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Dynamical stability analysis of a hose to the sky

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A B S T R A C T

The Stratospheric Shield was proposed as a geoengineering concept to control the Earth's climate and reverse global warming. This approach seeks to release sulphur dioxide (SO_2) aerosols in the stratosphere to decrease the amount of sunlight that reaches the surface of the Earth. It was proposed that this can be done by pumping liquefied SO_2 from the ground to the stratosphere in a 30 km long hose supported by aerostats.

In this paper we evaluate the dynamic stability of a hose to the sky considering distributed supportive aerostats and an atomiser nozzle that forces a radial discharge of the fluid at the free end of the pipe. We modelled the pipe as a taut string conveying fluid using the finite element method.

With a nozzle that discharges the flow straight through, we found that the pipe loses stability by buckling when the tension becomes null at least at one location along its length. This instability can be avoided by having a sufficient minimum tension T_0 throughout the whole length of the pipe. The distribution of aerostats does not influence this instability but it modifies the mode shapes and affects the complex frequencies. The atomiser discharging the flow radially at the tip of the pipe has for effect to remove the possibility of an instability; its use is thus recommended. Moreover, we showed that the Coriolis damping can be significant and that by appropriately selecting the number of aerostats as well as the dimensionless flow velocity, stability can be increased. With this in mind, a functional hose to the sky could be designed to maximise Coriolis damping and thus passively damp the motion of the pipe due to forcing from the wind.

1. Introduction

The dynamics of pipes conveying fluid has been the object of research since at least the late 1930s. Initially, the topic attracted researchers' interest because it displayed interesting dynamical behaviour by means of simple mathematical models, amenable to simple analytical or quasi-analytical solutions and to validations via relatively simple experiments (Païdoussis, 1993, 1998, 2008).

Most of the seminal research on the fundamentals, conducted in the 1950s and 60s, was curiosity-driven. Applications making use of the fruits of that research emerged 30, 40 and 50 years later, and they continue popping up at an accelerating pace: on ocean mining, drilling for oil and gas, carbon sequestration in the ocean, micro/nano applications (Païdoussis, 2010), and most recently on the "Stratospheric Shield" (Intellectual Ventures, 2009) which is the subject of the present study.

The stratospheric shield which has been the subject of a lot of attention in the popular press (Bradbury, 2008; Levitt and Dubner, 2009) is a geoengineering concept to control the Earth's climate and reverse global warming. This approach seeks to

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Nomenclature

g	gravitational acceleration
L	length of the pipe
ℓ	dimensionless length of the smallest pipe element
M	mass of the fluid per unit length
m	mass of the pipe per unit length
m_n	mass of the nth aerostat
N	number of aerostats
R	density ratio of the fluids inside and outside the aerostat
$T(z)$	tension along the pipe
T_0	uniform tension component
t	time
U	flow velocity inside the pipe
$\tilde{u}_{cr}$	dimensionless numerical critical flow velocity
u	dimensionless flow velocity
u_{cr}	dimensionless critical flow velocity
V_n	volume of the nth aerostat
W	weight of the pipe
$w(z,t)$	transverse displacement of the pipe
z	vertical coordinate
z_n	vertical coordinate of the nth aerostat
β	mass ratio
β_n	mass ratio of the nth aerostat
$\Gamma(\xi)$	dimensionless tension
Γ_0	dimensionless uniform tension component
δ_{nN}	Kronecker delta
ε	discharge parameter ($\varepsilon=0$, discharges straight through; $\varepsilon=1$ discharges radially)
η	dimensionless transverse displacement of the pipe
ξ	dimensionless coordinate
ρ_i	density of the gas inside the aerostat
ρ_o	density of air around the aerostat
τ	dimensionless time
ω	complex dimensionless frequency

increase the amount of sulphur dioxide (SO_2) aerosols in the stratosphere, so as to decrease the amount of sunlight that reaches the surface of the Earth. It amounts to reproducing the effect of a large volcanic eruption such as that of Mount Pinatubo in the Philippines in 1991. The cooling effect of limiting solar radiation is immediate and not long-lasting, as sulphur dioxide aerosols remain in the stratosphere for only a few years (Robock, 2002). By artificially pumping aerosols in the stratosphere, the blocked sunlight could partially offset the climate warming due to greenhouse gases.

On the downside, geoengineering through the release of SO_2 aerosols could have some serious adverse effects on the hydrological cycle of the Earth. Potentially, it could lead to widespread drought and reduced freshwater resources (Trenberth and Dai, 2007). Moreover, the concept of humans purposely modifying the climate raises important ethical issues (Crutzen, 2006; Shepherd, 2009). The consequences and implications of geoengineering are not completely understood and require additional research before any implementation should be attempted (Shepherd, 2009). On the other hand, better informed decision will result from further analyses to assess the feasibility of the technology. This is what we pursue here.

Where the fluid-conveying pipe comes into play in the stratospheric shield is that it was suggested as the simplest and most cost-effective way to deliver tons of SO_2 aerosols in the stratosphere (Intellectual Ventures, 2009; Davidson et al., 2012). It is proposed to use a 30 km long hose only a few centimetres in diameter held up vertically by aerostats (or balloons) to carry 100 000 metric tons of SO_2 up to the stratosphere every year. It is the goal of the present paper to investigate theoretically the dynamic stability of such a slender hose and to see if it would be subject to garden-hose instability (Païdoussis, 1998).

This problem is related to that of tethered aerostat stability. Williamson and Govardhan (1997) and Govardhan and Williamson (1997) showed that a tethered sphere could oscillate significantly when subjected to steady flow due to vortex-induced vibrations. Lambert and Nahon (2003) studied numerically through a lumped-mass approach the nonlinear dynamics of a streamlined aerostat tethered to the ground by one single tether. The aerodynamic forces on this streamlined aerostat were modelled with empirical lift, drag and moment coefficients and with no vortex-shedding forcing considered. The stability analysis showed the system to be stable at all wind speeds. Coulombe-Pontbriand and Nahon (2009) used the approach of Lambert and Nahon (2003) to model a spherical aerostat and added a sinusoidal forcing to account for vortex-shedding excitation. In essence, the design of an aerostat will influence its aerodynamic and inertial properties and if its shape is blunt, vortex-induced vibrations can occur. Because the effect of wind is so dependent on the exact geometry of the aerostat, we leave these effects for later studies.

In the current study, we focus our attention on the effect of the internal flow on the hose system. We investigate the effects on stability of (i) the see-saw tension along the pipe caused by distributed supportive aerostats, (ii) the point masses associated with the aerostats, and (iii) the atomiser nozzle that forces a radial discharge of the fluid at the free end of the pipe.

2. Methodology

We consider a pipe, a few centimetres in diameter and of length L, anchored to the ground and reaching 30 km up to the stratosphere, as depicted in Fig. 1(a). It is suspended from N equally distributed identical aerostats – or balloons – along its length.