ON THE SPINNING-DETONATION-LIKE PROPERTIES OF HIGH FREQUENCY TANGENTIAL OSCILLATIONS IN COMBUSTION CHAMBERS OF LIQUID FUEL ROCKET ENGINES

O. F. Ar'kov, B. V. Voitsekhovskii,
V. V. Mitrofanov, and M. E. Topchiyan

The physical nature of the high-frequency instability (HFI) of the combustion process in liquid fuel rocket engines (LRE) has not been, so far, fully revealed [1, 2], and HFI remains a complex scientific and technical problem.

Combustion instability in LRE is undoubtedly related to the general principle of Rayleigh, which states that acoustic waves are intensified when the heat release and pressure variations are in phase. Similar phenomena occur in gases behind the detonation wave front, where the existence of various transverse waves was experimentally disclosed. The instability of a plane detonation front has been theoretically proved [3-5].

Elucidation of the nature of HFI is of considerable interest because of its effect on the design of [rocket] engines, which may culminate in the destruction of nozzles and the burn-out of the combustion chamber walls.

The analysis of the so far known results of experimental investigations of HFI and of the method of its artificial induction [6-8] leads to the conclusion that this phenomenon is essentially caused by the onset of transverse detonation waves, not unlike those observed in spinning detonation.

Let us note a few basic facts related to the effect of HFI on the combustion chamber, as well as to the nature of the phenomenon itself.

1) Damage to the combustion chamber is localized at its periphery and close to the nozzle head.

2) The observed damage indicates a considerable temperature and pressure rise in the nozzle head neighborhood, and appears to be directional.

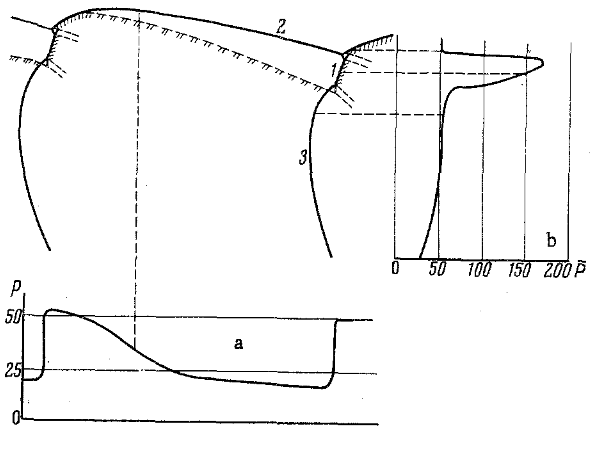

Fig. 1

3) Frequency of the fundamental harmonic of oscillations is the same as that of tangential acoustic oscillations of combustion products.

4) Overloading of a [combustion] chamber results in an increase of frequency of the HFI. The frequencies thus generated correspond to higher harmonics of oscillation, and the consequence of this is the spreading of destruction to the row of nozzles close to the chamber center line.

5) According to [6-8] the glow in a HFI wave has the shape of a line extending along the combustion chamber generatrix with its maximum intensity in the nozzle proximity.

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 11, No. 1, pp. 155-157, January-February, 1970. Original article submitted December 19, 1968.

TABLE 1

Engine	Thrust (tons)	Fuel	Rocket
*aJ*10-138	3.6	$a50 + N_2O_4$	Titan 3a 3rd stage
aJ-137	10	$a50 + N_2O_4$	Moon spacecraft Apollo
α*R*105-*Na* — 5	27	Kerosene + O_2	Atlas E, 2nd stage
α*R*91-*aJ* — 5	45	$a50 + N_2O_4$	Titan 2, 2nd stage
α*R*89-*Na* — 5	75	Kerosene + O_2	Atlas E, 1st stage
H-1	90	Kerosene + O_2	Saturn,1B, 1st stage
F-1	680	Kerosene + O_2	Saturn 5, 1st stage

6) A lateral shock often triggers the onset of HFI in combustion chambers whose operation under normal conditions is stable [6-8].

Comparison of these phenomena with those observed in spinning detonation shows them to be in many respects similar.

A region of very high temperature and pressure - a transverse wave - localized in the neighborhood of a detonation tube wall, is known to exist in spinning detonation. The rotation frequency of the spinning [detonation] head is the same as that of tangential acoustic oscillations [3, 4].

Overloading of a combustion chamber by increasing the fuel atomization, rate of supply, etc. is tantamount to moving away from limit conditions. With detonation in gas the transverse waves begin to move under such conditions throughout the tube cross section with oscillations occurring at higher harmonics of the frequency.

An acoustic trail, extending along the detonation tube generatrix, appears under conditions of spinning detonation with the highest intensity of glow close to the spin head.

The fundamental difference between a HFI and a spin is in that in a LRE there is no primary front forward of the transverse wave. Pressures in a combustion chamber, measured at distances from the nozzles approximately corresponding to the zone of mildly falling pressure in the trail (see Fig. 1b), exceed, in the absence of HFI, the mean pressure in the neighborhood of nozzles by a factor of 2-3, while in a spin these pressures reach 20-30 P_0.

This difference is, however, only apparent. The point is that the conditions in a spin and those in a combustion chamber ensuring a virtually instantaneous chemical reaction behind the transverse wave (curve 1), are reached in a different way. In the first case these are generated by the primary shock front PF (curve 2), which increases the initial mixture temperature to approximately 1150° K and the pressure to 20 P_0. In the second, these conditions obtain without preliminary compression, since in the region close to the nozzles temperatures of the order of 1200° K are reached in the presence of unburnt mixture. Thus the conditions created in proximity of nozzles of a LRE are the same as those behind the forward front of a spinning detonation. If in the latter case the state behind the primary front is taken as the initial, pressures in the considered region of the trail (curve 3) become the same as in a LRE in conditions of HFI.

One of the authors had already pointed out [9-11] the feasibility of a process in which combustion would be produced by transverse waves, provided the gas is fed through a plane [wall] with a large number of holes. It can be seen that exactly such conditions obtain in [combustion] chambers of LRE with a large number of nozzles fitted to the [chamber] end-wall. Preheating of the initial mixture which occurs in these chambers ensures short ignition arrests even after a single compression.

The above considerations permit to conclude that the HFI is a spinning detonation occurring in the specific conditions of a LRE combustion chamber. It is interesting to note in this context that LRE under development in the USA (see Table 1) are being fitted with special quenching devices in the shape of deflectors, partitions, cross-members, etc. for the purpose of preventing the occurrence of HFI.

The optimum dimensions of such partitions are undergoing development on specially equipped rigs for artifically inducing HFI by means of tangential shock impulses introduced into the combustion chamber [6-8].

The fitting of radial fins of a particular height in a detonation tube results in the collapse of spinning detonation. The selection of effective means for the suppression of HFI and its effects must obviously take into consideration the relationships observable in detonation in gases and, in particular, take into account the existence in which shock pressures may exceed the mean pressure in the proximity of the nozzle head by a factor of at least 7-8. This relation follows from the comparison of pressures forward and behind the transverse wave in a spinning detonation.

The most effective means [of combating HFI] would apparently be the use of transverse waves for [improving the] burning of fuel. It could ensure a more complete combustion in chambers of reduced dimensions, since the shock waves produce further atomization of [fuel] droplets and reduce ignition arrests.

LITERATURE CITED

1. A. P. Vasil'ev, V. M. Kudryavtsev, V. A. Kuznetsov, et al., Fundamentals of the Theory and Calculation of Liquid Fuel Rocket Engines [in Russian], Moscow, Vysshaya Skola, 1967.
2. D. K. Zarembo and V. A. Krasil'nikov, Introduction to Nonlinear Acoustics [in Russian], Nauka, Moscow, 1966.
3. B. V. Voitsekhovskii, V. V. Mitrofanov, and M. E. Topchiyan, Structure of the Detonation Front in Gases [in Russian], Izd. SO AN SSSR, Novosibirsk, 1963.
4. R. I. Soloukhin, Shock Waves and Detonation in Gases [in Russian], Fizmatgiz, Moscow, 1963.
5. Yu. N. Denisov, Ya. K. Troshin, and K. I. Shchelkin, "On the analogy of combustion in a detonation wave and in a rocket engine," Izv. AN SSSR, OTN, Energetika i Avtomatika, no. 6, p. 79, 1959.
6. S. S. Penner and F. A. Williams, ed., Detonation and Two-Phase Flow [Russian translation], Academic Press, New York-London, 1962.
7. R. L. Hefner, "Review of combustion stability: development with storable propellants," AIAA paper, no. 65-614.
8. F. H. Reardon, "Combustion stability characteristics of liquid oxygen and liquid hydrogen at high chamber pressures," IAAA paper, no. 65-612.
9. B. V. Voitsekhovskii, "Detonation spin and stationary detonation," Ychenyi Sovet po narodnokhozyaistvennomu ispol'zovaniyu vzryva, Izd-vo SO AN SSSR, Novosibirsk, no. 19, 1960.
10. B. V. Voitsekhovskii, "Stationary spinning detonation," PMTF [Journal of Applied Mechanics and Technical Physics], 10, no. 3, 1969.
11. B. V. Voitsekhovskii, "Stationary detonation," Dokl. AN SSSR, 129, no. 6, 1959.