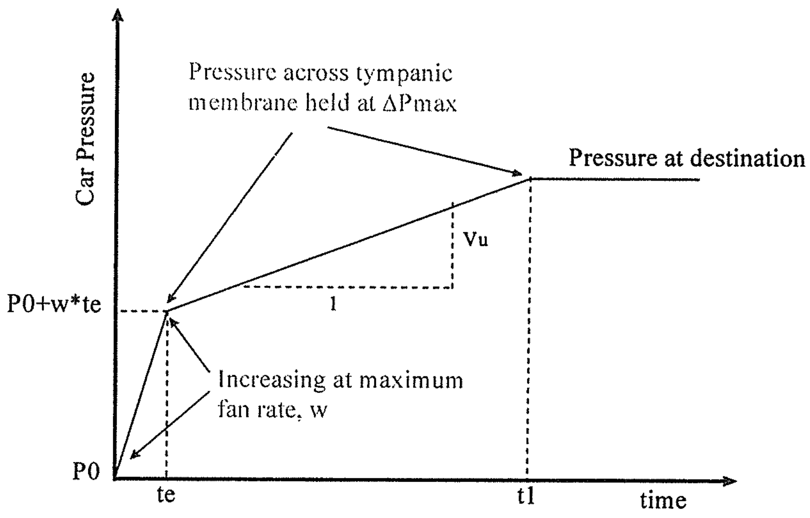
$$te = -\frac{2}{a}\left[12.01 * Vu + (w+b) * \log\left|1 - \frac{12.01 * Vu}{w}\right|\right] \text{ seconds, and}$$

Vu will be set by the coordination algorithm to a value less than or equal to Vear.

4) The car pressure should be held at the ambient pressure at the destination until the doors open, then it can shut down.

As shown in Reference 10, te is time needed to increase ΔP, of the ear pneumodynamic model, from zero to ΔPu, when the car pressure is changing at rate w. ΔPu is the equilibrium pressure of the ear pneumodynamic model if the rate of change of car pressure

Minimum Time Car Pressure Trajectory Where
ΔPu <= ΔPear and Car PressureRate-of-change <= w.



is 12.01*Vu. Setting Vu less than or equal to Vear will ensure that ΔP remains less than or equal to ΔPear. The time to accomplish the required pressure change for the descent is then

tp = (H-te*w/12.01)/Vu + te, where H is the descent height.

Motion Control Algorithm

It is assumed that the motion control algorithm includes one or more parameters that might be reduced to slow the ride if necessary to slow the trajectory to coordinate with the pressure control. The remainder of this paper assumes a minimum time motion trajectory with jerk, acceleration, and velocity constraints, and that the acceleration and jerk limits can be reduced by the same factor to provide a more comfortable ride if ear pressure constraints dictate the flight time.

Coordinating Algorithm

The coordinating algorithm ensures that car pressure reaches the destination pressure at the same time the car doors begin to open. It does this by comparing the predicted times to accomplish the pressure and motion trajectories and slowing either the pressure or motion trajectory, as appropriate. The pressure trajectory is slowed by setting Vu <= Vear. A lower rate of change will result in lower, and thus more comfortable, ear pressure differential. The motion trajectory is slowed by setting the motion controller's acceleration and jerk constraints, au and ju, to less than their nominal values, an and jn.

The coordinating algorithm is as follows (Reference 10):

Compute: Ve = g(H) and set Vu = minimum of Ve and Vear

Compute: ax = h(H) and set au = minimum of ax and an, and set ju = jn(au/an).

g(H) and h(H) are functions of the height to be descended, H. g(H) is the value of Ve which satisfies the equation:

$$H=\frac{Ve(\frac{Vp}{an}+\frac{an}{jn})-2*\frac{12.01}{a}\left(\frac{w}{12.01}-Ve\right)\left(Ve+\frac{(w+b)}{12.01}\log\left|1-\frac{12.01*Ve}{w}\right|\right)}{1-\frac{Ve}{Vp}}$$

, and

$$h(H)=\frac{Vp*Vear}{\left[H\left(1-\frac{Vear}{Vp}\right)-\frac{an*Vear}{jn}-\left(\frac{w}{12.01}-Vear\right)te\right]}.$$

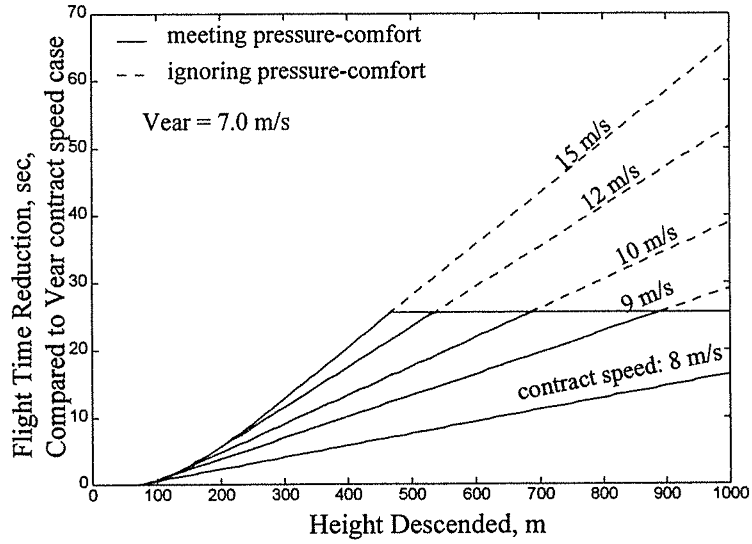
Vp, an, and jn are the nominal velocity, acceleration, and jerk constraints of the motion controller. Ve is the value of Vu that causes pressure trajectory to finish at the same time as the nominal motion trajectory. If the resulting Ve is less than Vear , the flight time is limited by the acceleration constraint and the predicted pressure across the passengers ears can be reduced to less than ΔPear. Otherwise, the flight time is limited by ear pressure comfort and that Vu should be set to Vear.

If ax and jx are the values of au and ju that cause the motion trajectory to finish at the same time as the pressure trajectory. ax < an implies that the flight time is limited by the pressure comfort constraint and the acceleration level can be reduced to less than an. Otherwise, the flight time is limited by acceleration constraints and that au should be set to an.

Analysis

The elevator flight times have been evaluated using an elevator simulation for a variety of contract speeds and descent distances. A fan that can pump up the ear pressure to its comfortable limit in 10 seconds was used. For example, with the active pressure control system, ear pressure comfort can be maintained without sacrificing the flight time gains

With a 10-Second Fan, Active Control of Pressure-Comfort Allows The Full Capability of a 15 m/s Car Can Be Used for Descents of Less Than 450 meters



expected with a 12 m/sec elevator for rises up to 520m. In the section of the graph where time saved increases with contract speed, the acceleration constraints determine the flight time. For longer descents, flight time will be determined by the pressure-comfort requirements. This is indicated on the graph by a maximum flight time reduction.

Reference 10 has estimated the amount of car air flow necessary to follow the optimal pressure trajectory. Compared to a normally ventilated car, active pressure control has similar flow rates but causes this flow to occur earlier in the flight.

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Biography

Dr. James Fuller is Senior Principal Engineer of Controls Technology at the United Technologies Research Center which provides research services to Otis Elevator and other United Technologies divisions. He has developed multivariable and adaptive control and estimation algorithms for helicopter flight control, X-wing flight control, missiles, HVAC systems, and elevators. He has also developed control theory in the areas of periodic systems, neural nets, optimal control, and fault resistant logic. Dr. Fuller received his Ph.D. in Applied Mechanics from Stanford. He also holds a M.S. degree in Engineering Systems from U.C.L.A. and a B.S. degree in Electrical Engineering from Cornell University.