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Stability of spinning satellite under axial thrust and internal mass motion

Frank L. Janssens [a], Jozef C. van der Ha [b,*]

[a] Wilhelminastraat 29, 2201 KA Noordwijk, The Netherlands
[b] 5808 Bell Creek Road, Deming, WA 98244, USA

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ABSTRACT

This paper considers a spinning rigid body and a particle with internal motion under axial thrust. This model is helpful for gaining insights into the nutation anomalies that occurred near the end of orbit injections performed by STAR-48 rocket motors. The stability of this system is investigated by means of linearized equations about a uniform spin reference state. In this model, a double root does not necessarily imply instability. The resulting stability condition defines a manifold in the parameter space. A detailed study of this manifold and the parameter space shows that the envelope of the constant solutions is in fact the stability boundary. Only part of the manifold defines a physical system and the range of frequency values that make the system unstable is restricted. Also it turns out that an increase of the spring stiffness, which restrains the internal motion, does not necessarily increase the stability margin. The application of the model is demonstrated using the orbit injection data of ESA's Ulysses satellite in 1990.

1. Introduction

After decades of successful upper stage firings using spinning solid rocket motors, the fast growth rates of the nutation angle that occurred toward the end of STAR-48 burns, came as a total surprise. Flandro et al. [1] provides a list of twelve PAM-D[1] orbit injections, of which nine showed an excessive nutation angle at the end of the burn. The STAR-48 was the engine commonly used in the 1980s as integrated in the Perigee Assist Motor module (PAM). A novel feature of the STAR-48 was that, in an attempt to shorten the engine length, the nozzle was made partially re-entrant in the combustion chamber. This design change introduced somehow, depending on the PAM/spacecraft configuration, an instability mechanism at the end of the burn.

This attitude instability inspired many investigations, see Refs. [1–18]. Eventually, it became clear that only two research directions were promising. The first pointed to instability of the gas dynamics within the combustion chamber due to the fact that the new complex shape of the burning surface changed the gas flow significantly. The second mechanism is known as the 'slag model'. It studies the internal motion of the combustion products (i.e., Al_2O_3 particles) that may accumulate as liquid slag within the collar of the STAR-48 re-entrant nozzle. A prospective explanation must involve a sufficiently large transverse torque to overcome the jet damping effect (see Ref. [19]) near the end of the burn. Gradually, a preference for the slag model mechanism emerged as the main cause of instability with a possible contribution of the internal gas flow.

A full description of the nutation problem should start from a set of non-linear time-varying equations coupled

* Corresponding author.
E-mail addresses: fjanssens@ziggo.nl (F.L. Janssens), jvdha@aol.com (J.C. van der Ha).

[1] PAM refers to the 'Perigee Assist Motor' upper stage. PAM-D is the stage that includes the STAR-48 solid motor which is the most frequently used perigee kick motor for geosynchronous injections; for Ulysses, the PAM-S was used.

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to the three-dimensional gas flow equations but its complexity would be overwhelming. A practical approach is to study somewhat restricted models that may explain some aspects of the observed instability. As a first step, it should be verified that a misaligned thrust or a realistic time-varying thrust profile cannot cause the instability. This issue is studied in Ref. [2].

Refs. [1,3,4] provide examples of gas dynamic studies. Flandro et al. [1] summarize the effects of an un-steady vortex flow by transverse torque components that are proportional to the transverse rates. His full model may indeed generate instability but is very sensitive to the system parameters and initial conditions. Meyer [3] starts by expanding classical flow results to include the entering (combustion front) and exit of the gases through the nozzle. Misterek et al. [4] perform numerical simulations on two two-dimensional steady-flow problems but obtains only stabilizing torques.

Janssens [5] uses Flandro's summarizing model [1] in a time-varying version. The expressions for the nutation frequency and jet damping take account of the variations of the mass and moments of inertia during the burn. The results give a higher nutation frequency and a reduced jet damping torque which agrees with the flight data. However, in order to overcome the jet damping, the instability needs to start at the beginning of the burn, which is not compatible with the flight data. Meyer [6] performs different gas dynamic studies and concludes that the gas dynamics effects may only provide a minor contribution to the observed instability. Unfortunately, none of the global investigations is capable of establishing good agreements with *all* available flight data.

The liquid-slag hypothesis has been proposed by Mingori, Or, et al. (see Refs. [7–11]). The main objective was to acquire better insights into the instability mechanism by studying the linearized equations that include the thrust and internal particle motion. These models use the constant mass properties at the end of the burn. For the internal particle motion several models have been proposed. In this paper the model of Refs. [7–9] is used where the particle may move in a plane perpendicular to the spin axis to which it is attached by a spring. This model indeed produces a coning instability due to the coupling of the nutation with a particle located aft of the system center of mass.

Other internal-motion models that may produce instability are a spherical pendulum or two pendulums in a meridian plane (see Refs. [10,11]). Cochran and Kang [12–14] simulate the non-linear dynamics of a body augmented with a spherical pendulum and show that parametric resonances are possible. However, Refs. [12–14] do not present compelling evidence that such resonances are compatible with the observed nutation instability. When modeling the internal motion by a pendulum, we only need its length and mass for which a range of realistic values is available. The instability should occur within this range of parameters which is in fact not the case in Ref. [10].

The physical meaning of the restoring force that counteracts the centrifugal force in the elastic spring model is not at all clear. Here, we interpret the spring stiffness as a 'tuning' parameter for matching the flight data. The introduction of a spring may be avoided by using the constraint force to keep the liquid slag in contact with either the nozzle collar or the combustion chamber wall depending on the spin-to-thrust ratio, see Meyer [6].

At the time in the 1980s when the nutation instabilities occurred, little was known about the amount of slag that may accumulate during a solid rocket burn of about 85 s. In fact, at the time of the Ulysses launch in 1990, the estimates for the STAR-48 varied from 10 kg to over 100 kg. As expected, also this topic generated lots of research (see, for instance, Ref. [15]). In 2000, Ref. [16] provides a list of 53 research papers on the most likely values of the slag masses. The current estimates start at 4 kg whereas Or and Challoner [11] use 9 and 27 kg in their work.

In a pioneering paper, Mingori and Yam [7] obtain a stability condition for their model in terms of two non-dimensional parameters, i.e. β^2 and T_0, which comprise all of the eight physical parameters of their model. This stability condition describes a manifold in the eight-dimensional parameter space. In this paper we clarify and interpret the meaning of this stability boundary in terms of the parameters (i.e., mass and spring stiffness) that define the particle's internal motion.

The next section introduces the nomenclature of the parameter space. The dependencies of the derived parameters on the particle and spring (which cause the instability) are separated, as far as possible, from the remaining six physical parameters. Subsequently, we rewrite the equations of motion from Ref. [7] in terms of the independent parameters of the body and particle components and not in the system parameters. Next, we treat two special cases, i.e. zero stiffness and the particle at the body Center of Mass (CoM), to obtain better insights in the dynamics. The results illustrate the complex relationship between the stability boundary and the physical parameters.

Subsequently, we establish the condition for the existence of constant (or stationary) solutions. This generates a family of linear equations $T_0(\beta^2)$. A new insight is that the envelope of these lines with respect to the inertia ratio produces the stability boundary. Afterwards, we derive the stability boundary by using complex variables and clarify the physical meaning of this transformation. We find the stability condition as an implicit function of the same two non-dimensional parameters $\{\beta^2, T_0\}$ as in Ref. [7] and not as a set of coupled equations. Next, we express the stability boundary in terms of the normalized particle mass and spring stiffness. The result shows that only part of the stability condition, as expressed in β^2 and T_0, corresponds to a physical system. Finally, we derive boundaries for the values of the double root on the stability boundary.

2. Model data and nomenclature

2.1. Physical model

Fig. 1 shows the physical model studied here which is identical to the one used in Refs. [7,8]. It consists of a symmetric rigid body of constant mass M and principal moments of inertia C (axial) and A_b (transverse). The body

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