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An Appliance Door Virtual Modeling For User Experience Design

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Abstract

Domestic appliance are widely used in all countries. During the design phase, it is very important to take advantage of new virtual prototyping technologies in order to improve the user expectations and put the feeling of the user with the device in the centre of the design. The paper deals with the complete simulation of the opening of the front door of an appliance like a refrigerator or an oven. The process is simulated with the use of ad-hoc built program that uses a combination of experimental parameters and virtual fluid dynamic simulations. Each moment involved during the opening of the door is evaluated and a comprehensive explanation of each of them is reported. The entire solving process is parametrized in order to use it in an iteration loop for eventually optimization of the User Experience and the comfort during the opening of the front door. A fridge case study is described and discussed.

Keywords: User Experience (UX), Virtual Prototypes (VPs), user centred design, experience design, door appliance.

INTRODUCTION

Each field of engineering is involved in studying new approaches and new methods in order to improve the environmental efficiency and the User Experience (UX) of each product with different methodologies [1, 2]. A wide field of interest are the domestic appliances, because they are widely used in all industrialized countries, among them the most used ones are domestic refrigerators and ovens. The users intensively use each component of these devices during a day so it is very important to optimize each single component in order to improve the efficiency during the entire life. A user centred design can help to satisfy the user Expectations and give it the best UX. The study is complex because it involves different aspects and the ways for simulating this problem can be experimental tests or virtual simulations. For this reasons, Virtual Prototypes (VPs) are developed in order to help to predict the interaction between user and appliance. The studies can be conducted for improving different aspects in different phases. One of these is the static condition, when the refrigerator or the oven work without interaction with the user. The problem involves the knowledge of the distribution of the air inside the refrigerator or the oven [3, 4], the efficiency of the sealing elements [5], the temperature exchange with the external environment [6, 7], the structural integrity of each material used [8]. For the study of the internal distribution of the air the better way is to use computational fluidynamics (CFD) simulations, from several years this approach is very reliable and it solves many engineering problems [9–13]. It is very useful in order to have, in preliminary design phase, information for to direct the project along the better way. The results of CFD simulations can be used for an optimization loop in a parametric model and so to link all the aspects of the problem [14]. A second condition is the interaction with the user, when the door must be open. The first aspect is the comfort and the difficulty relative to the opening of the door perceived by the user [15, 16], the second one is the mechanical and fluidynamics aspect during this process [17, 18]. In this case is not simple to simulate the interaction between user and device with virtual modeling, for this reason only experimental data exist in literature. A good review paper of the recent developments is proposed by Radermacher [19]. This article deals with the problem of the interaction between the user and domestic device. A combination of CFD results and physical formulation present in literature are used in order to solve the entire process of opening. This condition has been separated in two different phases and for each phase a complete explanation of the forces and moments involved is proposed. The entire process allows understanding which are the most important parameters in order to increase the comfort in opening phase. The use of CFD simulations helps to solve the problem of air and temperature interaction and help to have a better comprehension of the entire phenomena. All process is automatable and so it can be a good tool for investigating a design space.

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NOMENCLATURE:

A Gasket surface [m^2]

B Magnetic flux density [T]

a Heigh of the door [m]

b Width of the door [m]

c_e Gas expansion coefficient [K^{-1}]

C_M Coefficient of aerodynamic resistance to rotation of the door

f_1 Static friction coefficient of hinges

f_2 Dynamic friction coefficient of hinges

k Distance between the hinges axis and the vertical gasket [m]

K_g Stiffness of the gasket per unit of length [N/m^2]

I Door moment of inertia [kg m^2]

l width of the gasket [m]

M Torque exerted by the user [Nm]

W Door weight [kg]

T_i Internal temperature of the appliance [K]

T_e External temperature [K]

T_f Internal temperature of the appliance after opening [K]

ϑ Opening angle of the door [rad]

μ_0 magnetic constant or the permeability of free space [H/m]

ρ Air density [kg/m^3]

φ Air exchange coefficient at opening of the door

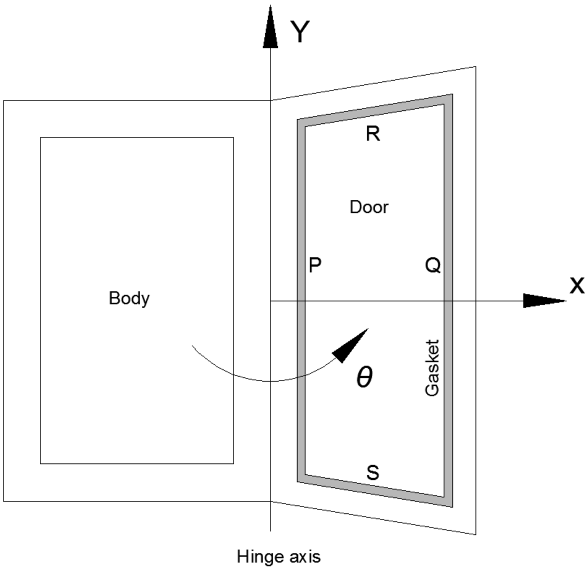

Figure 1: Reference system and gasket nomenclature

The global system has an integral reference system applied on the door of the appliance with the x-axis on the handle and an orthogonal y-axis on the hinge axis, as in Figure 1. The four elements that make up the gasket are defined by the letters P, Q, R, S, as in the figure. In particular P is the internal gasket, Q is the external gasket and R and S are the upper and lower gaskets. The opening angle of the door is called ϑ.

MATERIALS AND METHODS

To apply the dynamic equations to an appliance door, in order to evaluate the moments needed by the user during the time, it is necessary to distinguish two phases: Phase 1 while the door is closed yet but the user has started to exert a moment of opening and Phase 2 after the first detachment of the gaskets (Figure 2).

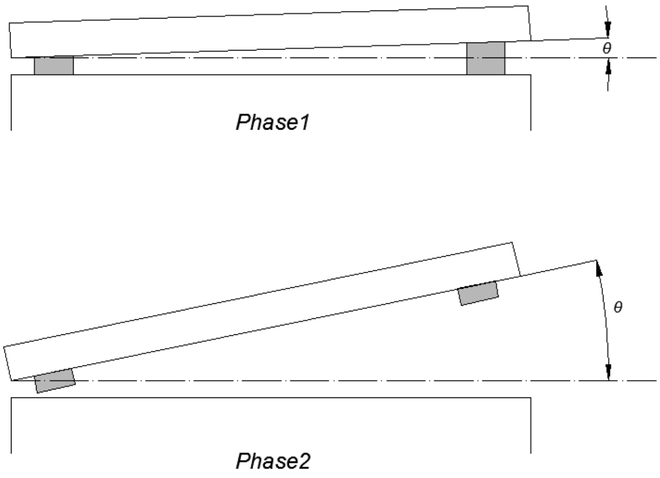

Figure 2: In the Phase 1 the door is closed yet, in the Phase 2 the door is opened

A generic appliance may have a magnet inside the gasket (typically the refrigerators) and has a thermal difference between the inside and the outside (refrigerators, ovens).

The door resistance equations are differential equations and depend not only on the opening angle of the door ϑ, but also on $\dot{\vartheta}$ and on $\ddot{\vartheta}$. For this reason it is necessary to hypothesize a user opening curve $\vartheta(t)$.

The proposed method follows the flow chart in Figure 3.

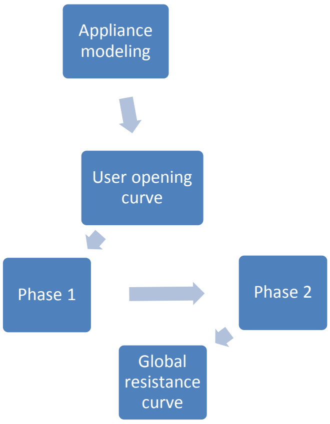

Figure 3: Flow chart of the applied method

In the Phase 1, it is possible to distinguish the following resistance that dimensionally are moments (the pole of the moments is taken on the hinge axis):

- Static frictional resistance of the hinges
- Magnetic attraction (if present)
- Elastic deformation of the gasket
- Thermal effect

In detail the components have been obtained as follows:

- Static frictional resistance of the hinges

$$M_{F_1} = f_1 W \frac{b}{2}$$

- Magnetic attraction

$$M_{M_1} = \frac{AB^2}{2\mu_0} b$$

- Elastic deformation of the gasket

The stiffness K_g is defined as:

$$F_g = K_g x$$

For each unit of length of the gasket, consequently the four different sections of gasket, identified with the subscripts P, Q, R and S, have different behaviour. In particular, the forces can be expressed as:

$$F_{g_P} = K_g \cdot k tan\vartheta \cdot a$$

$$F_{g_Q} = K_g \cdot (k+b) tan\vartheta \cdot a$$

$$F_{g_R} = F_{g_S} = K_g \cdot (k + \frac{b}{2}) tan\vartheta \cdot b$$

And the total moment due to the elastic deformation is:

$$M_g = M_{g_P} + M_{g_Q} + 2M_{g_R}$$
$$= F_{g_P} k + M_{g_Q}(k+b) + 2M_{g_R}(k + \frac{b}{2})$$

- Thermal effect

The thermal effect is caused by the difference of temperatures of the appliance interior after an opening and when the steady condition is reached. Particularly in refrigerators, because of the lowering of the temperature, the internal air increases his density causing an internal depression. Conversely, in ovens, the increase in temperature creates an expansion of the air and thus an overpressure.

$$M_T = \Delta p a \frac{b^2}{2} = p_0 c_e \Delta T a \frac{b^2}{2}$$

In which ΔT is the temperature difference between the internal temperature at the opening time and the internal temperature when the door was closed.

$$\Delta T = T_f - T_i$$

This value changes with the time, until it comes to a stationary condition. The value of the internal temperature at the time of opening depends on the amount of air exchanged with the exterior at the last opening. This amount, represented by the coefficient φ, depends on the volume of the appliance, its filling state and the time for which the door has been opened.

$$T_f = \varphi T_e - (1 - \varphi) T_i$$

The experimental evaluation of φ, it is quite complex and the CFD can represent an effective tool.

For the equilibrium, the total moment in the Phase 1 is:

$$M = M_T + M_g + M_{F_1} + M_{M_1}$$

Instead, in the Phase 2, after the first detachment of the gaskets, start the dynamic effects and the exchange of air between the interior and exterior of the appliance.

The components of the global moment are:

- Inertial moment
- Dynamic frictional resistance of the hinges
- Aerodynamic resistance
- Magnetic attraction (if present)

In detail, the components have been obtained as follows.

- Inertial moment

$$M_I = I\ddot{\vartheta}$$

- Dynamic frictional resistance of the hinges

$$M_{F_2} = f_2 W \frac{b}{2}$$

- Aerodynamic resistance

$$M_D = \frac{1}{2} C_M \rho a b^4 \dot{\vartheta}^2$$

For the evaluation of the coefficient of aerodynamic resistance to rotation of the door, C_M, a CFD analysis was conducted.

- Magnetic attraction

Also in this case, the four different sections of gasket P, Q, R and S, have different behaviour. In particular, the forces can be expressed as:

$$M_P \propto \int_0^a \frac{1}{k^2 tan^2\vartheta} dy = \frac{a}{k^2 tan^2\vartheta}$$

and

$$M_Q \propto \int_0^a \frac{1}{(k+b)^2 tan^2\vartheta} dy = \frac{a}{(k+b)^2 tan^2\vartheta}$$

and

$$M_R \propto \int_k^{b+k} \frac{(k+x)}{x^2 tan^2\vartheta} dx = \left| \frac{lnx}{tan^2\vartheta} - \frac{k}{xtan^2\vartheta} \right|_{k}^{b+k} = \frac{\ln\left(\frac{b+k}{k}\right)^{(b+k)} + b}{(b+k)tan^2\vartheta}$$

consequentially

$$M_{M_2} = f\left(\frac{a}{k^2 tan^2\vartheta} + \frac{a}{(k+b)^2 tan^2\vartheta} + 2\frac{\ln\left(\frac{b+k}{k}\right)^{(b+k)} + b}{(b+k)tan^2\vartheta} \right)$$

For the equilibrium, the total moment in the Phase 2 is:

$$M = M_I + M_D + M_{F_2} + M_{M_2}$$

RESULTS AND DISCUSSION

Case Study

As a case study, has been chosen a commercial built-in fridge, class A +, 207 l. External dimensions mm 1218x540x549 (Figure 4).

Figure 4: The case study fridge

The main geometrical and physical characteristics are:

- a 1.19 m;
- b 0.54 m;
- l 0.02 m;
- K_g $0.9 \cdot 10^3$ N/m^2;
- B 0.07 T;
- c_e $3.66 \cdot 10^{-3}$ K^{-1};
- f_1 0.8;
- f_2 0.5;
- k 0.05 m;
- I 4.77 Kg m^2
- W 5 kg;
- T_i 273 K;
- μ_0 $1.25 \cdot 10^{-6}$ H/m;

The following environmental parameters has been assumed:

- ρ 1.225 N/m^3;
- T_e 293 K;

Aerodynamic resistance

For the parameter C_M and φ, as discussed in the Materials and methods section, experimental or virtual tests are required. In the present case, a 2D CFD method has been used with RANSe. The volume of control (Figure 5) is a circular area with in the centre the door. The area diameter/door width ratio is 8. The volume of control was divided into two different concentric circular zones. In the inner one, the initial grid is triangular, with a size of 1 mm and a maximum skewness of 0.2. In the outer zone, the grid has a size of 250 mm and the same skewness limit. The door is modelled as a rigid body with dynamic mesh condition. The interior has a springing deforming condition and a re-meshing occurs when the threshold of 0.3 in skewness is reached. Simulations ranged from 0 to 40 ° at five different angular speeds: 0.5, 1.0, 1.5, 2.0, 2.5 rad/s. The flow it is assumed laminar. The time domain is discretized in fixed time step of 10-4 s.

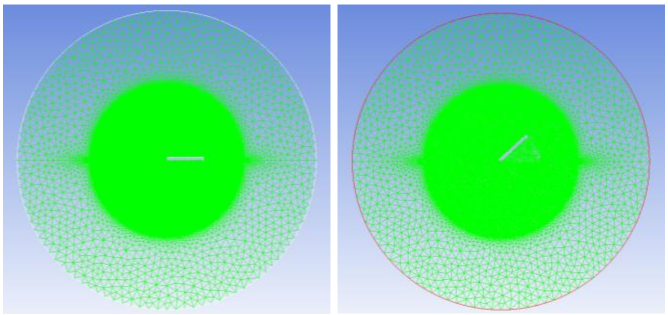

Figure 5: Volume of control at θ 0° (left) e θ = 40° (right)

In Figure 6 it is showed the field of pressure around the door and in Figure 7 the pathlines.

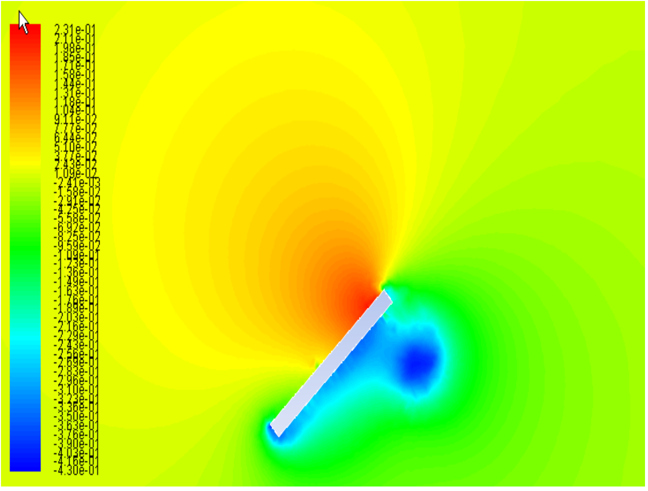

Figure 6: Pressure field around the door

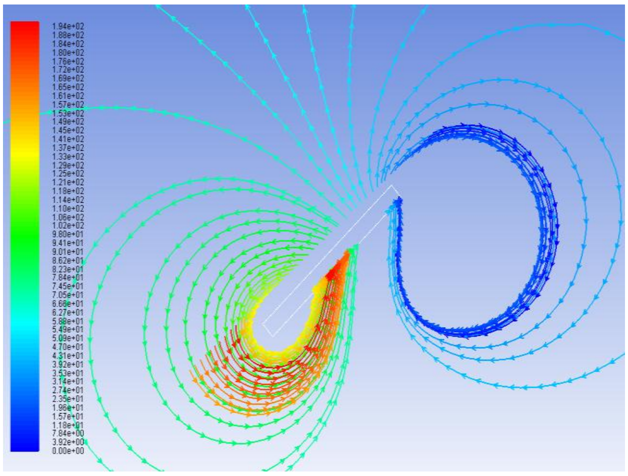

Figure 7: Pathlines

The results obtained at the five different angular velocities are reported in terms of moment of resistance and relative resistance coefficient in Table 1 and in Figure 8. The moment takes negative values as it is a resistance.

Table 1: Aerodynamic moment and coefficient of resistance

$\dot{\vartheta}$	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**[rad/s]**
M_D	-0.01	-0.08	-0.19	-0.32	-0.49	**[Nm]**
C_M	-0.72	-0.94	-1.04	-1.02	-1.00	-

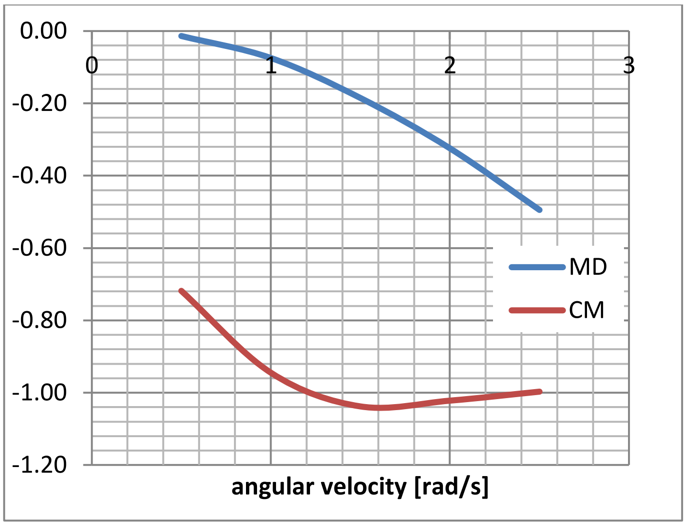

Figure 8: Aerodynamic moment and coeffiecient of resistance

The Figure 9 shows the time course at a given angular velocity. The constant trend highlights the achievement of stationary condition.

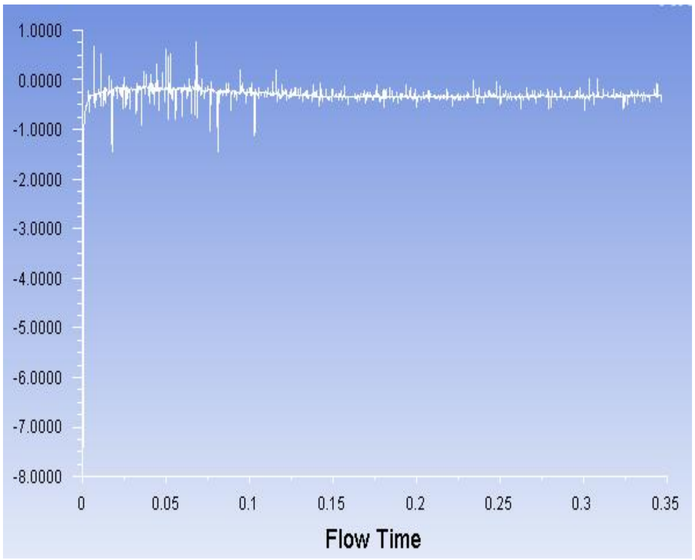

Figure 9: Aerodynamic resistance Vs Time

Throughout the speed field, it is possible to observe how, while increasing the moment of resistance, the coefficient remains almost constant. The average values and standard deviation are given in the Table 2.

Table 2: Average value of C_M and Standard deviation

Average value of C_M	**-0.94**
Standard deviation	0.13

Moreover, it must be considered that, at lower speeds, the aerodynamic effect becomes practically negligible. So it is assumed that $C_M = -0.94$.

Thermal effect

Even in this case, the virtual model is a good solution in terms of reliability of the result and speed. A 2D volume of control was developed, with the modeling of the external environment and the interior of the refrigerator. Initial conditions of T_i 273 and T_e 293 K K are assumed. The energy equations were enabled. In this case the fridge was hypothesized empty.

The Figure 10 refers to four different instants; the colours represent the temperatures (red is 293 K and blue 273 K). The first instant is at the initial phase, when the door is opening, the second one is near to the maximum opening, the third one when the door is closing and the fourth one when the door it is already close again. As it is possible to see, after closing, a little cool air has spilled into the surrounding environment, and a little warm air has entered the fridge. With the CFD software it is possible to calculate the amount of this air exchange and the final new internal temperature.

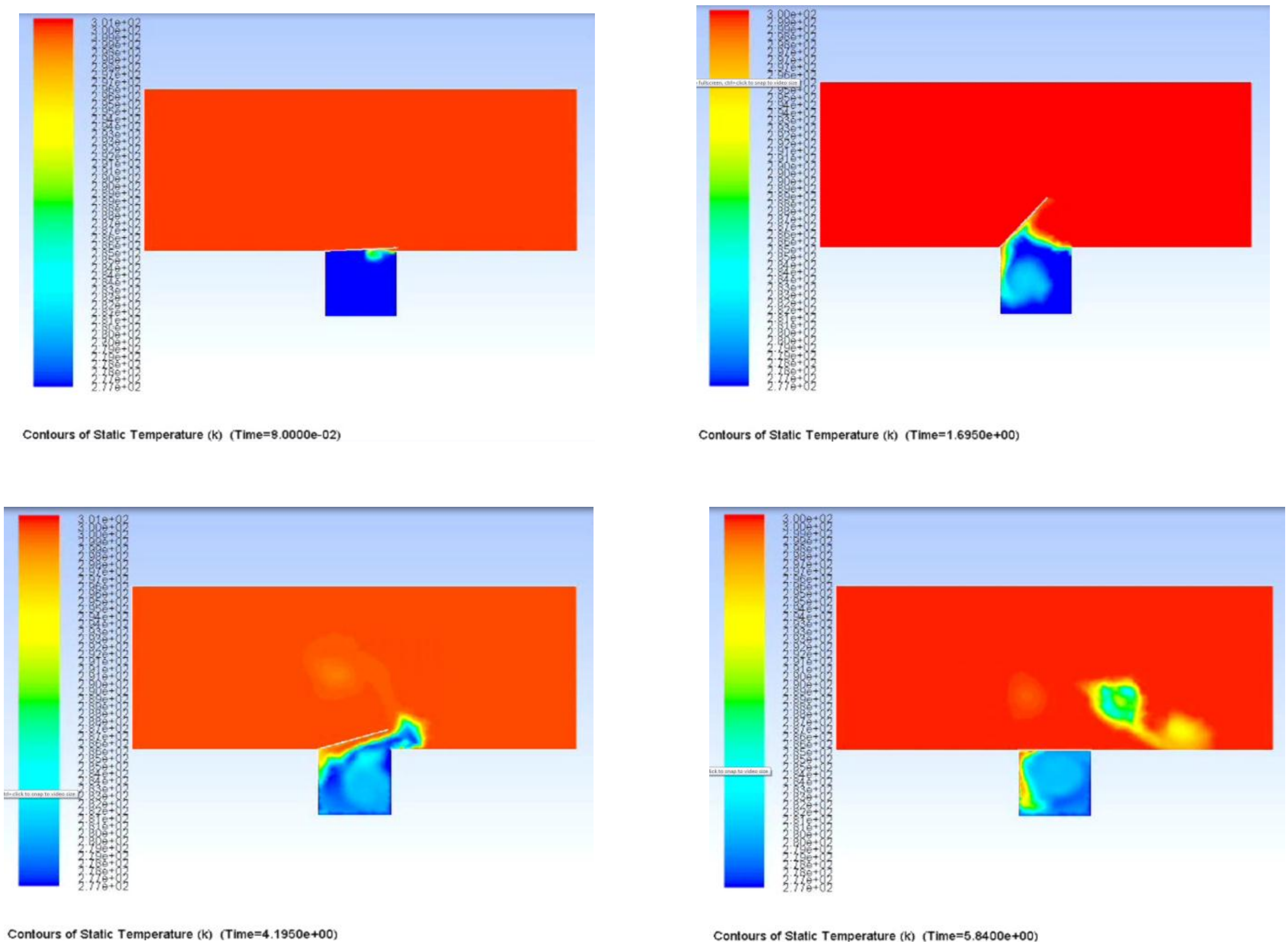

Figure 10: Contours of temperature at four different instants

In this case study, the obtained coefficient is φ= 0.21, that implies an internal final temperature of 277.2 K.

Global moment

In the case of study, the user opening curve in Figure 11 has been assumed, from which it is possible to obtain, integrating the curve, the angular velocity (Figure 12) and acceleration curves (Figure 13). At the end of the opening, corresponding to the maximum angular position, velocity and acceleration are null.

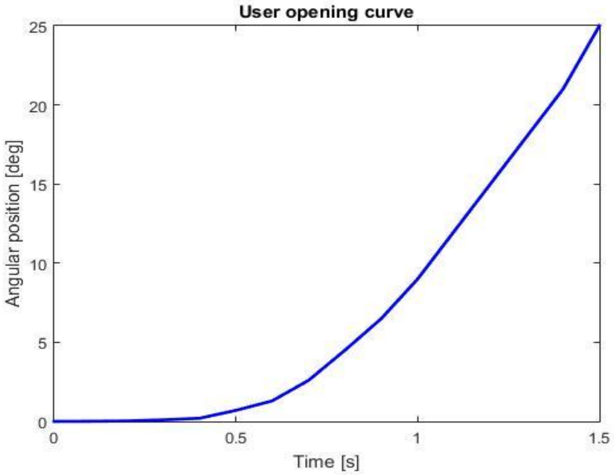

Figure 11: User opening curve – Angular position

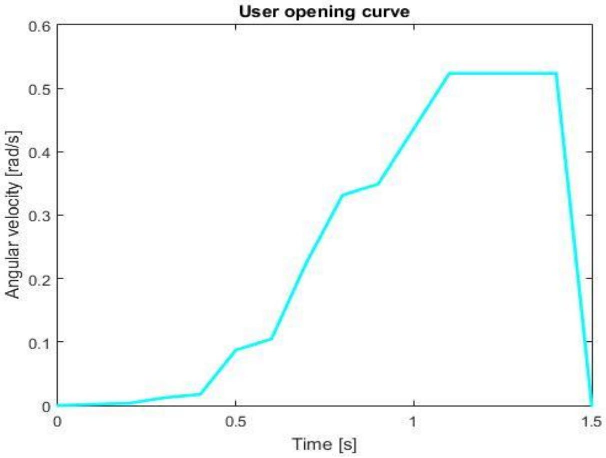

Figure 12: User opening curve - Angular velocity

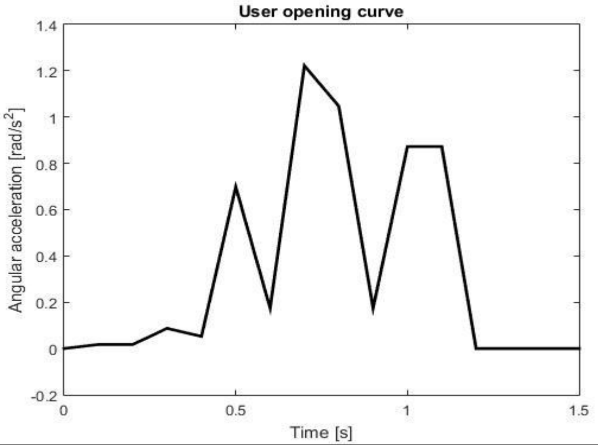

Figure 13: User opening curve - Angular acceleration

The hypothesized opening curve applied by the user generates the global moment of resistance showed in Figure 14. In the picture the two phases, the first one with the door closed yet and the second one after the detachment of the gasket, are well visible.

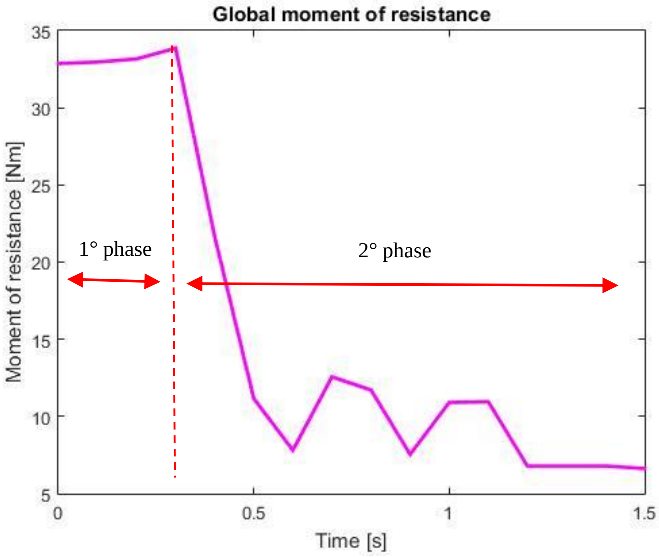

Figure 14: Global moment of resistance. The two phases are highlighted

As it is possible to see, in the first phase, the global moment grows to a maximum, subsequently it decays rapidly with some oscillations. The various components of resistance are showed in the charts, divided into the two phases, respectively in Figure 15 and Figure 16.

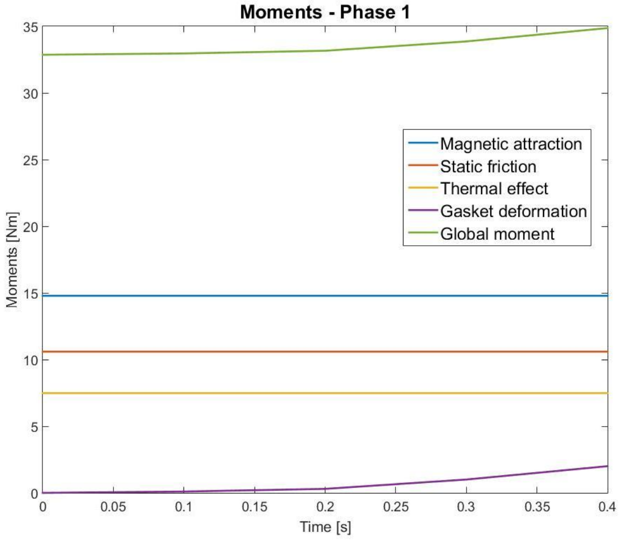

Figure 15: Components of the moment of resistance during Phase 1

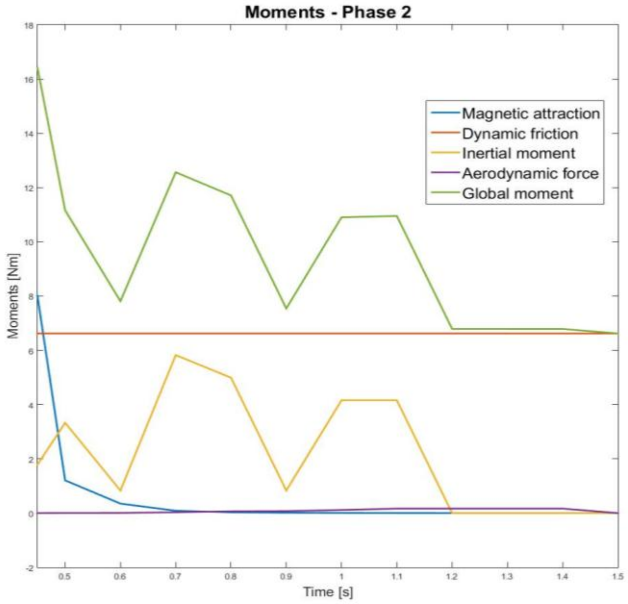

Figure 16: Components of the moment of resistance during Phase 2

The percentage weight of each resistance component is shown in the Table 3, for the phase 1, and in Table 4, for the phase 2.

Table 3: Percentage components of the moment of resistance during Phase 1

Time [s]	Magnetic attraction	Static friction	Thermal effect	Gasket deformation	Global moment
0	45%	32%	23%	0%	100%
0.1	45%	32%	23%	0%	100%
0.2	45%	32%	23%	1%	100%
0.3	44%	31%	22%	3%	100%
0.4	42%	30%	21%	6%	100%

Table 4: Percentage components of the moment of resistance during Phase 2

Time [s]	Magnetic attraction	Dynamic friction	Inertial moment	Aerodynamic resistance	Global moment
0.4	68%	31%	1%	0%	100%
0.5	11%	59%	30%	0%	100%
0.6	4%	85%	11%	0%	100%
0.7	1%	53%	46%	0%	100%
0.8	0%	57%	43%	1%	100%
0.9	0%	88%	11%	1%	100%
1	0%	61%	38%	1%	100%
1.1	0%	60%	38%	2%	100%
1.2	0%	98%	0%	2%	100%
1.3	0%	98%	0%	2%	100%
1.4	0%	98%	0%	2%	100%

From the case study analysis, it can be seen that in the Phase 1, the global moment of resistance is composed of several components that are of the same order of magnitude. The magnet gives the most important contribution, however static friction and thermal effect are not negligible. In the Phase 2, the magnetic component decays rapidly and the most significant components are the dynamical friction of the hinges and the inertial moment. Conversely, the aerodynamic component is practically negligible.

CONCLUSIONS

The paper describes as it is possible to model the opening phase of the front door of a domestic appliance. The problem of the opening is divided in two distinct phases, Phase 1 is when the door is closed yet but the user has started to exert a moment of opening and Phase 2 after the first detachment of the gaskets. For each of them, a complete evaluation of all forces and moments is obtained. An interesting part concerns the use of the Compyutational Fluidynamics (CFD) to find the aerodynamical resistance coefficients of the door during the opening movement and the thermal effects caused by the difference of temperature between the external and internal environment. Thanks to mesh motion is possible to evaluate these quantities and understanding the path flow during this phase. The other moments are evaluated with formula that describe the physical phenomena. The interaction with the user is defined with an opening user curve. The first phase all moments are in the same order of magnitude, however, during the second phase, the most important contribution is from the dynamical friction of the hinges and the inertial moment. The moment caused by aerodynamical resistance is negligible. The approach is very simple and can be used in an automatic optimization loop for understanding the impact of design parameters on the final results. Thanks to this virtual approach is possible avoid the use of experimental facilities that request additional time and costs and speed up the process of design.

REFERENCES

[1] Barone S, Cucinotta F, Sfravara F (2017) A comparative Life Cycle Assessment of utility poles manufactured with different materials and dimensions. In: Adv. Mech. Des. Eng. Manuf. Springer International Publishing, pp 91–99

[2] Cucinotta F, Guglielmino E, Sfravara F (2017) Life cycle assessment in yacht industry: A case study of comparison between hand lay-up and vacuum infusion. J Clean Prod 142:3822–3833. doi: 10.1016/j.jclepro.2016.10.080

[3] Laguerre O, Ben Amara S, Moureh J, Flick D (2007) Numerical simulation of air flow and heat transfer in domestic refrigerators. J Food Eng 81:144–156. doi: 10.1016/j.jfoodeng.2006.10.029

[4] James SJ, Evans J (1992) The temperature performance of domestic refrigerators. Int J Refrig 15:313–319. doi: 10.1016/0140-7007(92)90047-X

[5] Masjuki H., Saidur R, Choudhury I., et al (2001) The applicability of ISO household refrigerator–freezer energy test specifications in Malaysia. Energy 26:723–737. doi: 10.1016/S0360-5442(01)00028-7

[6] Mergui S, Penot F (1999) Convection naturelle en cavité carrée différentiellement chauffée : investigation expérimentale à Ra = 1,69 × 109 = Natural convection in a differentially heated square cavity: experimental investigation at Ra = 1.69 X 109. Int J Heat Mass Transf 39:563–574.

[7] Laguerre O (2011) Heat transfer and air flow in a domestic refrigerator. Math Model Food Process Contempora:445–474.

[8] Cucinotta F, Guglielmino E, Risitano G, Sfravara F (2016) Assessment of Damage Evolution in Sandwich Composite Material Subjected to Repeated Impacts by Means Optical Measurements. Procedia Struct Integr 2:3660–3667. doi: 10.1016/j.prostr.2016.06.455

[9] Brusca S, Cucinotta F, Galvagno A, et al (2015) Oscillating water column wave energy converter by means of straight-bladed Darrieus turbine. Energy Procedia 1–10.

[10] Cucinotta F, Nigrelli V, Sfravara F (2017) A preliminary method for the numerical prediction of the behavior of air bubbles in the design of Air Cavity Ships. pp 509–516

[11] Chhanwal N, Anishaparvin A, Indrani D, et al (2010) Computational fluid dynamics (CFD) modeling of an electrical heating oven for bread-baking process. J Food Eng 100:452–460. doi: 10.1016/j.jfoodeng.2010.04.030

[12] Boulet M, Marcos B, Dostie M, Moresoli C (2010) CFD modeling of heat transfer and flow field in a bakery pilot oven. J Food Eng 97:393–402. doi: 10.1016/j.jfoodeng.2009.10.034

[13] Cucinotta F, Nigrelli V, Sfravara F (2017) Numerical prediction of ventilated planing flat plates for the design of Air Cavity Ships. Int J Interact Des Manuf. doi: 10.1007/s12008-017-0396-x

[14] Cella U, Cucinotta F, Sfravara F (2017) Sail Plan Parametric CAD Model for an A-Class Catamaran Numerical Optimization Procedure Using Open Source Tools. pp 547–554

[15] Strolz M, Mörtl A, Graf M, Buss M (2009) Development, control, and evaluation of an actuated car door. IEEE Trans Haptics 2:170–180. doi: 10.1109/TOH.2009.19

[16] Shin S, Lee I, Lee H, et al (2012) Haptic simulation of refrigerator door. Haptics Symp 2012, HAPTICS 2012 - Proc 147–154. doi: 10.1109/HAPTIC.2012.6183783

[17] Strolz M, Groten R, Peer A, Buss M (2011) Development and evaluation of a device for the haptic rendering of rotatory car doors. IEEE Trans Ind Electron 58:3133–3140. doi: 10.1109/TIE.2010.2087292

[18] Strolz M, Ehinger C, Buss M (2009) Design of a device for the high-fidelity haptic rendering of rotatory car doors. Proc - 2009 2nd Conf Hum Syst Interact HSI '09 202–209. doi: 10.1109/HSI.2009.5090979

[19] Radermacher R, Kim K (1996) Domestic refrigerators: recent developments. Int J Refrig 19:61–69. doi: 10.1016/0140-7007(95)00069-0