



Research

Dynamics and Stability
of Capsules
In Pipeline Transportation

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1996

UNIVERSITY OF MINNESOTA
CENTER FOR
TRANSPORTATION
STUDIES

FUNDING ACKNOWLEDGEMENT

This project was conducted with funding provided by the Center for Transportation Studies (CTS). The CTS supports the University of Minnesota's research mission with a broad program covering many topics related to transportation. The program includes both fundamental and applied research, with the goal of expanding the existing body of transportation knowledge.

Technical Report Documentation Page

1. Report No. MN/RC - 96/17	2.	3. Recipient's Accession No.	
4. Title and Subtitle DYNAMICS AND STABILITY OF CAPSULES IN PIPELINE TRANSPORTATION		5. Report Date May 1996	
		6.	
7. Author(s) Yiyuan Zhao and Thomas S. Lundgren		8. Performing Organization Report No.	
9. Performing Organization Name and Address Aerospace Engineering and Mechanics Department University of Minnesota 107 Akerman Hall 110 Union Street SE Minneapolis Mn 55455		10. Project/Task/Work Unit No.	
		11. Contract (C) or Grant (G) No. (C) 72274 TOC# 148 (G)	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Final Report 1994-1995	
		14. Sponsoring Agency Code	
15. Supplementary Notes			
16. Abstract (Limit: 200 words) <p>This project studies a new system concept for freight transportation. The idea is to use capsules to transport cargos in concealed pipelines powered by linear electric motors. Such a concept advocates the separation of freight transportation from human movement and can be very effective in reducing the ever-increasing highway congestion problem.</p> <p>This report examines the technical aspects of such a freight pipeline system powered by linear induction motors. Forces acting on a capsule are first discussed, followed by the study of aerodynamic drag forces on a capsule and linear induction thrust forces. Stabilities of both a single capsule and a multiple capsule system are also discussed. These results reveal the basic characteristics of a freight pipeline system, propelled by linear induction propulsion. Various technical issues are discussed.</p> <p>Several related topics are recommended for future research.</p>			
17. Document Analysis/Descriptors Freight Pipelines Tube Transportation Linear Electric Propulsion		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 40	22. Price

DYNAMICS AND STABILITY OF CAPSULES IN PIPELINE TRANSPORTATION

Final Report

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May 1996

Published by

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail Stop 330
117 University Avenue
St Paul, Minnesota 55155

This report presents the results of research conducted by the authors and does not necessarily reflect the official views or policies of the Minnesota Department of Transportation.

Acknowledgments

The authors would like to acknowledge and thank the following individuals for their participation on the Technical Advisory Panel for this project and contributions to this document:

John Sampson	Mn/Dot Environmental Services
Dr. Larry Foote	Mn/Dot Environmental Services
Greg Paul Busacker	Mn/Dot Environmental Services
Richard Lambert	Mn/Dot Office of Railroads & Waterways
Don Kieffer	Mn/Dot Office of Investment Management
Don Botz	Mn/Dot Office of Research Administration
Steve Sweney	DPS Office of Pipeline Safety
Charles Kenow	DPS Office of Pipeline Safety

We also thank Prof. D. D. Joseph at the University of Minnesota and Mr. W. Vandersteele at Ampower, Inc. for many helpful discussions.

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Executive Summary

This project studies a new system concept for freight transportation. The idea is to use capsules to transport cargos in concealed pipelines powered by linear electric motors. Such a concept advocates the separation of freight transportation from human movement and can be very effective in reducing the ever-increasing highway congestion problem. In addition, it provides an efficient mode of freight transportation for special corridors such as between an airport and a city center, between two locations within a city, or between two major cities.

The concept of freight pipelines has existed for many years. However, the freight pipeline systems that have been extensively examined so far employ pneumatic blowers as the power source. Pneumatic pipelines suffer from short haul range, high noise level, and poor energy efficiency. In the proposed concept, linear electric motors are used as the power source. The use of linear electric motors is always more efficient than that of pneumatic blowers, with little environmental pollution and much longer range capability. Underground pipeline systems have little impact on environmental surroundings. In comparison with a subway system, a pipeline system is easier to build and to maintain. It also eliminates potential dangers to human presence. An automated pipeline system can operate around the clock. In Minnesota, such a system can operate regardless of the weather conditions.

This report examines the technical aspects of such a freight pipeline system powered by linear induction motors. Forces acting on a capsule are first discussed, followed by the study of aerodynamic drag forces on a capsule and linear induction thrust forces. Stabilities of both a single capsule and a multiple capsule system are also discussed. These results reveal the basic characteristics of a freight pipeline system, propelled by linear induction propulsion. Various technical issues are discussed.

1. Introduction: Freight Transportation via Pipeline

It has been well recognized that the current highway system is approaching saturation with the ever-increasing traffic in both freight transportation and human movement. Many of the nation's roads are clogged and congestion continues to worsen. The conventional approach of building more roads has ceased to be effective in most areas of the country for both fiscal and environmental reasons. Research is being conducted to enhance the capacities of the existing infrastructure. At the same time, it is very important to study new transportation infrastructures.

Freight transportation and human movement have different characteristics. Moving people requires flexibility, convenience, and speed; transporting freight requires cost-effectiveness, on-time delivery, and security in transit. Today, most human movement is achieved with a combination of personal automobiles and air flight. On the other hand, freight transportation is mainly achieved by long overhaul trucks. Truck transportation offers more flexibility but not necessarily at a lower cost than trains.

However, the mixture of freight transportation and human movement presents a constraint to the highway capacity and safety. Truck drivers often have to operate the vehicles for a long time and while fatigued. During Minnesota winters, trucks are especially intimidating to travelers in automobiles. At the same time, personal automobiles also present a challenge to trucking operation. Truck drivers have to yield for cars and have to be ever-watchful of small cars. In fact, the separation of freight transportation from human movement will increase the efficiency and safety of both [1].

In this report, we study the use of electricity-powered pipelines in efficient freight transportation. The idea is to use capsules for carrying cargos in concealed pipelines powered by linear electric motors. This report focuses on the technical aspects of such a pipeline system. In particular, we examine the basic characteristics and technological requirements associated with the use of linear induction motors.

The proposed system concept can also be used for human movement. Detailed requirements for freight transportation and human movement will be different. For example, people capsules would have to have their own air supply to insure that air pressure changes

could not harm passengers. Nonetheless, the preliminary technical analysis conducted in this report will apply to both cases.

1.1 Freight Transportation via Pipelines

Freight transportation via pipelines is not a new concept. Among the first advocates, George Medhurst proposed pipeline systems both for freight transportation and for passenger movement [2]. Small diameter pipelines powered by pneumatic blowers have been in use since before World War II for high-priority movement of documents. After World War II, large diameter pipelines for transporting limestone and garbage were developed in Japan and Russia. Freight pipelines have been the subject of extensive studies [3-8].

Indeed, pipeline systems for freight transportation have many desirable features. Freight pipelines buried underground would have little environmental impact on surroundings once installed. These systems can be fully automated and do not interfere with human movement. Pipeline systems are closed and can thus be operated regardless of weather conditions.

Freight pipeline systems so far use pneumatic blowers as the power source. They move capsules through a duct by using a vacuum or air pressure. However, booster pumps have to be used to transport cargos beyond a distance of several miles. Since capsules cannot go through the pumps, it becomes necessary to interpose a set of valves and airlocks through which the capsules can bypass the booster pumps. In addition, pneumatic pipelines suffer from low energy efficiency and high noise level. Coupled with the fact tunneling technologies were very expensive and challenging until recently, these system concepts were deemed impossible and were dubbed "pipe dream." Except for transporting coal and other materials over short ranges, pneumatic pipelines have not been widely used.

1.2 Electrical Motor Freight Pipelines

Over the last several decades, technological advances in two areas have made a different but similar concept very feasible. Developments in linear electric motors have made them desirable for freight pipelines. Indeed, the use of electric motors would retain all the advantages of a pipeline system and yet eliminate disadvantages of pneumatic propulsion.

In particular, pipelines powered by electric propulsion will be able to carry freight with much higher efficiency, and lower noise and pollution. At the same time, developments in tunneling technology have made underground pipelines much easier to build [9]. As a result, underground pipelines system powered by electrical motors have become quite feasible.

In 1984, Ampower Corporation of Alpine, New Jersey proposed and patented a capsule pipeline system powered by linear induction propulsion [10]. Economic analyses were conducted to demonstrate the feasibility of such a concept [11]. However, the technical details are yet to be developed. Recently, Japanese researchers have constructed and tested a prototype linear tube transportation system powered by linear synchronous motors [12].

Therefore, we here examine a freight pipeline system powered by linear electric motors. Conceptually, any rotary motor has a linear counterpart. While all electric motors operate based on principles of electromagnetic interactions, there are different types of motors. Polyphase synchronous motors and induction motors both use alternating current as input electricity source [13]. Direct current motors are normally used for small horsepower applications. Correspondingly, there are linear synchronous motors (with permanent magnet or wound field), linear induction motors, and linear direct current motors. The economically feasible choices for a pipeline system are linear induction motors (LIM) and linear synchronous motors (LSM).

The choice between linear induction motors and linear synchronous motors depends on specific system designs and will be examined further in later research. In general, linear synchronous motors can achieve better energy conversion levels than linear induction motors at the expense of higher costs per motor. In particular, the secondary of a LIM does not require any physical contact with the external power source, while the secondary of a LSM needs direct current to generate a magnetic field or has to use a permanent magnet. A LIM with a solid-iron secondary is very rugged and requires low maintenance. In the current study, linear induction motors are used for freight pipelines.

A linear induction propelled pipeline system has some additional advantages. It would require low maintenance effort compared to other modes of freight transportation. Beside addressing the highway congestion problem partially caused by trucks, this concept may

help to reduce the wear and tear of trucks on highways and the associated maintenance costs. In addition, this concept may lend itself to accept standard size containers.

The use of linear induction motors brings in a host of technical challenges. Although many research results on pneumatic pipelines are of reference value, LIM-powered pipelines really represent an entirely different transportation concept. In a pneumatic pipeline system, for example, high air pressures produced by blowers are the driving forces to capsule motions. In a LIM-powered pipeline, on the other hand, the air pressure should be maintained low to avoid high drags. Correspondingly, designs of capsules and pipelines in the two systems are very different.

This report presents results of technical research on the basic characteristics of a LIM-powered pipeline system. It represents the only technical work on this subject that we know of.

1.3 System Layout

Figure 1.1 shows a schematic drawing of the proposed pipeline transportation system. In this system, freight is contained in capsules mounted on wheels. Linear induction motors are used to provide the driving force.

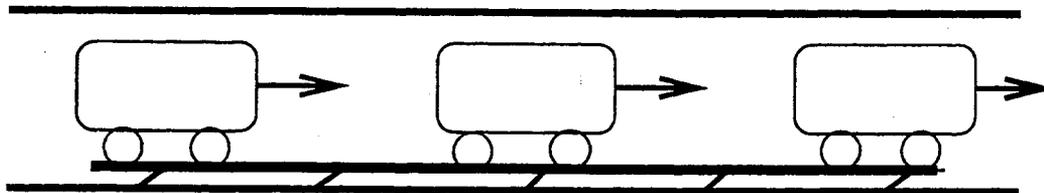


Figure 1.1 A Pipeline Transportation System

A linear induction motor (LIM) consists of a *primary* and a *secondary*. When powered by three-phase alternating current, a moving flux is produced in the primary winding [14-20]. Current induced in the secondary reacts with the flux, producing a mechanical force (Figure 1.2). Both the primary and the secondary of LIMs are flat structures. The

interaction of flux and current moves the secondary linearly. In particular, LIM secondaries are much simpler and less costly than the rotors of conventional induction motors.

There are two choices in using LIMs in pipelines. (1) One can put primaries of LIMs on the freight capsules. This configuration requires complicated windings on the capsule cart, and electrical current transfers between the traveling capsules and the stationary pipetubes via some sliding connection. (2) Alternatively, one can put primary windings on the pipetubes and build capsules as secondaries. The latter configuration makes the system much simpler. If the number of capsules is very small, the second configuration is less efficient than the first one because primaries produce flux without moving secondaries. The proposed pipeline transportation concept is envisaged to move a block of capsules at a time. We assume the second configuration in the current analysis. In fact, German researchers also recommend the second configuration for use in the high-speed train TRANSRAPID system [21-26].

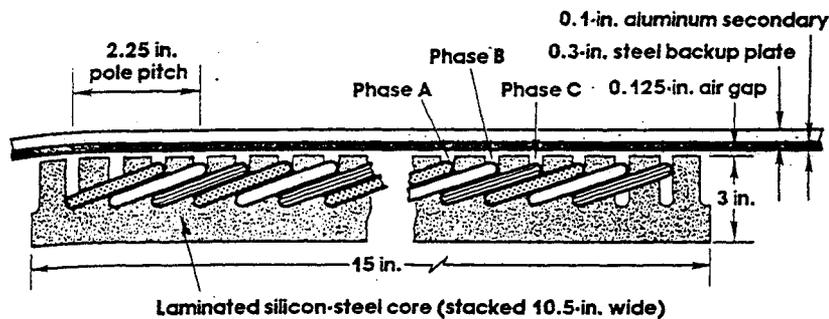


Figure 1.2 Anatomy of a Linear Induction Motor

Figure 1.3 shows the free-body diagram of a capsule in the vertical direction. Forces in the vertical direction that affect the longitudinal motion include: LIM thrust force (F), LIM normal force (P), aerodynamic drag on the capsule (D), rolling friction acting on the capsule wheels (f), normal force acting on the wheels (N), and capsule weight component ($mg \cos \phi$). Forces in the lateral direction include: restraining forces on the wheels from rails (F_{s1}, F_{s2}), side aerodynamic force (Y) that can be assumed small, and force due to gravity caused by tilting surfaces ($mg \sin \phi$). In addition, there are inertial forces due to accelerations. These forces will be automatically included in derivation of equations

of motion. The LIM normal force is generally an attraction force between primary and secondary, but becomes repulsion at high frequencies. This normal force is typically 10% of the thrust force [14].

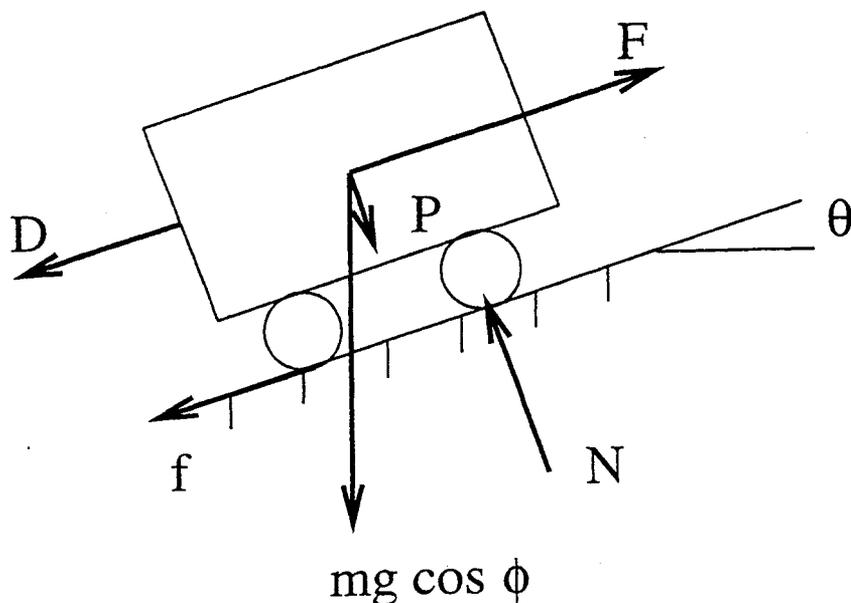


Figure 1.3 Capsule Free Body Diagram

Among these forces, aerodynamic drag on a capsule and LIM thrust force must be studied first before any further analysis can be made. The following chapters present results on capsule drag and LIM thrust force.

1.4 Summary of Main Results

Aerodynamic drag constitutes a major force on capsules. In this study, the total drag force is divided into three components: pressure force on the frontal surface, pressure drop caused by friction along the capsule length, and pressure force on the back of a capsule. Drag modeling leads to the understanding of an interesting phenomenon. If the annular gap between a capsule and the pipeline is small, the flow speed along the gap could become sonic and restrict the flow through the gap. This phenomenon, called “choking”, would cause much larger drag and should be avoided during normal operations. As a result, there is a limit on how fast a capsule can travel for a given gap between capsule and pipetube. On the other hand, the choking phenomenon can be used advantageously as a passive

braking and/or collision avoidance technique. Fins that can be extended may be mounted on capsule surfaces. The extension of these fins can be controlled through a collision surveillance sensor and/or pipeline control station. When extended, these fins increase the cross-sectional area of a capsule and thus decrease the gap. As a result, aerodynamic drag will increase suddenly to serve as a slowing force.

In a linear induction motor (LIM), alternating current is applied to the primary winding directly and is induced in the secondary winding via transformer action. When excited from a balanced polyphase electric source, an LIM will produce a magnetic field in the air gap between the primary and the secondary. This magnetic field will travel at a synchronous speed determined by the number of poles and applied frequency at the primary, exerting a thrust force on the secondary. The thrust force depends on the difference between the synchronous speed and speed of the secondary, the number of poles, and the voltage and frequency applied at the primary. The transient behavior of an induction motor usually disappears very rapidly in comparison with mechanical transients. For our purpose, a steady-state relation between secondary speed and LIM's thrust force is adequate. This relation is discussed. The thrust force of an LIM can be controlled by changing either voltage or frequency of the applied electric current at the primary.

There are three active braking methods for a linear induction motor: regenerative braking, counter current braking, and dynamic braking. (1) In *regenerative braking*, the applied frequency is changed to lower the synchronous speed, so that a capsule would travel in a generator mode. The linear induction motors extract energy from the capsules and thus slow the vehicles down. This method is the most convenient of the three. (2) In *counter current braking*, primary winding polarities are switched to produce a thrust force of opposite direction. This method can produce a large braking force resulting in an abrupt stop. (3) In *dynamic braking*, the polyphase electric source is replaced by heavy resistors. Capsules would stop gradually after losing energy. This method produces a very small braking force at low speeds. These braking properties of linear induction motors make them much more ideal than traditional blowers as the power plant for the pipeline system.

Results on capsule stabilities indicate that feedback control efforts are needed to keep precise capsule spacing. A single capsule is always stable in speed and neutrally stable

in position. In other words, a capsule will resume its nominal speed some time after being perturbed from the nominal speed. During this process, it will develop a finite deviation from the nominal position history. On the other hand, a multiple-capsule system is unstable. Due to differences in weight, aerodynamic drag, thrust force, and/or friction, any two capsules will tend to either drift away infinitely or lose sufficient separation. The flow wake structure behind a capsule is a low pressure region. As the next capsule approaches the capsule in front, this low pressure region will exert a suction force toward the second capsule. Because every capsule would experience the same thrust force from linear induction motors at the same speed, a multiple capsule system will become unstable as capsules get closer to each other. Therefore, it is necessary to keep enough separation between capsules to avoid capsule oscillations and collisions.

2. Capsule Drag Modeling

Aerodynamic drag constitutes a major force on a capsule in a pipeline system. As a result, its modeling is crucial to the understanding of capsule dynamics in a pipeline. In addition, a phenomenon called “choking” plays an important role in the design of pipeline systems.

2.1 Aerodynamic Drag on a Capsule

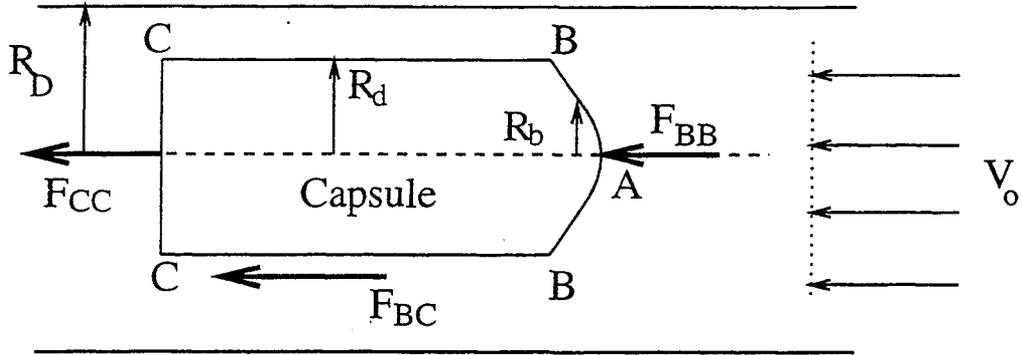


Figure 2.1 Aerodynamic Drag of a Capsule

Figure 2.1 shows the drag determination model used in this method. The total aerodynamic drag on a capsule inside a pipetube is divided into three components: the inviscid pressure drag caused by high pressure on the capsule nose and low base pressure at the rear, a viscous contribution caused by shear stresses in the high speed annular gap region between the capsule and the tube wall and a contribution due to a viscous pressure drop in this gap which causes an additional decrease in the base pressure. These effects are modeled here term by term.

- (1) The momentum integral theorem provides a formula for inviscid drag. For steady flow in a reference frame attached to the capsule

$$D_i = \int_{upstream,a} (p + \rho u^2) dA - \int_{rear\ face,e} (p + \rho u^2) dA$$

$$= A_t(p_a + \rho V^2) - (p_e A_t + (A_t - A)\rho w^2) \quad (2-1)$$

where w is the velocity in the gap, V is the approach velocity at the upstream station a , A_t is the tube area, A is the capsule area, and p_e is the pressure in the gap which is assumed to be the same over the whole capsule rear face, where the velocity is zero. By the Bernoulli equation [27],

$$p_a + \frac{1}{2}\rho V^2 = p_e + \frac{1}{2}\rho w^2 \quad (2-2)$$

and by conservation of mass

$$V A_t = w(A_t - A) \quad (2-3)$$

By eliminating w from the last two equations, we find

$$p_a - p_e = \frac{1}{2}\rho V^2 \left(\frac{A_t^2}{(A_t - A)^2} - 1 \right) \quad (2-4)$$

Using this and w from Eq. (2-3) gives

$$D_i = \frac{1}{2}\rho V^2 A C_{Di} \quad (2-5)$$

with

$$C_{Di} = \beta/(1 - \beta)^2 \quad (2-6)$$

where $\beta = A/A_t$ is the blockage area ratio.

- (2) The shear stress contribution may be obtained by assuming that the gap is small compared to the length l of the capsule and that the flow in the gap is like a turbulent channel flow. In this case

$$D_f = C_f \frac{1}{2}\rho w^2 2\pi R l \quad (2-7)$$

where C_f is a friction coefficient (per Schlichting [28]). Using Eq. (2-3) for w gives

$$D_f = C_f \frac{1}{2}\rho V^2 \left(\frac{A_t}{A_t - A} \right)^2 2\pi R l \quad (2-8)$$

and therefore

$$C_{Df} = \frac{C_f}{(1 - \beta)^2} \frac{2l}{R} \quad (2-9)$$

(3) The pressure drop in the annular channel is given by

$$\Delta p(A_t - A) = C_f \frac{1}{2} \rho w^2 2\pi(R + R_t)l \quad (2 - 10)$$

or

$$\Delta p = \frac{1}{2} \rho V^2 \left(\frac{A_t}{A_t - A} \right)^2 \frac{2l}{R_t - R} C_f \quad (2 - 11)$$

Since this lower pressure is felt over the whole rear face, the additional drag is

$$D_{\Delta p} = A\Delta p = \frac{1}{2} \rho V^2 A \left(\frac{1}{1 - \beta} \right)^2 \frac{2l}{R_t - R} C_f \quad (2 - 12)$$

and this gives

$$C_{D\Delta p} = \frac{1}{(1 - \beta)^2} \frac{2l}{R_t - R} C_f \quad (2 - 13)$$

Combining these into a single drag coefficient one finds

$$\begin{aligned} C_D &= C_{Di} + C_{Df} + C_{D\Delta p} \\ &= \frac{\beta}{(1 - \beta)^2} + \frac{(1 + \beta^{1/2})}{(1 - \beta)^3} \frac{2l}{R} C_f \end{aligned} \quad (2 - 14)$$

where C_f depends on the Reynolds number in the gap.

When applied to a situation where the capsule has velocity V and the tube carries air with velocity v one should calculate the drag using the relative velocity, i.e.

$$D = C_D \frac{1}{2} \rho (V - v)^2 A \quad (2 - 15)$$

using Eq. (2 - 14) for the drag coefficient. Values of the drag coefficient obtained from Eq. (2 - 14) are very close to experimental results reported by Tsuji [29].

2.2 Choking Phenomenon and Aerodynamic Braking

The analysis shown in the last section was for incompressible flow. While in most cases the capsule has a fairly low velocity compared to the speed of sound, the velocity in the gap is much larger and can approach sonic if the gap is small. If this occurs the analysis must be modified to account for the compressibility of air. When the gap velocity reaches the speed of sound the mass flow through the gap is restricted and the flow is said

to be “choked” [30]. Calculations reported by Hammitt [6] show that the drag coefficient stays close to the incompressible value until the gap Mach number nearly reaches one and then rapidly increases to a value which is easily double the incompressible value. This can occur at moderate capsule speeds if the gap is small.

Flow choking should be avoided during normal capsule operation. As a result, the gap must be large enough for high speed capsule operation. Correspondingly, capsule design speed is limited by a maximum value for the blockage area ratio.

The choking phenomenon may be used as an aerodynamic braking technique. Specifically, fins that can be extended may be mounted on the capsule surface. These fins are held under the capsule surface during normal operation and can be extended to stop the capsule. The extensions can be controlled remotely in the operation station. They can also be triggered by a sensor mounted on the capsule nose to avoid collisions, or by some mechanical device at the exit station to stop the vehicle. The proposed concept of aerodynamic braking is similar to the concept discussed in Tsuji, Morikawa & Seki [31].

2.3 Efficiency of Linear Electric Propulsion

In a pneumatic system, simply stated, a pump/blower raises the pressure on one end of the tube and blows the capsules through the tube. Under ideal operating conditions the capsules are moving at the same speed as the pumped air and there is no aerodynamic drag on the capsules. The pressure difference required across the ends of the tube is the same as required to pump air at that speed, namely

$$\Delta p A_t = \frac{1}{2} \rho V^2 2\pi R_t C_f \quad (2 - 16)$$

where Δp is the pressure difference, A_t is the tube area, ρ the density of air, V the capsule speed, R_t and L_t the tube radius and length and C_f is a friction coefficient. The power required is

$$P_{pn} = \frac{1}{2} \rho V^3 2\pi R_t C_f \quad (2 - 17)$$

This is independent of the number of capsules in the tube. This formula neglects rolling friction, which would require an additional pressure drop across each capsule to overcome

this friction, and a consequent air speed in the tube which is greater than the capsule speed.

In the linear electrically driven system each capsule is individually driven by the motor force and is resisted by aerodynamic drag. In a tube, which is open to the atmosphere at both ends, the moving capsules force part of the air to pass through the gap between the capsule and the tube wall and also force some air to flow through the tube. The balance between these effects is determined by the size of the gap. If the gap is very small more air is pushed through the tube. In this sense the linear electric motor takes the place of the pump in the pneumatic system. The pressure distribution in the tube, proceeding in the direction of motion, consists of pressure increases across each capsule and pressure drops between the capsules because of the air friction with the tube walls.

The force on a single capsule is

$$\frac{1}{2}\rho(V-v)^2AC_D \quad (2-18)$$

where A is the cross section area of the capsule, the drag coefficient C_D is given in section 2.1 and v is the velocity of the air in the tube. It may be shown that

$$C_D = (V-v) = \frac{V}{(1+\alpha)} \quad (2-19)$$

where

$$\alpha = \sqrt{\frac{\beta R_t n C_D}{2 L_t C_f}} \quad (2-20)$$

Here n is the number of capsules in the tube and $\beta = A/A_t$ is the blockage ratio. The formula takes into account the frictional resistance of the pushed air, which depending on parameters, can offer less resistance than forcing the air through the gap.

The total power required to drive n capsules is

$$P_{li} = \frac{1}{2}\rho V^3 An C_D / (1+\alpha)^2 \quad (2-21)$$

and therefore the two power requirements may be compared by the efficiency ratio

$$\frac{P_{li}}{P_{pn}} = \frac{\alpha^2}{(1+\alpha)^2} \quad (2-22)$$

where α is the relative friction parameter defined above. This ratio is always less than one. Under maximum traffic conditions (large n) it approaches one. However, when there are only a few capsules in the tube, it becomes much smaller than one. This is because the pneumatic blower has to maintain the same power independently of the number of capsules, in order to keep the speed up. One may therefore conclude that the linear electrical system is always more efficient, and can be much more efficient when the traffic is light.

3. Linear Induction Propulsion Forces

Linear electric motors belong to a special group of electrical machines that convert electrical energy *directly* to mechanical energy in translational motion [13-20]. Linear electric motors in general include d.c. motors, induction motors (asynchronous motors), synchronous motors, and so on. Among these, the most popular one is the linear induction motor.

A linear motor can be obtained by cutting a rotary motor along its radius from the center axis of the shaft to the external surface of the stator core and rolling it out flat. The stator becomes the primary and the rotor becomes the secondary (Figure 3.1). The principles of an LIM are basically the same as of a rotary induction (asynchronous) motor. For simplicity, we use the rotary motor as an example to explain the principles of induction motors.

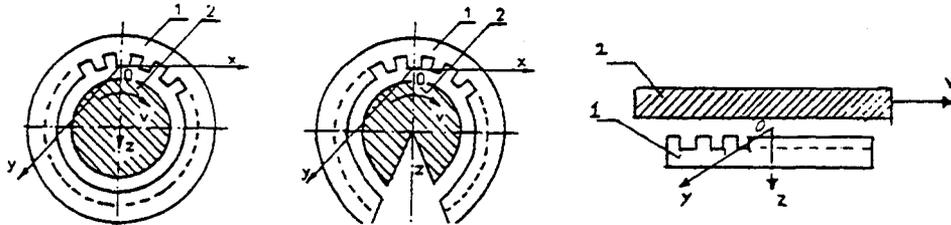


Figure 3.1 Evolution of a Rotary Induction Machine into LIM

3.1 Principles of Induction Motors

In the induction motor, alternating current is applied to the stator winding directly and to the rotor winding by transformer action or induction from the stator. When excited from a balanced polyphase source, it will produce a magnetic field in the air gap rotating at a synchronous speed n_1 (rpm) determined by

$$n_1 = \frac{120f}{p} \quad (3-1)$$

where p is the number of poles in the stator, and f is the frequency (in Hz) of applied current at the stator.

Now assume that the rotor is turning at the steady speed n (rpm) in the same direction as the rotating stator field. The rotor is then traveling at a speed $(n_1 - n)$ rpm backwards with respect to the stator field, or the *slip* of the rotor is $(n_1 - n)$ rpm. Slip is usually expressed as a fraction of synchronous speed. The per-unit slip s is:

$$s = \frac{n_1 - n}{n_1} \quad (3 - 2)$$

This relative motion of flux and rotor conductors induces voltages of frequency sf , called slip frequency, in the rotor. In the induction motor, the rotor terminals are short-circuited. At starting, the rotor is stationary, the slip is $s = 1$, and the rotor frequency equals the stator frequency f . The field produced by the rotor currents therefore revolves at the same speed as the stator field. A starting torque results, tending to turn the rotor in the direction of the stator-induced field. If this torque is sufficient to overcome the shaft load, the motor will come up to the operating speed. The operating speed can never be exactly equal to the synchronous speed n_1 , for the rotor conductors would then be stationary with respect to the stator field and no voltage would be induced in them.

The transient behavior of the induction motor can be studied by assuming that a 3-phase short-circuit takes place at its terminals. The machine will feed current into the fault because of the trapped flux linkage with the rotor circuit. This current will, in time, decay to zero. In practical cases, it is seen that, while the initial short-circuit current of an induction machine is relatively high compared with its normal current, the transient usually disappears rapidly in comparison with the duration of mechanical transients. As a result, the electrical transients in induction machines are frequently neglected. Hence, for many purposes the steady state situation can be used for dynamic analysis.

3.2 Models of Thrust Forces

Figure 3.2 shows a typical steady-state torque-slip curve for electric induction machines, where both motor and generator region are shown. A reasonably good representation of the torque-slip relation in steady state operation of an induction motor is given by:

$$\frac{T}{T_{\max}} = \frac{2}{s/s_{cr} + s_{cr}/s} \quad (3-3)$$

where T_{\max} is the maximum torque possible, s_{cr} is the critical slip or slip at maximum torque. The maximum torque, T_{\max} , depends on the applied voltage, resistance and reactance of the motor and other physical properties of the motor. Therefore, T_{\max} is a design parameter.

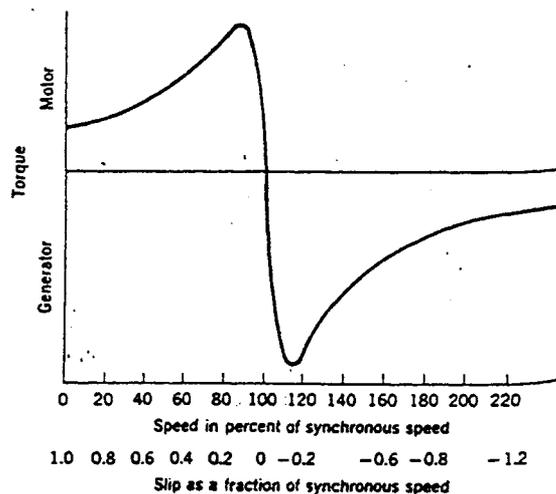


Figure 3.2 Induction Machine Torque-Slip Curve

The formulation for the linear induction motor is very similar to the rotary one except for extremity effects. One can replace rotary variables by their linear counterparts. For example, torque and angular velocity should be changed to force and linear velocity, respectively. The formulas are given as follows:

$$v_s = \frac{2\tau}{T} = 2f\tau = \frac{\omega}{\pi}\tau \quad (3-4)$$

$$s = \frac{v_s - v}{v_s} \quad (3 - 5)$$

$$F = \frac{2F_{max}}{s/s_{cr} + s_{cr}/s} \quad (3 - 6)$$

where τ is the pole pitch or the distance between two poles in the primary, f is the applied frequency at the primary, v is the secondary speed, v_s is the synchronous speed, and F is the linear induction motor thrust force. Again, the maximum thrust force F_{max} is a design parameter.

To use LIMs in a pipeline transportation system, we need to be able to control the thrust force. The thrust force of an LIM can be controlled by changing one of the three things: pole pitch (τ), slip (s), and/or input frequency (f).

Pole pitch (s) is the distance between two winding poles in the primary. A change in the pole pitch of an LIM corresponds to a change in the number of poles of a rotary induction motor. It can only be done in LIMs in a discrete way by designing two or more independent windings with different pole pitches. Therefore, it is not practical to use pole pitch as thrust control.

The slip (s) can be controlled in an LIM with shorted secondary by changing the input voltage, and in an LIM with wound secondary by changing both the input voltage and the secondary circuit resistance. Thrust control by changing the input voltage alone is not economical over a broad speed range, because both efficiency and speed stability are adversely affected.

Thrust control via changing the input frequency (f) can be achieved by feeding an LIM from a variable frequency source, e.g. a converter. We can keep the input voltage constant or variable. If the voltage is changed as well in proportion to the frequency, the flux will remain constant resulting in no change in force. Thrust control by means of voltage and frequency variation also allows the motor to operate not only at speeds below the rated velocity, but also at speeds above the rated velocity. The majority of LIMs can be operated under such conditions without mechanical or thermal problems. This method is suggested to be used for this project.

Figure 3.3 shows the effects of frequency and voltage in thrust control. Three cases are shown: (a) variable frequency f , constant voltage V_1 , (b) variable voltage V_1 , constant frequency f , (c) $\frac{V_1}{f} = \text{const}$. In Figure 3.3, F_r = rated thrust, F_{max} = maximum thrust, and v_s = synchronous velocity.

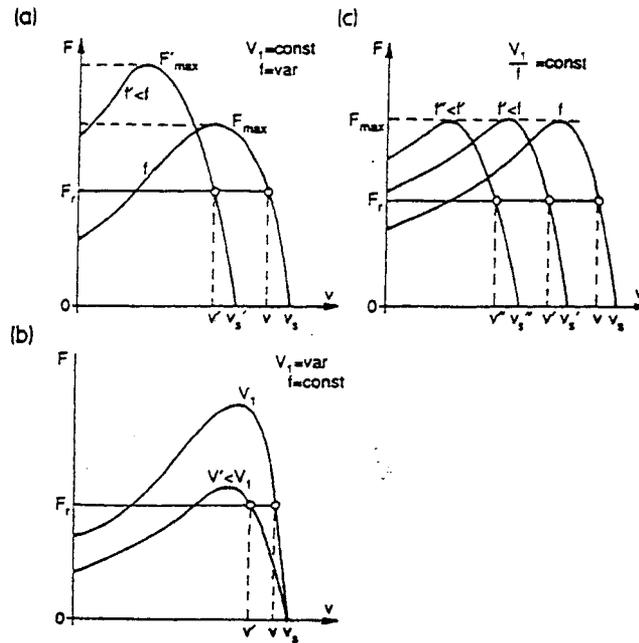


Figure 3.3 Thrust Control in LIMs

3.3 Linear Induction Motor Braking Methods

For the safe operation of a pipeline system, there must be reliable mechanisms to stop capsules in emergency and/or at exit stations. Capsules may be stopped with mechanical devices, aerodynamic drag, and/or linear induction motor thrust forces. Mechanical braking devices are widely used in trains and other ground transportation systems. Design experiences on these systems are well documented. Mechanical braking devices need to be employed to secure a capsule to a specified location once it is stopped. On the other hand, aerodynamic and electrical braking capabilities represent unique and desirable features of the proposed pipeline transportation system.

Electrical braking occurs when the thrust is in the opposite direction of velocity [14-20]. There are three braking methods available on a linear induction motor. Figure 3.4 shows the motor thrust force versus capsule speed in three braking modes. (1) *Regenerative braking* occurs when the speed of the LIM is greater than the synchronous speed, i.e. $v > v_s$. In this case, the LIM operates in a generator mode and thus extracts energy from the moving capsule. Regenerative braking is implemented by decreasing the synchronous velocity below the motor's speed. It can be done by reducing the pole pitch (τ) or the input frequency (f). (2) *Counter current braking or plugging* is obtained by reversal of the primary winding connections while the LIM is running. When the plugging method is used, the input voltage is often reduced to avoid excessive primary current. This method of braking is similar to braking a direct current motor by reversing the input voltage while it's running. (3) Finally, *dynamic braking* occurs when the primary windings are excited by direct current immediately after their disconnection from the three-phase source. This method is similar to braking a direct current motor by disconnecting it from the voltage source and closing the circuit with a resistor.

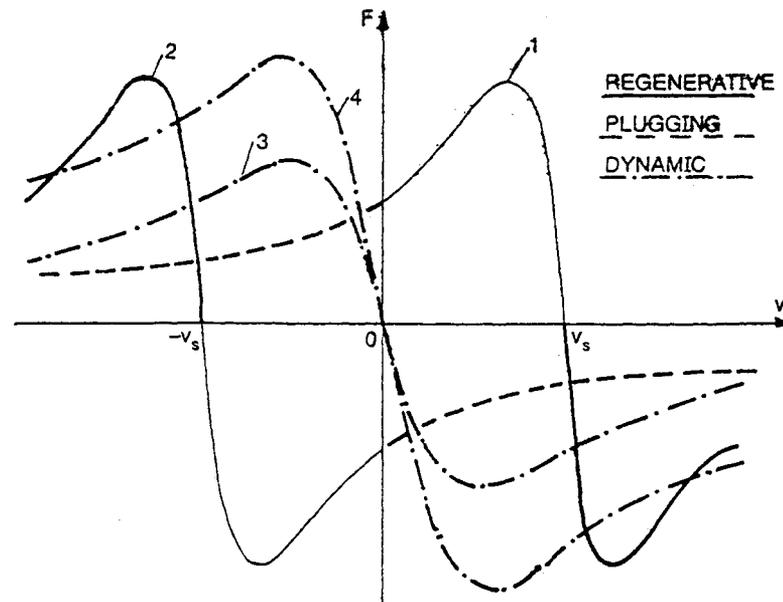


Figure 3.4 Thrust Force versus Speed in LIM Braking Modes

Availability of these methods makes linear induction motors even more desirable than pneumatic blowers as the power source for a pipeline system. In comparison, the regenerative braking method is the easiest to use. It can be achieved gradually through normal capsule speed control and does not require any additional switching logic. The plugging method may produce excessive current and can be used to stop capsules in an emergency. The dynamic braking method produces very small braking forces at low velocities.

4. Stability Analysis

In an operational pipeline system, capsules should travel at specified speeds despite possible imperfections and disturbances in the system. We now examine capsule stabilities in a pipeline system following specified speeds and time histories of capsule positions.

4.1 Normalized Equations of Motion

Equations of motion for a capsule can be derived from the capsule free-body diagram in Figure 1.3.

$$m\ddot{x} = F - \frac{1}{2}\rho v^2 A_d C_D - f_r - mg \sin \theta \quad (4-1)$$

Models of each component are discussed in previous sections. For simplicity, we assume that $\phi = 0$ and LIM normal force $P = 0$ in the following analysis. Nonzero ϕ and/or P will not change the conclusions below.

From Eq. (3-6), the LIM thrust force can be expressed in terms of capsule speed v as

$$F = \frac{2F_{\max} s_{\text{cr}} v_s (v_s - v)}{(v_s - v)^2 + v_s^2} \quad (4-2)$$

Since rolling friction is usually given by

$$f_r = \mu mg \cos \theta \quad (4-3)$$

the capsule equation of motion is

$$m\ddot{x} = \frac{2F_{\max} s_{\text{cr}} v_s (v_s - v)}{(v_s - v)^2 + v_s^2} - \frac{1}{2}\rho A_d C_D v^2 - mg(\mu \cos \theta + \sin \theta) \quad (4-4)$$

Eq. (4-4) can be written equivalently as a set of two first-order ordinary differential equations for convenience. We now introduce the following normalized variables in order to identify key parameters in the capsule equation of motion.

$$\bar{x} \triangleq \frac{x}{v_s^2/g} \quad (4-5)$$

$$\bar{v} \triangleq \frac{v}{v_s} \quad (4-6)$$

$$\bar{t} \triangleq \frac{t}{v_s/g} \quad (4-7)$$

Denote

$$\frac{d(\cdot)}{d\bar{t}} = (\cdot)' \quad (4-8)$$

The normalized equations are

$$\bar{x}' = \bar{v} \quad (4-9)$$

$$\bar{v}' = \frac{2\bar{F}_m s_{cr}(1-\bar{v})}{\bar{v}^2 - 2\bar{v} + 1 + s_{cr}^2} - \bar{D}_s \bar{v}^2 - \mu_e \quad (4-10)$$

where

$$\bar{F}_m = \frac{F_m}{mg} \quad (4-11)$$

$$\bar{D}_s = \frac{\frac{1}{2}\rho v_s^2 A_d C_D}{mg} \quad (4-12)$$

$$\mu_e = \mu \cos \theta + \sin \theta \quad (4-13)$$

Therefore, there are four key parameters affecting the capsule motion: s_{cr} , \bar{F}_m , \bar{D}_s , and μ_e . The critical slip s_{cr} is a function of secondary resistance. It determines the shape of thrust vs. speed curve in Eq. (3-6). \bar{F}_m is the maximum LIM thrust force per unit capsule weight and \bar{D}_s is the aerodynamic drag at synchronous speed per unit capsule weight. μ_e can be considered as a combination of rolling friction and landscape gradient. It is a constant in the equation of motion and does not affect capsule stability. It does affect the steady-state operating speed.

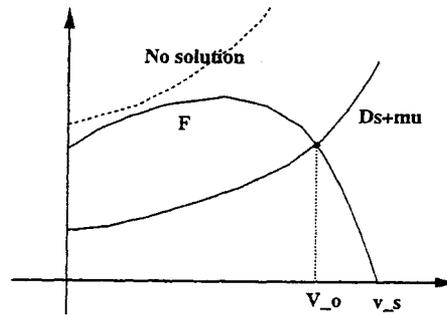


Figure 4.1 Existence of Steady-State Speed Solution

At steady-state operation,

$$\bar{v}' = 0 \quad (4-14)$$

We have from Eq. (4 – 10),

$$\frac{2\bar{F}_m s_{cr}(1 - \bar{v})}{\bar{v}^2 - 2\bar{v} + 1 + s_{cr}^2} - \bar{D}_s \bar{v}^2 - \mu_e = 0 \quad (4 - 15)$$

As shown in Figure 4.1, this equation normally has a solution between (0, 1). Correspondingly, there exists a steady-state capsule speed between (0, v_s). Such a solution does not exist only if the linear induction motor thrust force is less than the aerodynamic drag plus friction force. In this case, the capsule simply will not start.

To numerically determine this speed, we manipulate Eq. (4 – 15) and obtain a fourth order polynomial.

$$\bar{v}^4 - 2\bar{v}^3 + \left(1 + s_{cr}^2 + \frac{\mu_e}{\bar{D}_s}\right) \bar{v}^2 + 2 \left(\frac{\bar{F}_m}{\bar{D}_s} s_{cr} - \frac{\mu_e}{\bar{D}_s}\right) \bar{v} + \frac{1}{\bar{D}_s} [(1 + s_{cr}^2)\mu_e - 2\bar{F}_m s_{cr}] = 0 \quad (4 - 16)$$

A Newton-type of iteration scheme is used. Figure 4.2 plots the steady-state capsule speed as a function of the normalized characteristic drag \bar{D}_s and normalized thrust force \bar{F}_m , at $s_{cr} = 0.2$ and $\mu_e = 0.015$. A solution always exists as long as the normalized thrust force is large enough. Figure 4.2 shows that the steady-state capsule speed decreases as the drag increases or the thrust force decreases.

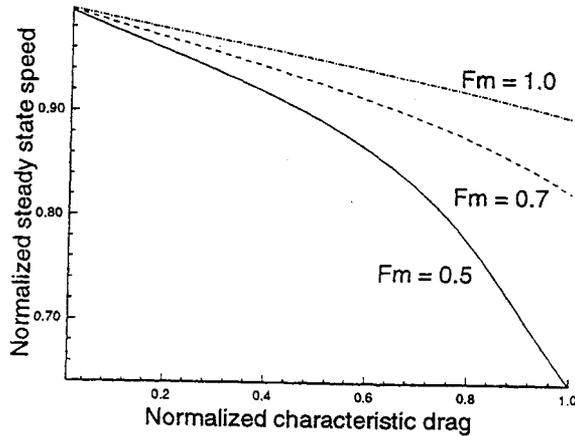


Figure 4.2 Steady-State Capsule Speed

4.2 Single Capsule Stability

We now linearize Eqs. (4 – 9) and (4 – 10) around a steady-state solution: \bar{v}_o and $\bar{x}_o = \bar{v}_o \bar{t}$. In the following, $\delta\bar{v}$ and $\delta\bar{x}$ denote perturbations from this nominal solution. In other words,

$$\bar{x} = \bar{x}_o + \delta\bar{x} \quad (4 - 17)$$

$$\bar{v} = \bar{v}_o + \delta\bar{v} \quad (4 - 18)$$

From Eqs. (4 – 9) and (4 – 10), we have

$$\delta\bar{x}' = \delta\bar{v} \quad (4 - 19)$$

$$\delta\bar{v}' = -A(\bar{v}_o; \bar{F}_m, \bar{D}_s, s_{cr})\delta\bar{v} \quad (4 - 20)$$

where

$$A_0 \triangleq A(\bar{v}_o; \bar{F}_m, \bar{D}_s, s_{cr}) = 2\bar{D}_s\bar{v}_o - 2\bar{F}_m s_{cr} \frac{\bar{v}_o^2 - 2\bar{v}_o + 1 - s_{cr}^2}{(\bar{v}_o^2 - 2\bar{v}_o + 1 + s_{cr}^2)^2} \quad (4 - 21)$$

From classical control theories [32], a positive A_0 guarantees the stability of capsule speed. There are two eigenvalues in the system: 0 and $-A_0$. The zero eigenvalue corresponds to position and $-A_0$ corresponds to speed. If $A_0 > 0$, the capsule will return to a steady-state speed after perturbations. In this case, the position mode has a neutral stability. Namely, any perturbation will result in a constant offset in the capsule position. If $A_0 < 0$, the system is unstable and any perturbation will cause the capsule to deviate away from its nominal solution.

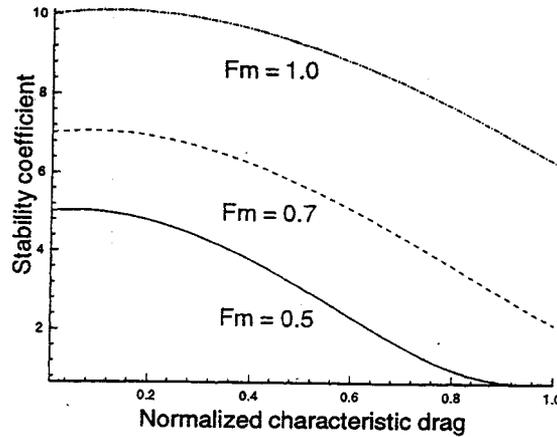


Figure 4.3 Capsule Stability Coefficient

For the physical system, it is always true that $A_0 > 0$. Therefore, a single capsule is always speed-stable. Figure 4.3 plots the stability coefficient A_0 as a function of the normalized drag and thrust force. As the drag increases and/or the thrust force decreases, the capsule becomes less stable and it will take the capsule a longer time to return to its nominal speed once perturbed. With larger drag and/or smaller thrust force, the capsule will take longer time to reach an operating speed from start.

Figure 4.4 shows a typical time history of capsule speed starting from rest. The capsule reaches the steady operating speed monotonically. This curve is obtained from numerical integration of Eqs. (4 – 9) and (4 – 10). A fourth-order Runge-Kutta method is used.

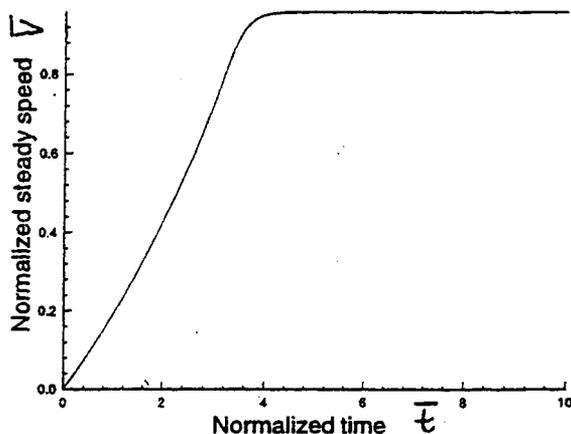


Figure 4.4 Capsule Speed History

4.3 Multiple Capsule Stability

There is a low pressure region behind each capsule. As the second capsule approaches the wake of the first capsule, it will experience less drag on its nose due to the low pressure in the first capsule wake. However, the thrust force on the capsule is still the same at the same speed. As a result, the net force on the second capsule increases. Due to the net force increase, the second capsule will accelerate forward. It may collide with the first capsule or oscillate back and forth while traveling forward. For safety reasons, it is recommended to keep a large distance between any two capsules. In theory, this distance is on the order

of 10 times of the capsule radius. Tsuji [29] shows experimental results where there is little effect at a spacing half of this.

The phenomenon that the second capsule experiences a smaller drag as it approaches the capsule in front is called drafting effect. This local drafting effect, widely used in car racing and bicycling, should be distinguished from the large scale drafting. Large scale drafting occurs in tunnels when multiple trains cause a large air motion which affects all the trains equally. Gawthorpe [33,34] document the average drag reduction when the number of trains increases.

A mathematically simple way to examine multiple capsule stability is by studying the perturbed motion of a single capsule when thrust force, drag, capsule weight, or even friction coefficient changes. Different capsules will definitely have different weights due to difference in cargos. Aerodynamic drag and friction force are also different due to imperfections in capsule manufacturing. Therefore, \bar{F}_m , \bar{D}_m , and μ_e in Eqs. (4 – 9) and (4 – 10) are different for different capsules. Let's assume that these differences are small and around some nominal values, denoted by $()_0$, we have

$$\bar{F}_m = \bar{F}_{m0} + \delta\bar{F}_m \quad (4 - 22)$$

$$\bar{D}_s = \bar{D}_{s0} + \delta\bar{D}_s \quad (4 - 23)$$

$$\mu_e = \mu_0 + \delta\mu_e \quad (4 - 24)$$

As a result, capsule speed and position will deviate from the nominal histories as expressed in Eqs. (4 – 17) and (4 – 18). By linearizing Eqs. (4 – 9) and (4 – 10) around the nominal values, we obtain

$$\delta\bar{x}' = \delta\bar{v} \quad (4 - 25)$$

$$\delta\bar{v}' = -A_0\delta\bar{v} + \frac{2s_{cr}(1 - \bar{v}_0)}{\bar{v}_0^2 - 2\bar{v}_0 + 1 + s_{cr}^2}\delta\bar{F}_m - \bar{v}_0^2\delta\bar{D}_s - \delta\mu_e \quad (4 - 26)$$

It is clear from these equations that any small changes in the nominal thrust, drag, or friction coefficient will cause the capsule speed to deviate away from the nominal speed.

For example, consider the case with only drag perturbation while assuming $\delta\bar{F}_m = 0$ and $\delta\mu_e = 0$. From Eqs. (4 – 25) and (4 – 26), we obtain

$$\delta\bar{v} = -\frac{\bar{v}_0^2\delta\bar{D}_s}{A_0} \left(1 - e^{-A_0\bar{t}}\right) \quad (4 - 27)$$

$$\delta\bar{x} = -\frac{\bar{v}_0^2\delta\bar{D}_s}{A_0} \left(\bar{t} + \frac{1}{A_0}e^{-A_0\bar{t}}\right) \quad (4 - 28)$$

These equations show that a capsule with a different drag coefficient than predicted will deviate from its nominal position history of time infinitely. Therefore, any two capsules will either become infinitely far apart or approach each other over time. As a result, some capsules in a multiple capsule system will collide with one another. Consequently, a multiple capsule system is unstable without precise position control.

5. Recommendations for Future Work

The following topics are recommended for future research. These topics address engineering aspects of the proposed pipeline concept.

5.1 Effects of Adits

The choking phenomenon seriously limits the maximum speed of capsule motion for a given pipetube/capsule geometry. To avoid drag penalties associated with choking, capsule diameters have to be small compared to inside pipetube diameter at high speeds. Alternatively, we envision a pipeline freight system to consist of two parallel tubes connected by pressure relief cross tunnels or adits. As the capsules are driving in opposite directions in the tubes, they force air to move with them which forms a large circulation in each adit loop. Thus all capsules participate in a large scale drafting effect which reduces the drag on each capsule. This can be a large benefit for a small annular gap between the capsule and wall. It will be worthwhile to study these interactions.

5.2 Capsule Position Control

The multiple-capsule stability analysis points out the need for precise capsule position control. To conduct feedback control design, we need to consider end effects of linear induction motors. In the modelings so far, we have treated linear induction motors as a continuum of primary windings. In a practical pipetube, we need at least three separate LIM primary windings; one for accelerating capsules into operating speed, one for steady-state travel phase, and one for slowing down and stopping capsules. Furthermore, each of these LIMs may be implemented as a series of disconnected segments for better energy efficiency.

Unlike rotary motors, linear motors have ends and capsules traveling near the ends of LIMs will experience different thrust forces from those in the middle. These end effects may play an important role in the stability properties of capsules. Basically, it is important to determine distances between LIM segments so that capsules can travel smoothly. Namely, the thrust force changes occur in much shorter time intervals than the response time constant of a capsule.

5.3 Different System Configurations

There are many related questions on the system configuration design of a pipeline system. For example, a dual pipeline would be advantageous to ship freight in both directions during the same period. In addition, a dual system could be used in the same direction at the same time if there is a heavy demand for one way travel at different times of the day. The proposed pipeline system creates heat underground. This heat can be viewed as a bi-product and used for road or building heating.

5.4 Computer Animation

The availability of high-speed and low-cost computers has certainly changed the engineering design process. Computer animations can be used to display capsule motions in a pipeline system operation.

6. Conclusions

This report presents results of technical analysis on a pipeline transportation system powered by linear induction propulsion. A concealed pipeline transportation system does not interfere with human movement and has little effect on the environmental surroundings, and has thus been studied for a long time. However, traditional pipeline systems use pneumatic blowers as the power source. Pneumatic pipelines suffer from short travel range, high noise, and low efficiency. This report proposes the use of linear electric motors as the power source in a pipeline transportation system.

The use of linear electric propulsion has many advantages and makes the pipeline concept truly desirable. Linear electric propulsion is always more efficient than that of pneumatic blowers in terms of energy. Further, it can carry freight over a much longer distance and produces little environment pollution.

This report examines the technical aspects of such a freight pipeline system concept using linear induction motors. Aerodynamic drag on a capsule is determined as a sum of three drag components: pressure force on the frontal surface, pressure drop caused by friction along the capsule length, and pressure force on the back of a capsule. As a result, we found an expression for the drag coefficient which is confirmed by published experimental results. In addition, drag modeling leads to the understanding of a phenomenon called “choking.” If the annular gap between a capsule and the pipeline is small, the flow speed along the gap could become sonic and restrict the flow through the gap. Under these conditions, the flow is said to be “choked.” Choked flow would cause much larger drag and should be avoided during normal operations. As a result, there is a limit on how fast a capsule can travel for a given gap between capsules and pipetube. On the other hand, the choking can be used as a passive braking technique by increasing the capsule cross-sectional areas through extended fins.

In a linear induction motor (LIM), alternating current is applied to the primary winding directly and is induced in the secondary winding via transformer action. When excited from a balanced polyphase electric source, a LIM will produce a magnetic field in the

air gap between the primary and the secondary. This magnetic field will travel at a synchronous speed determined by the number of poles and applied frequency at the primary, exerting a thrust force on the secondary. In addition to being energy efficient, linear induction motors provide three ways of active braking, making them even more desirable than pneumatic blowers as the power source. The thrust force of a LIM can be controlled by changing the frequency of the applied electric current at the primary. For use in the pipeline system, we propose to put primary windings on the pipeline and use capsules as secondaries.

Analysis of capsule stabilities indicate that an uncontrolled multiple-capsule system is unstable. In other words, capsules would approach each other and may collide with each other if left uncontrolled. Active capsule position control is needed.

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